



PHOSPHORUS AVAILABILITY IN AN ACID TROPICAL SOIL AMENDED WITH PHOSPHATE ROCKS

A.R. ZAHARAH, H.A.H. SHARIFUDDIN
Universiti Putra Malaysia,
Serdang, Selangor, Malaysia

Abstract

The fate of P from phosphate rocks applied to Malaysian soils has not been studied in detail. Since the plantation sector is the major consumer of phosphate rock (PR) in Malaysia, studies on the dissolution and agronomic effectiveness of PR are of great interest to the country. Thus a series of greenhouse and laboratory experiments involving conventional chemical extractants and ^{32}P isotopic techniques was carried out to evaluate the agronomic effectiveness of PR sources of different reactivity.

Phosphorus and other chemical properties of the soil and PRs studied were determined. The P solubility tests by 2% formic acid, 2% citric acid and neutral ammonium citrate gave positive correlation with P uptake by one-year old oil palm seedlings. Neutral ammonium citrate proved to be a better indicator of PR solubility and its correlation coefficient with P uptake improved by expressing citrate solubility as a percentage of the rock rather than as a percentage of total P_2O_5 content.

The agronomic effectiveness of TSP and 6 PR sources was evaluated in glasshouse conditions with oil palm seedlings for one year-period. The percentage of PR dissolution varied greatly among PR sources. The PR dissolution was assessed by 0.5 M NaOH, Pi strip, L-value and 1 M ammonium citrate-dissolved Ca. Irrespective of the methods used, the more reactive PR such as North Carolina and Tunisia dissolved more P than the lower reactive sources such as Christmas Island and China PR. All the four methods used gave positive correlation with plant P uptake, with 0.5M NaOH being the best indirect method for determining PR dissolution. Less than 30% of the applied P was dissolved during the one-year period, with only about 15 to 40% of the dissolved P being taken up by the oil palm seedlings.

A laboratory ^{32}P isotopic exchange method was also carried out in this acid soil to assess the soil P status parameters. A low water soluble P concentration (C_p) was found for all PRs used. The ratio of the specific activity of ^{32}P remaining at one minute over initial radioactivity (r_1/R) was less than 0.2 in all sources of PR used, thus showing the very high P fixing capacity of this soil. This isotopic technique also demonstrated that PR from North Carolina and Tunisia were more readily available to plants than the less reactive PR from Jordan, Morocco, Christmas Island and China.

1. INTRODUCTION

Malaysian soils are deficient in available P due to very low orthophosphate ion concentrations in the soil solution. The abundance of variable charge colloids in these soils together with low pH and low CEC has led to the presence of high amounts of oxides and hydroxides of Fe and Al. The oxides and hydroxides fix large amounts of soluble P leading to low concentrations of available P in soil solution [1]. Thus, large amounts of phosphate fertilizers are required to attain high yields from crops. Phosphate rocks (PR) have been long used in Malaysian agriculture since 1930 when Gafsa PR from Tunisia was introduced. Around 1950, the use of Christmas Island PR became more prominent because of its closer proximity to Malaysia until 1987 when its production diminished. From this time on, more PR sources are being imported into the Malaysian fertilizer market. Phosphate rock has been popular because they are cheaper than the water-soluble P fertilizers. The agronomic effectiveness (AE) of these various PR sources, however, has never been evaluated in detail. This study was conducted to evaluate the AE of 6 sources of PR commonly found in Malaysia (North Carolina, Tunisia, Jordan, Morocco, Christmas Island and China) and triple superphosphate using oil palm seedlings. In addition a dissolution study of these PRs using 0.5M NaOH, 2% citric acid, 2% formic acid, 0.5M ammonium citrate, and ^{32}P isotopic techniques was carried out in the same Ultisol.

2. MATERIALS AND METHODS

A topsoil (0-30 cm) bulk sample of the Rengam series soil (Typic Paleudult) having the following physical and chemical properties was collected. The particle size distribution consisted of clay

(0-2 μm) at 47.2%, fine silt (2-20 μm) at 4.1%, course silt (20-50 μm) at 3.3%, fine sand (50-200 μm) at 11.1%, and course sand (200 – 2000 μm) at 34.3%. The soil had 2.51% organic matter, 1.46% organic carbon, 1.16% total N and a C:N ratio of 12.6. Its total P content was 80.5 mg kg^{-1} , Olsen-P of 3.45 mg kg^{-1} and Bray-2 P of 12.6 mg kg^{-1} . Its exchangeable Ca, Mg, K, Na, Mn, Al and H were 0.24, 0.17, 0.14, 0.03, 0.01, 1.24 and 0.15 cmol (+) kg^{-1} soil, respectively. The soil pH measured in water and 1M KCl solution in a 1:2.5 soil to solution ratio were 4.60 and 4.00, respectively. Fifteen kg of air-dried soil sieved through 2 mm sieve were weighed and placed in black polyethylene bags. Four sets of each treatment were harvested at 3, 6, 9 and 12 months after treatments. All the soil was labeled with 300 $\mu\text{Ci } ^{32}\text{P}$ solution containing 5 mg P as carrier using 3 L distilled water per bag. The first set that was harvested at 3 months was labeled at the beginning of the experiment. The second set was labeled at the third month and harvested at 6 months. The third set was labeled at the 6th month and harvested at 9 months. The fourth set was labeled at the 9th month and harvested at 12 months after planting. The treatments used were: control (^{32}P only), Triple superphosphate (TSP), and phosphate rocks from North Carolina, USA (NCPR), Gafsa from Tunisia (TPR), Jordan (JPR), Morocco (MPR), Christmas Island (CIPR) and China (CPR). The chemical and physical characteristics of the fertilizers tested are given in Table 1. A total of 4 g P kg^{-1} soil was added for each of the P sources tested and each treatment was replicated four times. Uniform 3 month-old Dura x Pesifera oil palm seedlings were planted into each of the pots. The initial P content of the oil palm seedlings was determined.

After each 3-month interval, the first set of palms were destructively sampled, oven-dried at 70°C, and weighed out. The dry weights were recorded, the tissues were cut into small pieces and the different plant parts were sub-sampled, incinerated at 450°C, and dissolved in 2M HCl solution. Phosphorus-32 activity in the samples were counted using Packard 2300 liquid scintillation counter and inorganic P present in the plant tissues were determined colorimetrically using the method of Scheel [2]. L values were calculated using the formula of Larsen [3] and P derived from the fertilizers by the plants (PdfF) was calculated using the isotope dilution formula described by Zapata and Axmann [4].

To determine P dissolution from PR with time, another complete set of soils was set up without ^{32}P addition and without planting palms. The soils were air-dried, ground to pass 2 mm sieve and P was extracted with 0.5M NaOH [5] and Pi-strip [6]. Calcium was extracted with 1 M ammonium acetate at pH 7.0. The parameters describing the P status of the original soil was determined according to the method described by Morel and Fardeau [7]. Measurements were made at 3,6,9 and 12 months after the start of the experiment.

The data collected were analyzed using analysis of variance (ANOVA) and the differences in the means were analyzed using the least significant difference (LSD) value. These statistical analyses were carried out using the SAS package [8].

3. RESULTS AND DISCUSSION

3.1. Chemical and mineralogical characteristics of phosphate rocks

The highest total P content was found in CPR and the lowest was in NCPR (Table I). However, total P content is not an indication of PR agronomic effectiveness [9]. The Ca concentration varied from 31% in NCPR to 33% in CPR. Heavy metals content (Zn, Mn, Pb, Cd, and Cu) ranged between 144-407 mg/kg for Zn, 21-505 mg/kg for Mn, 21-505 mg/kg for Pb, 3-54 mg/kg Cd and 15-56 mg/kg Cu. Besides the heavy metals, Al and Fe were present in substantial amounts in some PRs. The forms in which Fe and Al are present in PR (either bound to P or present as oxides) may play a significant role in the release of inorganic P from these rocks. Mineralogical properties have been identified using X-ray diffraction. In general, these PRs contain apatite as the primary mineral with quartz as the impurity mineral (Fig. 1).

The Ca:P ratio ranged from 1.29 for CIPR to 1.84 for TPR (Table I). It has been shown that when neutral ammonium citrate-soluble P (expressed as percentage of rock and as percentage of total P_2O_5) was plotted against the molar ratio of Ca:P of apatite in PR, the solubility of PR increased as the Ca:P

ratio increased. The substitution of CO_3^{2-} for PO_4^{-3} in the apatite structure causes a decrease in unit cell a-axis that results in a decrease in crystalline size of apatite, thus increasing the chemical reactivity of apatite mineral [10]. The PR reactivity ranked according to Ca:P molar ratio was in the order of $\text{NCPR} > \text{TPR} > \text{JPR} > \text{MPR} > \text{CPR} > \text{CIPR}$ (Table I).

3.2. Solubility characteristics of phosphate rocks

The magnitude of PR solubility in 2% citric acid and 2% formic acid and neutral ammonium citrate as percentage of rock and total P_2O_5 (Table II) showed that all PR can be ranked in the same order as the Ca:P molar ratio, i.e. $\text{NCPR} > \text{TPR} > \text{JPR} > \text{MPR} > \text{CIPR} > \text{CPR}$. Correlation coefficients of P extracted by these three methods to total P taken up by one-year old oil palm plants showed that neutral ammonium acetate gave the highest r^2 value as compared to 2% formic acid or 2% citric acid. The r^2 also improved when the solubility of the PRs were expressed as percentage of the rock rather than total P_2O_5 content (Table IV).

3.3. Dissolution of PR in the soil

Phosphorus dissolution measured by the methods of Pi-strip, 0.5M NaOH, L-value method, and dissolved Ca method by leaching with 1 M NH_4OAc showed marked differences in the extent of dissolution of PR with time.

3.4. Availability of P from PR added to soil using E-value determination

The water-soluble P concentration (C_p) in untreated soil was 0.04 mg/L (Table V). This value increased with the addition of P fertilizers used. The highest increase was with the addition of TSP. The ratio of radioactivity remaining at 1 minute to the initial radioactivity (r_1/R) in PR treated soil was found to be < 0.2 . This indicated the soil had a high P fixing capacity [11, 12]. The E1 values for each treatment were calculated using the equation $E1 = 10C_p/(r_1/R)$. This is a good approximation of the quantity of free phosphate ions in a soil-solution system that is available to plants [11, 13]. The E1 value was highest in the soil amended with TPR and NCPR, while soil amended with MPR, JPR, CIPR and CPR showed lower E1 values indicating the low P availability in soil amended with P from these sources. The E1 values of soils at 3, 6, 9 and 12 months after PR addition were also found to follow the same pattern as the E1 values.

3.5. Oil palm dry matter yield and P uptake

The dry matter yield and total P yield of oil palm seedlings harvested at 3, 6, 9 and 12 months after planting showed great variability with the fertilizer treatments (Table VI). The P uptake in the first 3 months was almost similar among the PRs tested. The uptake increased with time for NCPR and TPR showing higher P uptake compared to CIPR and CPR. More than 80% of the total P in the plant was derived from the fertilizers added (Table VII), with TSP being the highest contributor of P towards plant P ($> 96\%$). Triple superphosphate supplied the highest amount of P to the palms at 601 mg P for a 12 month-period of growth (Table VII). This corresponded to 15% of the total amount of P added at the beginning of the experiment. Among the PRs tested, NCPR had the highest PdfF at 208 mg P/palm followed by GPR at 160 mg/palm. The PRs, JPR, MPR and CIPR, had equivalent PdfF values, while CPR showed the lowest value of 101 mg P/palm. Fertilizer use efficiency of the PRs ranged between 5.21% for NCPR to 2.15% for CPR (data not shown).

3.6. Relationship between PR solubility to plant P uptake

The magnitude of PR solubility in formic acid, citric acid, and neutral ammonium citrate as a percent of rock has been shown by Chien [14] to be more appropriate since values expressed as percent of total P content may give misleading comparisons, especially for PRs with low total P content [15]. Correlation coefficients obtained when the three methods of PR solubility tests were compared to plant P uptake showed that neutral ammonium citrate gave the best r^2 value (Table IV).

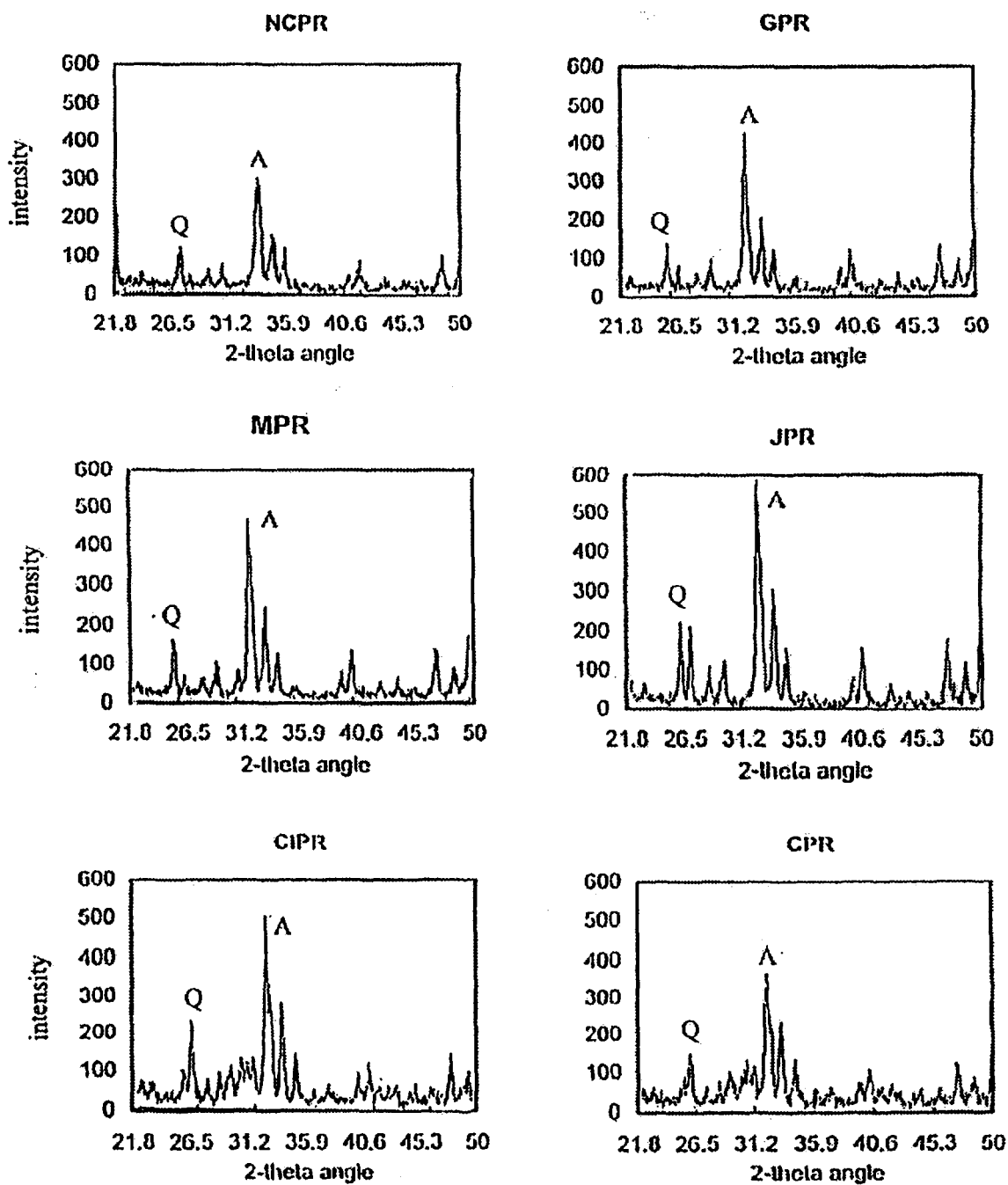
TABLE I. CHEMICAL CHARACTERISTICS OF PHOSPHATE FERTILIZERS TESTED

P Source	P (%)	Ca:P ¹	P ₂ O ₅	Ca	CaO	(mg kg ⁻¹)					
						Fe	Cd	Cu	Zn	Mn	Pb
NCPR	13.1	1.83	30.1	31.0	43.4	4080	54	18	407	21	54
TPR	13.4	1.84	30.7	31.8	44.5	1560	35	15	358	36	55
JPR	14.1	1.79	32.3	32.6	45.6	1570	9	17	224	21	56
MPR	14.4	1.79	33.0	33.4	46.7	1640	23	40	309	38	55
CIPR	14.5	1.29	33.2	24.2	33.9	28700	5	56	407	443	70
CPR	14.7	1.54	33.7	29.2	40.9	9240	21	21	144	505	207
TSP	20.4	0.62	46.7	11.6	16.2	10380	3	18	379	99	213

¹ mole ratio.

TABLE II. SOLUBILITY OF PHOSPHATE FERTILIZERS TESTED

P Sources	Total P ₂ O ₅	Formic Acid soluble P		Citric Acid soluble P		Neutral Ammonium Acetate soluble P	
		% of Rock	% of Total	% of Rock	% of Total	% of Rock	% of Total
			P ₂ O ₅		P ₂ O ₅		P ₂ O ₅
NCPR	30.1	24.7	82.2	12.1	40.4	5.83	19.4
TPR	30.7	20.8	67.9	11.7	38.2	4.97	16.2
JPR	32.3	20.4	63.1	10.8	33.4	4.52	14.0
MPR	33.0	17.9	54.2	10.6	32.0	4.42	13.4
CIPR	33.2	11.6	34.9	9.3	28.0	3.59	10.8
CPR	33.7	8.0	23.8	7.5	22.3	2.73	8.1
TSP	46.7	43.3	92.6	41.9	89.7	40.3	86.2



Note: d spacing for apatite (A) - 0.269 nm
d spacing for quartz (Q) - 0.426 nm

Fig. 1. X-ray diffraction patterns of P rocks studied.

TABLE III. PHOSPHORUS AND Ca DISSOLVED FROM SOIL TREATED WITH P FERTILIZER SOURCES AND PLANTED WITH OIL PALM

Time	P sources	<i>Dissolved P (mg/kg)</i>			Dissolved Ca (mg/kg)
		0.5M NaOH	Pi-strip	L-value	
3 months	NCPR	406 b	246 b	890 b	634 c
	TPR	400 b	227 bc	689 c	926 a
	JPR	305 c	235 bc	578 d	607 c
	MPR	263 d	157 d	661 d	584 c
	CIPR	238 d	146 c	578 cd	303 d
	CPR	258 d	148 d	432 e	188 e
	TSP	3577 a	711 a	1177 a	686 b
	Control	37 e	24 e	40 f	56 f
6 months	NCPR	624 b	281 b	536 c	634 c
	TPR	525 bc	261 b	667 b	2353 a
	JPR	468 c	209 c	379 d	2326 a
	MPR	472 c	210 c	377 d	2010 b
	CIPR	305 d	135 e	302 d	740 d
	CPR	343 d	176 d	287 d	593 d
	TSP	3711 a	742 a	1442 a	1078 c
	Control	37 e	12 f	41 e	43 e
9 months	NCPR	767 b	385 b	1066 b	1955 b
	TPR	650 c	292 c	1074 b	2280 a
	JPR	327 e	220 d	714 c	1906 b
	MPR	462 d	209 d	733 c	1640 c
	CIPR	343 e	209 d	466 d	1046 d
	CPR	319 e	180 e	481 d	906 d
	TSP	3306 a	811 a	3565 a	1876 b
	Control	28 f	10 f	27 e	42 e
12 months	NCPR	858 b	404 b	1254 b	2113 ab
	TPR	632 c	368 b	975 c	2180 a
	JPR	338 d	280 cd	662 d	1953 c
	MPR	408 d	313 c	625 de	1460 d
	CIPR	294 d	255 d	417 f	1113 e
	CPR	291 d	180 e	506 ef	853 f
	TSP	3234 a	727 a	3155 a	1935 bc
	Control	27 e	4 f	20 g	41 g

Values in the same column for each time period that are followed by the same letters are not significantly different at P=0.05.

TABLE IV. CORRELATION COEFFICIENT (r^2 VALUES) OF SOLUBILITY TESTS WITH P UPTAKE BY OIL PALM SEEDLINGS GROWN FOR 12 MONTHS

Variable	r^2 value	
	% of Rock	% of Total P ₂ O ₅
2% formic acid (% of rock)	0.88*	0.88*
2% citric acid (% of rock)	0.90*	0.88*
Neutral ammonium citrate (% of rock)	0.92**	0.91*

* significant at P≤0.10. ** significant at P≤0.05

TABLE V. ISOTOPICALLY EXCHANGEABLE P PARAMETERS OF THE SOIL WITH THE ADDITION OF 4 mg P/g OF SOIL

Parameters	Soil <i>Alone</i>	Soil + <i>NCPR</i>	Soil + <i>TPR</i>	Soil + <i>JPR</i>	Soil + <i>MPR</i>	Soil + <i>CIPR</i>	Soil + <i>CPR</i>	Soil + <i>TSP</i>
Cp (mg P/L)	0.04 e ¹	0.57 b	2.12 a	0.28 cd	0.41 bc	0.19 de	0.39 bc	165
E1 (1 min, mg/kg)	3.2 d	58 b	150 a	26 c	32 c	9.1 d	35 c	3840
Capacity factor (ml/g)	91 ab	101 a	70 c	90 ab	78 bc	48 d	86 abc	23
n	0.149	0.146	0.097	0.174	0.123	0.115	0.109	0.016
E-1 day (mg/kg)	10 d	161 b	281 a	85 c	77 c	18 d	75 c	2086
E-3 mths (mg/kg)	0.34 c	11 a	9.9 a	6.0 b	12 a	0.93 c	0.34 c	1583
E-6 mths (mg/kg)	0.12 d	23 a	17 b	14 bc	11 c	3.2 d	3.2 d	1732
E- 9 mths (mg/kg)	0.5 c	46 b	91 a	43 b	34 b	6.7 c	6.0 c	614
Pool A (mg/kg)	9.6 d	160 b	279 a	84 c	76 c	18 d	75 c	1920
Pool B (mg/kg)	7.3 d	138 a	137 a	96 b	55 c	12 d	46 c	73
Pool C (mg/kg)	3 d	61 a	53 ab	46 b	24 c	5.3 d	19 c	22
Pool D (mg/kg)	63 e	3724 c	3610 d	3855 b	3927 b	4046 a	3942 b	1901
%Pdff (1-day)	0	86.2 b	93.5 a	68.6 c	76.1 c	17 d	75 c	99.8
%Pdff (3-months)	0	89.9 a	91.5 a	83.9 ab	77.9 b	18 d	73 c	98.7
%Pdff (6-months)	0	90.2 a	91.4 a	84.7 b	78.3 b	19 d	73 c	98.6
%Pdff (9-months)	0	90.7 a	91.7 a	85.7 b	79.3 bc	23 d	74 c	98.6
%Pdff (12-months)	0	90.4 a	91.4 a	85.5 b	78.7 bc	20 d	73 c	98.5

¹ Means in a row followed by the same letters are not significantly different at P=0.05.

TABLE VI. DRY MATTER YIELD (DMY) AND TOTAL P (TP) OF OIL PALM SEEDLINGS ACCUMULATED DURING 0-3, 3-6, 6-9 AND 9-12 MONTHS OF GROWTH

P sources	0-3 months		3-6 months		6-9 months		9-12 months		Total	
	DMY	TP	DMY	TP	DMY	TP	DMY	TP	DMY	TP
TSP	2.0	31.6	19.6	159	17.9	209	31.6	214	71.1	614
NCPR	2.6	13.0	19.1	56	9.6	21.4	40.8	128	72.1	218
TPR	2.1	10.3	18.9	58	11.1	13.0	38.4	81.9	70.5	163
JPR	2.3	11.0	18.1	51	14.1	21.1	30.9	87.4	65.4	179
MPR	1.6	10.0	21.5	59	10.9	3.3	29.0	91.8	63.0	177
CIPR	1.0	6.6	21.3	62	14.2	3.5	31.1	95.1	67.5	177
CPR	1.4	7.1	19.9	44	13.0	1.7	21.3	54.8	55.8	106
LSD P=0.05	1.8	4.7	10.7	28	12.8	45.0	10.3	45.2	-	-
	n.s	*	n.s	**	n.s	**	**	**	-	-

TABLE VII. P DERIVED FROM FERTILIZERS (PERCENTAGE AND mg/PLANT) IN OIL PALM SEEDLINGS AT DIFFERENT TIMES OF HARVEST

P sources	PdfF (%)				PdfF (mg/plant)				Total
	3 months	6 months	9 months	12 months	3 months	6 months	9 months	12 months	
TSP	94.8	96.1	98.7	99.0	30.0	153.4	206.0	211.9	601
NCPR	93.1	89.2	96.3	98.2	12.1	50.5	20.6	125.8	209
GPR	92.3	87.7	96.4	97.4	9.5	50.4	12.6	79.8	152
JPR	93.1	86.6	95.6	96.9	10.2	43.9	20.5	84.8	168
MPR	91.2	84.8	94.4	96.3	9.1	50.1	3.7	88.4	163
CIPR	91.9	83.8	92.3	93.7	6.1	51.7	3.1	89.3	159
CPR	89.4	81.2	88.6	95.5	6.3	35.2	2.0	52.4	101
LSD	25.0	35.0	16.7	16.5	4.6	24.6	42.0	43.8	36
P=0.05	n.s	n.s	n.s	n.s	**	**	**	**	**

4. CONCLUSIONS

Chemical and mineralogical properties played an important role in the solubility and dissolution of PR. The extractant used for measuring PR dissolution tends to remove some of the undissolved PR during the extraction process. The extent of this 'induced dissolution' depends on the nature of the extractant and PR. The use of 0.5 N NaOH was found to be a better extractant for determining the extent of PR dissolution in soil while neutral ammonium citrate was the better extractant for determining the solubility of PRs. However, irrespective of the chemical extractants used, PR dissolution in the soil was higher for PR from North Carolina and Tunisia compared to the sources from China and Christmas Island. The dissolution of PR from Morocco and Jordan was in the intermediate range.

The ^{32}P isotopic exchange technique could be applied to determine and explain the immediate and residual effectiveness of various sources of PR. This technique gave the most complete analysis of soil P status, in particular available P, and provided information on the P dissolution and retention from PR sources. In this study P applied as NCPR and TPR was more readily available than JPR, MPR, CIPR and CPR. This method can be also used to predict the %Pdff value and the RAE of any P fertilizer added at a given rate in a given time. This method has an advantage over the chemical extractant methods because it does not disturb the soil components.

The E-value or L-values obtained from the isotopic technique showed that NCPR and TPR showed the highest P utilization as compared to all the other PRs from Morocco, Jordan, Christmas Island and China.

The effectiveness of these P sources used for oil palm seedlings can be ranked as follows: NCPR>GPR>JPR>MPR>CIPR>CPR. This ranking is similar to the ranking made from the solubility of these PRs in 2% formic acid, 2% citric acid or neutral ammonium citrate expressed as a percentage of the rock. Correlation coefficients obtained when these three solubility tests were compared with plant P uptake showed that ammonium citrate correlated best to plant P uptake when compared with the formic and citric acid extractants.

ACKNOWLEDGEMENTS

Financial and technical supports of the International Atomic Energy Agency under research contract No. MAL-7404 is greatly appreciated.

REFERENCES

- [1] OWEN, G., Determination of available nutrients in Malayan soils, *J Rub Res Inst Malaya* **14** (1953) 109-120.
- [2] SCHEEL, K.C., Calorimetric determination of phosphoric acid in fertilizers with the Pulfrich photometer, *Zeitschrift fur Analytische Chemie* **105** (1936) 256-269.
- [3] LARSEN, S., The use of ^{32}P in studies on the uptake of phosphorus by plant, *Plant and Soil* **4** (1952) 1-10.
- [4] ZAPATA, F., AXMANN, H., ^{32}P isotopic techniques for evaluating the agronomic effectiveness of rock phosphate materials, *Fert. Res.* **41** (1995) 189-195.
- [5] MACKAY, A.D., SYERS, J.K., TILLMAN, R.W., GREGG, P.E.H., A simple method to describe the dissolution of phosphate rock in soil, *Soil Sci. Soc. Am. J.* **50** (1986) 291-296.
- [6] MENON, R.G., CHIEN, S.H., HAMMOND L.L., HENAO, J., Modified technique for preparing paper strips for the new Pi soil test for phosphorus, *Fert. Res.* **19** (1989) 85-91.
- [7] MOREL, C., FARDEAU, J.C., Phosphorus bioavailability of fertilizers: A predictive laboratory method for its evaluation, *Fert. Res.* **28** (1991) 1-9.
- [8] SAS, SAS User's Guide: Statistics (5th ed.) SAS Institute, North Carolina, USA (1985).
- [9] CHIEN, S.H., Chemical, mineralogical and solubility characteristics of phosphate rocks for direct application. In: Dahanayake K et al (eds) *Proc Inter Workshop on Direct Application of Phosphate Rock and Appropriate Technology Fertilizers in Asia: What Hinders Acceptance*

- and Growth, pp 49-58 Inst Fundamental Studies, Sri Lanka and Inter Fert Devt Centre, Muscle Shoal, Alabama, USA (1995).
- [10] LEHR, J.R., MCCLELLAN, G.H., A revised reactivity scale for evaluating PR for direct application. Bull Y-43, TVA National Fertilizer Development, Muscle Shoals, Alabama, USA (1972).
 - [11] TRAN, S.T., FARDEAU, J.C., GIROX, M., Effect of soil properties on plant-available phosphorus determined by isotopic dilution phosphorus-32 method, Soil Sci. Soc. Am. J. **52** (1988) 1383-1390.
 - [12] MOREL, C., FARDEAU, J.C., Native soil and fresh fertilizer phosphorus uptake as affected by rate of application and P fertilizers, Plant and Soil **115** (1989) 123-128.
 - [13] SALCEDO, I.H., BERTINO, F., SAMPAIO, E.V.S.B., Reactivity of phosphorus in Northeastern Brazilian soils assessed by isotopic dilution, Soil Sci. Soc. Am. J. **55** (1991) 140-145.
 - [14] CHIEN, S.H., MENON, R.G., Factors affecting the agronomic effectiveness of phosphate rock for direct application, Fert. Res. **41** (1995) 227-234.
 - [15] CHIEN, S.H., HAMMOND, L.L., A comparison of various laboratory methods for predicting the agronomic potential of phosphate rocks for direct application, Soil Sci. Soc. Am. J. **42** (1978) 935-939.