MANAGING PHOSPHORUS
Under Acid Soils Environment

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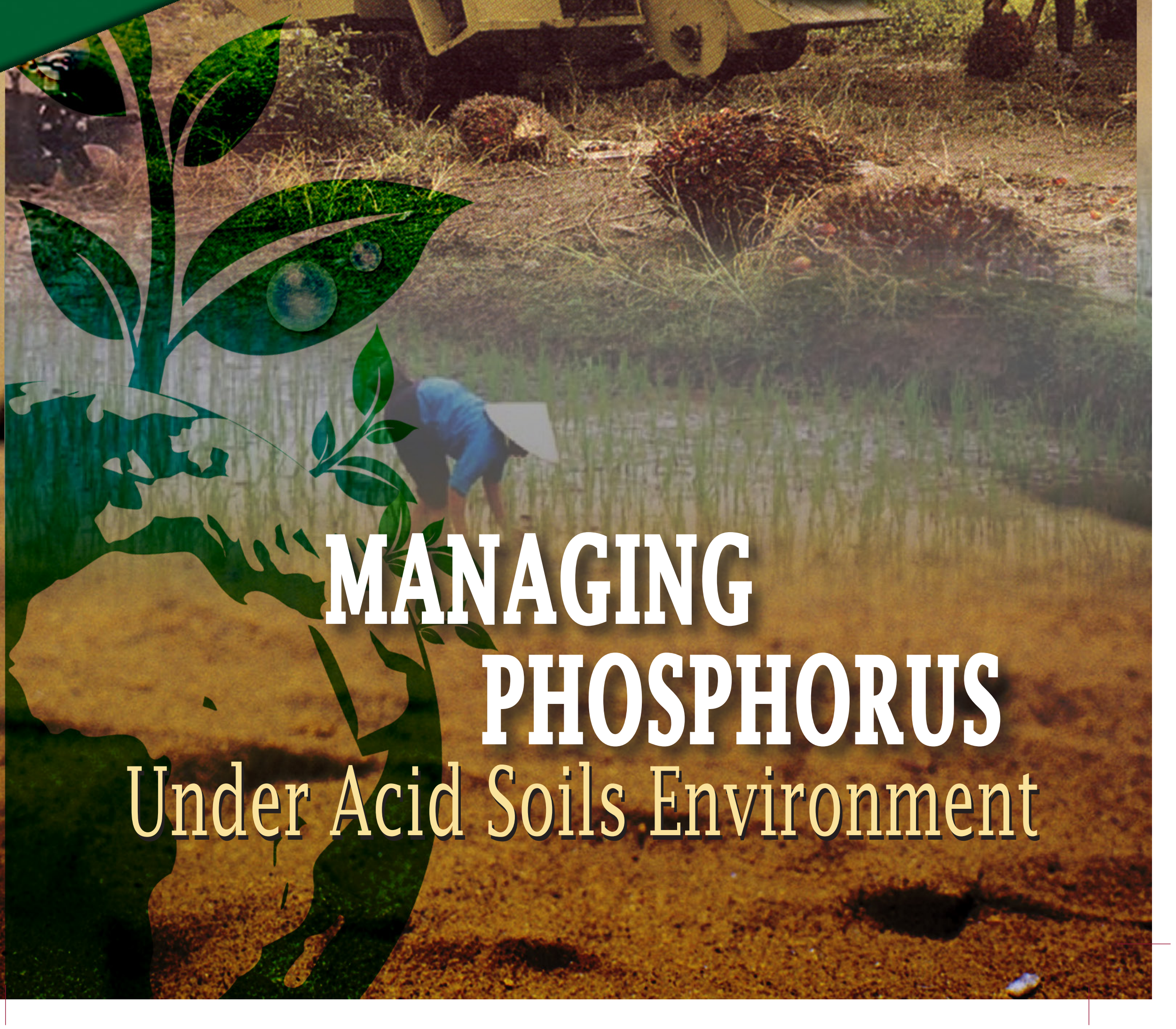

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INTRODUCTION

Malaysia lies within the world's humid tropical region with high humidity, abundant annual rainfall (2,000-3,000 mm), and very little variation in temperature (averaging 27°C). As a result, the soils are highly weathered with low pH, high in aluminium (Al), and of poor nutrient status. These soils are inherently low in water-, diluted acid- or alkali-soluble phosphorus (P) with values of less than 10 mg P kg^{-1} (Owen, 1947; 1953), while total soil P for soils suitable for agriculture practices is commonly less than 300 mg P kg^{-1} soil (Law and Tan, 1973). Consequently, P deficiency is widespread and P fertilisers are required to improve the fertility status of the soil for crop production.

Phosphorus is one of the major elements for plant nutrition and is usually taken up by plants in relatively smaller amounts compared to nitrogen (N) or potassium (K). Phosphorus occurs in plants in numerous forms, such as phosphorylated sugars and alcohols, and as phospholipids which have a wide range of functions (Tisdale and Nelson, 1975). The main function is in energy transfer as a component of adenosine triphosphate (ATP). On hydrolysis, the high energy pyrophosphate bond in ATP releases energy to drive other plant processes, such as those involved in the active uptake of plant nutrients.

Although the nutrient status of Malaysian soils is poor, especially for P, a substantial amount of Malaysia's income (RM 55.0 billion) is expected to be derived from agricultural activities in 2010 (Wong, 2007). The major export contributors (54.5% of total agricultural exports) are oil palm, rubber, cocoa, tea, and pepper crops which are planted in the estate and sub-estate sectors. The success of such plantation-based crops in Malaysia depends on chemical fertiliser inputs, such as that of N, P, and K.

PHOSPHORUS SUPPLY AND DEMAND

The P sources for Malaysian agricultural production have normally been obtained either from water soluble- or from water insoluble-P sources. It is widely accepted that the former includes triple superphosphate (TSP), single superphosphate (SSP), and diammoniam phosphate (DAP), the latter being mainly phosphate rock (PR) materials. As there has been no phosphate minerals deposits discovered in Malaysia, the majority of phosphate sources are imported from several countries (Table 1).

Table 1 Country of origin of which P fertiliser is imported by Malaysia in 2007.

Country	Quantity (Tone)	Proportion (%)	CIF Value (RM Million)	Proportion (%)
Natural Ca-PO_4, Al & Ca-PO_4, and PO_4-chalk (unground)				
Egypt	10,700	90.4	2.73	68.9
Thailand	798	7.0	0.86	22.0
Others#	554	5.0	0.60	15.0
Natural Ca-PO_4, Al & Ca-PO_4, and PO_4-chalk (ground)				
Egypt	172,156	28.9	48.59	27.9
Christmas Island	123,150	20.7	32.12	18.5
Australia	100,218	16.8	25.89	14.9
Tunisia	96,085	16.2	36.50	21.0
Algeria	53,468	9.0	15.64	9.0
Others#	49,814	8.0	15.16	9.0
Superphosphates				
Australia	51,350	68.3	12.91	49.5
China	9,542	12.7	8.04	30.8
Egypt	7,924	10.5	3.03	11.6
Others#	6,392	8.0	2.12	8.0

Other phosphatic and mineral or chemical fertilizers				
Australia	179,090	53.1	55.31	50.8
Egypt	91,096	27.0	26.03	23.9
Tunisia	17,875	5.3	5.58	5.1
China	17,764	5.3	9.89	9.1
Others[#]	31,585	9.0	11.98	11.0
Mineral or chemical fertilizers containing N, P, and K				
Korea	96,785	26.1	89.34	26.4
Belgium	70,057	18.9	74.50	22.0
China	65,128	17.5	34.16	10.1
Russia	41,260	11.1	37.12	11.0
Norway	36,657	9.9	31.20	9.2
Finland	26,009	7.0	27.03	8.0
Netherland	20,953	5.6	24.29	7.2
Others[#]	14,449	4.0	20.34	6.0
Mineral or chemical fertilizers containing P and K				
Indonesia	74	38.9	0.22	5.9
China	46	24.2	0.11	29.9
Canada	28	14.9	0.11	30.2
Japan	20	10.5	0.01	3.4
Spain	13	6.6	0.08	21.9
Others[#]	9	5.0	0.03	9.0

[#] Contribution of each country with ≤5.0%

The P sources imported are categorised into: (i) Natural Ca-PO4, Al & Ca-PO4 and PO4-chalk (un-ground), (ii) Natural Ca-PO4, Al & Ca-PO4 and PO4-chalk (ground), (iii) Superphosphates, (iv) Other phosphatic and mineral or chemical fertilisers, (v) Mineral or chemical fertilisers containing N, P, and K, and (iv) Mineral or chemical fertilisers containing P and K. The amount of P sources imported has increased tremendously over the last 18 years (1990-

2008) (Figure. 1). The highest import value of P sources was about RM 1.33 billion for the January-October 2008 period (Figure 2). The origin of major P sources imported based on year 2007 statistics varied widely with the water soluble-P (superphosphate) mainly from Australia (about 68% of import) and water insoluble-P from several countries (Table 1). The most significant water insoluble-P sources were notably from Egypt, Australia/Christmas Island, Tunisia, Algeria, and Jordan. The majority is in natural ground or un-ground phosphate form (Natural C_a-PO_4, Al-Ca-PO_4 and PO_4 chalk). The natural ground phosphates are used as the P source for direct application.

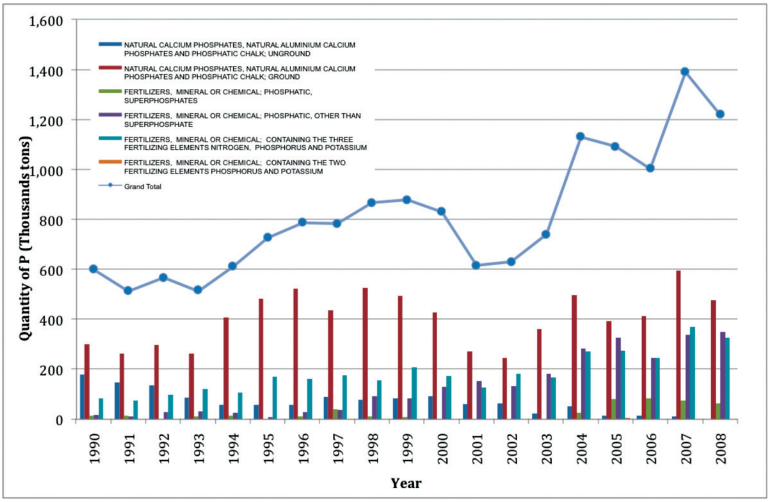


Figure 1 Quantity of various types of P sources imported from 1990 to 2008 (Source: Statistics Department, 2009).

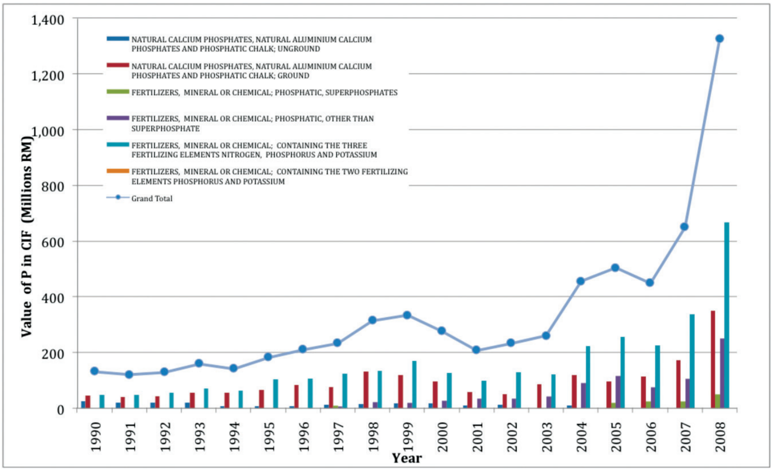


Figure 2 The value of various types of P sources imported from 1990 to 2008 (Source: Statistics Department, 2009).

FUTURE OUTLOOK OF PHOSPHORUS

The area under agriculture land use (Table 2) increased from 5.893 million ha in 2000 to 6.383 million ha in 2005. Further, it is expected to grow by about 1.5% in 2010 to 6.891 million ha (Wong, 2007). Major crops that are commonly cultivated are oil palm, rubber, paddy, fruits, coconut, cocoa, vegetables, tobacco, and pepper. Based on the recommended fertiliser rates provided by several agencies and the areas of land cultivated with these crops on mineral soils (Table 3), P consumption in Malaysia is expected to increase by 8.0% (annual growth rate of 1.5%) from 882,454 tonnes P_2O_5 in 2005 to 952,740 tonnes P2O5 in 2010. Hence, the amount of P sources required is estimated to be 2.722 million tons based on 35% P_2O_5 content. This annual growth of P consumption is in line with the forecast value for fertiliser reported by several models i.e. 1.2% annual growth for the period 1990-1920 (Bumb and Baanante, 1996) and 0.7 to 1.3% for between 1995/97 and 2030 (FAO, 2004a).

Table 2 Agriculture land use, 2000-2010.

Crop	Hectares ('000)			Average Annual Growth Rate (%)		
				8MP		9MP
	2000	2005	2010	Target	Achieved	Target
Oil Palm	3,377	4,049	4,555	3.2	3.7	2.4
Rubber	1,431	1,250	1,179	-2.7	-2.7	-1.2
Paddy[1]	478	452	450	-0.5	-1.1	-0.1
Fruits	304	330	375	5.1	1.7	2.6
Coconut	159	180	180	-0.6	2.5	0.0
Cocoa	76	33	45	-2.4	-15.2	6.2
Vegetables	40	64	86	4.2	9.9	6.1
Tobacco	15	11	7	2.5	-6.0	-7.4
Pepper	13	13	14	2.1	0.0	0.6
Total[2]	**5,893**	**6,382**	**6,891**	**1.5**	**1.6**	**1.5**

Source : After Wong (2007).
Notes : [1]Based on paddy parcel.
[2]Excludes areas for other crops like tea, coffee, herbs, and aquaculture.

Table 3 Recommended fertiliser rates for crops on mineral soils.

Crop Group	Crop	Rates			PPD	Recommending agency
		N	P_2O_5	K_2O		
		——— kg ha^{-1} ———			ha^{-1}	
Industrial	Rubber	109.8	163.93	281.25	450	MRB
	Coconut	71.7	93.21	107.55	239	DOA
	Oil-palm	128	144	200	160	MPOB
	Cocoa	117.3	54.7	140.7	1,241	DOA
	Coffee	134.4	62.72	161.28	1,280	DOA
	Paddy	90	35	25	500(m^{-2})	DOA
	Sugar cane	100	118	140	-	FELDA
	Tea	95	75	120	-	DOA
	Tobacco	80	205	130	17,932	DOA
Fruits	Starfruit	116.76	116.76	165.41	278	DOA
	Papaya	84	84	119	2,000	DOA
	Cempedak	118.08	115.62	126.69	123	DOA
	Durian	97.5	97.5	150	100	DOA
	Sweet orange	100.1	100.1	142.8	400	DOA

	Mango	82.16	82.16	126.4	158	DOA
	Mongosteen	117.48	117.48	166.43	178	DOA
	Pineapple	297	297	352	36,900	DOA
	Jackfruit	51.48	51.48	72.93	130	DOA
	Banana	554.4	554.4	680.4	1,680	DOA
	Rambutan	73.44	73.44	104.04	170	DOA
	Watermelon	84	84	59	2,000	DOA
Vegetables	Chinese spinach	60	60	85	-	MARDI
	Lady's fingers	120	120	170	5487	DOA
	Chili	180	180	255	8570	DOA
	Long bean	84	84	119	21333	DOA
	Cucumber	60	60	85	21333	DOA
	Tomato	180	180	255	21 333	DOA

PPD = Plant population density

*DOA Represents Peninsular Malaysia's Department of Agriculture unless otherwise stated

Source: After FAO (2004b).

DIRECT APPLICATION OF PHOSPHATE ROCK

One of the most important factors which determines the ability of a P fertiliser to increase the supply of PO_4^{3-} ions in soil solutions in the short-term is its solubility in water. Water soluble P sources, such as triple superphosphate (TSP), can be expected to release a large proportion of P immediately following absorption of water although some will revert back to less soluble forms (Lindsay and Stephenson, 1959ab). PR is often considered as an alternative to the more expensive soluble P fertiliser (TSP) for certain soils and crops. Studies wherein soil has been treated with varying PR amounts indicate good impacts to perennial and annual crops cultivation (Hanafi and Syers, 1994bc; Zaharah *et al.,* 1997).

ORIGIN OF PHOSPHATE ROCK

Commonly, there are two main types of PR deposits—sedimentary and igneous (Van Kauwenbergh, 2003). About 80% of the total world production of PR derives from sedimentary phosphate deposits. The use of the term PR includes both unprocessed rocks and beneficiated concentrate. Most of the P fertilisers commercially available in the market are based on PR materials containing variable quantities and forms of the mineral apatite.

Igneous PR materials are produced from deposits that are commonly mined in Russia, the Republic of South Africa, Brazil, Finland, and Zimbabwe. The quality of these ores is often low grade (P_2O_5) which can however be upgraded from as low as 30% to a high-grade product of over 40% P_2O_5.

Sedimentary PR materials occur throughout the geological time scale. Hence, they exhibit a wide range of chemical compositions and also show great variations in physical form. These PR deposits are commonly found in North Africa (Senegal, Togo, Morocco, Algeria, and Tunisia), the Middle East (Jordan, Israel, and Egypt), and the United States (Florida, North Carolina, and Idaho) (Cathcart, 1980). Economically important deposits most commonly occur as one or more thick high-grade beds that are unconsolidated, have a uniform granular texture and composition, shallow overburden, and minimum structural deformation. In some cases, insular deposits are formed when sedimentary PR deposits occur in association with oceanic islands (Ocean Island, Christmas Island, and Nauru Island). PR from Christmas Island was the most important source of P for Malaysia and the region for more than 100 years. However, due to over exploitation the PR materials were totally depleted and mining operations ceased.

DISSOLUTION OF PHOSPHATE ROCK AND ITS PHOSPHORUS AVAILABILITY TO PLANTS

The dissolution of PR materials and the availability of the P to plants vary, depending on several factors (Khasawaneh and Doll, 1978; Hammond *et al.,* 1986; Bolan *et al.,* 1990a): (i) the chemical composition and physical form of the PR; (ii) soil properties; (iii) climatic conditions; and (iv) type of crop or pasture species grown.

FACTORS AFFECTING DISSOLUTION OF PHOSPHATE ROCK

Chemical Composition and Physical form of Phosphate Rock

Based on their mineralogical composition, PR materials can be classified into three groups in order of increasing economic importance: Fe-Al-phosphates, Ca-Fe-Al-phosphates, and Ca-phosphates (McClellan and Gremillion, 1980). The most common mineral groups of the Fe-Al-phosphates are wavellite, variscite, and strengite. These deposits are usually found in Tropical regions, such as in Brazil and Senegal. The Ca-Fe-Al-phosphates include crandallite and millisite. This group of minerals is commonly found in the leached zone of Florida deposits in the USA and in the C-zone of Christmas Island deposits. The Ca-phosphate mineral group is characterised by a common mineral structure belonging to the mineral apatite. Mineral apatites vary widely in chemical, physical, and crystallographic properties (Lehr, 1967). Generally, they vary from the mineral fluorapatite ($Ca_{10}(PO_4)_6F_2$) to the mineral carbonate apatite (Francolite) ($Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_{3x}F_{0.4x+2})$), where x refers to the extent of CO_3^{2-} substitution for PO_4^{3-} in the crystal structure. In most cases, x ranges from zero to about 1.2 in commercial PR (McClellan and Lehr, 1969; Lehr, 1980). This mineral group is commonly found as extensive sedimentary deposits.

The stability of the three classes of PR usually follows a weathering sequence, with Fe and Al phosphates representing the most highly weathered and apatite representing the least weathered of PR materials (McClellan and Gremillion, 1980).

The PR components, such as carbonate apatite (francolite) dissolve congruently in acid soils according to the following reaction (McClellan and Lehr, 1969):

$$Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{2+0.4x} + 12H^+ = (10\text{-}a\text{-}b)Ca^{2+} + aNa^+ + bMg^{2+} + (6\text{-}x)\ H_2PO^{4-} + xH_2O + xCO_2 + (2+0.4x)F^- \qquad [1]$$

Isomorphous substitution of CO_3^{2-} for PO_4^{3-} in the apatite crystal structure has important practical consequences. It decreases both the unit-cell size (*a* and *c* dimensions) and crystallite size (Smith and Lehr, 1966; McClellan and Lehr, 1969; McClellan, 1979). For example, *a* values range from 9.322 Å for highly-substituted francolite to 9.376 Å for zero substitution (fluorapatite), whereas the *c* dimension ranges from 6.877 Å to 6.900 Å, respectively (McClellan and Gremillion, 1980); the values for crystallite size range from 300 to 2000 Å (McClellan and Lehr, 1969). This causes an increase in specific surface area (porosity) of the PR particles, with a consequent increase in susceptibility to chemical breakdown (chemical reactivity) (Khasawneh and Doll, 1978; McClellan, 1978). In addition, CO_3^{2-} substitution for PO_4^{3-} has often been reported to decrease apatite stability by decreasing the free energy of formation of apatite (Chien and Black, 1976) and the free energy of neutralisation with hydrogen ions (Chien, 1977). In some PR, such as the Bayovar deposit (Sechura) in Peru, OH^- substitutes to some extent for F^- (Bolan *et al.,* 1990a).

As PR materials have very low solubility in water, the first step in plant utilisation of P from PR applied as direct application fertiliser is the partial dissolution of the PR. Thus, the physical form of the PR influences both the rate of dissolution and the spatial availability of P following dissolution of the PR. In this respect, the surface area of contact of PR particles plays a very important role in promoting the dissolution reaction in soil.

It is generally accepted that PR materials should be ground to pass through 100 mesh (<150 μm) to be agronomically effective (Caro and Hill, 1956; Armiger and Fried, 1958; Khasawneh and Doll, 1978). An increase in P availability with increaseding fineness of grinding has been reported in reviews of field experiments conducted with finely-ground PR in the United States (Salter and Barnes, 1935; Rogers *et al.,* 1953; Khasawneh and Doll, 1978), in the United Kingdom (Cooke, 1979) and in the Federal Republic of Germany (Amberger, 1979).

Soil Factors Affecting Phosphate Rock Dissolution

As shown in Eqn. [1], the forward reaction requires an adequate supply of moisture and protons (H^+), and the removal of Ca^{2+}, $H_2PO_4^-$ and F^- from the reaction site. At the Ca^{2+} and H^+ ion concentrations likely to be found near dissolving particles, F^- actually should be controlled by the precipitation of CaF_2 (Lindsay, 1985; Resseler and Werner, 1989). The dissolution rate of the PR will therefore depend on the lowering of Ca^{2+} and $H_2PO_4^-$ ion activities, through diffusion and surface exchange and adsorption reactions (Wilson and Ellis, 1984; Bolan and Hedley, 1989) and the supply of protons (Kanabo and Gilkes, 1987). Based on this, the most likely important soil factors are (i) the concentration of H^+ in the soil solution and the pH-buffering capacity of the soil (proton supply), (ii) concentration of Ca^{2+} in the soil solution and Ca-sink size, and (iii) concentration of P in the soil solution and P-sink size.

It has been pointed out by several authors (Gregg *et al.,* 1989; Bolan *et al.,* 1990a) that it is important to distinguish between the soil factors affecting the dissolution rate of PR materials and soil factors affecting the subsequent availability to plants of the dissolved P.

Soil pH and Proton Supply

It has been generally observed that the agronomic effectiveness of a PR material is higher in an acid soil than in neutral or alkaline soil (Peaslee et al., 1962; Ensminger et al., 1967; Barnes and Kamprath, 1975). This has led to the belief that soil acidity (H^+) is the single most important factor influencing the dissolution of PR. Specifically, Peaslee *et al.* (1962) have indicated that soil pH is the most important soil factor affecting PR dissolution. Later on, Robinson and Syers (1990) critically evaluated the effect of pH, Ca-sink, and P-sink interaction on the dissolution of reactive Gafsa

PR (GPR) in a non-soil system. They found that, in the absence of a Ca sink, an acid pH buffer and/or a P sink had little effect on the amounts of P dissolved from GPR. However, in the presence of a Ca sink, especially in conjunction with a P sink at pH 4.5, dissolution of GPR markedly increased to over 85%. The direct effect of soil acidity on the dissolution of a PR material is in providing protons to disrupt chemical bonds at the apatite surface (Chien, 1977). The disruption of a chemical bond in apatite depends on the standard free energy of reaction of apatite in an acid solution (Chien, 1977). This energy is in fact a combination of the standard free energy of dissolution and the standard free energy of neutralisation. As the standard free energy of apatite is always positive and is relatively independent of carbonate substitution, the driving force for the dissolution reaction is usually determined by the standard free energy of neutralisation with a hydrogen ion (H^+). The standard free energy of reaction for carbonate apatite (francolite) was found to be much lower than that of fluorapatite (Chien, 1977). This indicates that a given proton supply should increase the dissolution of francolite more than that of fluorapatite. Moreover, francolites are thermodynamically quite unstable under acid conditions (Chien and Black, 1976). This is in agreement with the reaction of water-soluble P in soil in which the initial reaction products are metastable and change toward more stable, less-soluble end products (lower energy state) (Lehr *et al.,* 1959; Lindsay and Stephenson, 1959a,b). In neutral and calcareous soil, the ultimate product of reaction is hydroxyapatite, whereas in acid or moderately acid-soil they are thought to be Al- or Fe-phosphates (Khasawneh and Doll, 1978).

An initial step in the dissolution process is the adsorption of hydrogen (H^+) ions at the external surface of apatite (Pickering, 1983). Thus, the larger the surface area per unit weight (i.e. the fineness and porosity of apatite) and the higher the concentration of H^+ ions, the faster is the dissolution reaction. The most rapid attack generally occurs at active surface sites (e.g. defect centres and surface irregularities). Hence, it is not surprising that the more porous carbonate apatites dissolve more readily as compared to the more highly-crystalline fluorapatite, in soil.

Protons are mostly supplied by the exchange of H and Al (exchange acidity) from the surfaces of soil minerals and organic matter. However, according to Kanabo and Gilkes (1987), soil pH values *per se* (intensity factor), may be a poor predictor of PR dissolution. Alternatively, they suggested that the pH-buffering capacity (quantity factor) should be considered in identifying soils suitable for direct application of PR materials. Mechanisms, such as isomorphous substitution, pH-dependent charge, and the charge created by adsorption of potential-determining ions by allophanic materials, are thought to be responsible for the development of surface charge and the acidity associated with it (Uehara and Gillman, 1981; Bache, 1988). The pH-buffering capacity is usually measured by titratable acidity or lime requirement (Coleman and Thomas, 1967; Wheeler and Edmeades, 1984; Kanabo and Gilkes, 1987; Bache, 1988).

Soil Ca and Ca-sink Size

The affinity of a soil for Ca promotes the dissolution of PR because it provides a sink for the Ca released by congruent dissolution of the apatite. The solubility-product principle suggests that the lowering of Ca^{2+} and/or $H_2PO_4^-$ concentrations by removal from the reaction site should increase the dissolution of apatite. The extent of dissolution can be illustrated using fluorapatite in which 10 moles of Ca^{2+} dissolve for every 6 moles of $H_2PO_4^-$ which go into solution. However, the presence of free $CaCO_3$ in many PR deposits may increase the Ca:P ratio to above 15:6. A low soil affinity for Ca^{2+}

increases the amount of Ca^{2+} at the apatite surface and consequently the activity of $H_2PO_4^-$ decreases according to the solubility-product principle. When the Ca^{2+} and $H_2PO_4^-$ concentrations exceed the solubility product of apatite, the dissolution of PR will cease.

The soil sink for Ca is provided by the cation exchange capacity (CEC), thus enabling the Ca released from PR surfaces to become part of the exchange complex (Khasawneh and Doll, 1978). The affinity of a soil for Ca is high when percent Ca saturation is low, which is the case when the overall percent base saturation and pH are low (Khasawneh and Doll, 1978). This condition is quite common in acid, tropical soils, thus providing a favourable situation for PR to be used for direct application. Conversely, the affinity of a soil for Ca is low when the exchange complex of the soil is largely saturated with Ca. This condition often occurs when the soil is limed. Liming of an acid soil just prior to the application of PR has been reported by several researchers to decrease the dissolution of PR in laboratory and glasshouse studies (Khasawneh and Doll, 1978; Mackay and Syers, 1986; Bolan and Hedley, 1990; Robinson *et al.,* 1991) and in the field (Engelstad *et al.,* 1974; Juo and Kang, 1978). These researchers (Khasawneh and Doll, 1978; Mackay and Syers, 1986; Bolan and Hedley, 1990; Robinson *et al.,* 1991) suggested that liming a soil will increase both soil pH and exchangeable Ca. To separate the effect of soil pH from that of exchangeable Ca, Khasawneh and Doll (1978) compared the effect of $CaCO_3$ with that of $SrCO_3$ on the agronomic effectiveness of North Carolina PR. They found that $CaCO_3$ depressed plant yield more than did $SrCO_3$ at the same soil pH after liming. In another study, Mackay and Syers (1986) compared the effect of $CaCO_3$ and $CaCl_2$ on the dissolution of Sechura PR in a soil. They found that dissolution and Olsen-extractable P decreased more in $CaCO_3$- than in $CaCl_2$-treated soils. They attributed this to the decrease in Ca-sink size and proton supply in $CaCO_3$-treated soil. Similarly, a lower performance of some reactive PR materials in Australia, compared to New Zealand field experiments was ascribed to an inadequate Ca-sink size in the Australian soils (Bolan *et al.,* 1990a).

It is a well known fact that soil organic matter promotes the dissolution of PR (Drake, 1964; Chien, 1979). Following the hydrolysis of organic matter, some organic functional groups or anions, such citrate and oxalate, can effectively complex Ca^{2+} released from PR, thus lowering the activity of Ca^{2+} in the soil solution. Direct evidence of the complexing of Ca^{2+} by hydrolysed soil organic matter has been reported by Chien (1979). This mechanism may also explain, in part, why some experiments with farmyard manure increased the availability of P (Guzman *et al.,* 1980).

Soil P and P-sink Size

The level of soil P plays a role in PR dissolution similar to that of Ca^{2+}. It is generally expressed by the activity of $H_2PO_4^-$ or by the phosphate potential, pH_2PO_4 + ½pCa. Congruent dissolution of PR can be maintained if the soil is able to provide a sink for P. If soil P is supersaturated with respect to the solubility-product of apatite, the PR will neither dissolve nor participate in supplying P to plant roots (Khasawneh and Doll, 1978; Mackay and Syers, 1986). Thus, a fertile soil with a moderately-high P concentration in the soil solution may not benefit from PR application. On the other hand, maximum benefit can be achieved in soils which are severely to moderately deficient in P, although some water-soluble P may be required to correct a serious P deficiency.

The soil sink for P is predominantly the P-sorption complex, which is determined mostly by the amounts of Fe and Al oxides and hydrous oxides. The soil minerals involved are haematite, goethite, lepidocrocite, and gibbsite (Schwertmann and Taylor, 1977). These minerals have a varying but usually high capacity to sorb P (Parfitt *et al.,* 1975; Parfitt, 1979) and amorphous analogues have much higher capacity (McLaughlin *et al.,* 1977). The potential of a soil to adsorb P is usually estimated by the P-retention capacity method (Saunders, 1965). Minerals with a high P-retention capacity are often abundant in Malaysian soils, such as Oxisols and Ultisols, thus providing a large soil sink for P. This property, in conjuction with a low soil pH and Ca status, should provide favourable soil conditions for PR use in Malaysia.

Soil Factors Affecting Availability of Phosphorus to Plants

The model developed by Kirk and Nye (1986) predicts that the adsorption of P by soil surfaces will minimise the P concentration around a dissolving PR particle, which enhances the dissolution of PR. Consequently, a soil with high P-retention capacity will enhance the dissolution of PR (Khasawneh and Doll, 1978; Smyth and Sanchez, 1982; Syers and Mackay, 1986; Kanabo and Gilkes, 1987; Bolan and Hedley, 1989). However, the quantity of water-extractable P (Chien *et al.,* 1980b) and Olsen-, resin-, and Bray I-extractable P (Smyth and Sanchez, 1982; Mackay and Syers, 1986) in soils treated with PR materials decreased as soil P-retention capacity increased. These results indicate that although dissolution increases as soil P-retention capacity increases, this does not necessarily result in an increase in the amount of plant-available P in soils. Thus, the availability of P from a PR in a particular soil is also influenced by the P-retention capacity of the soil. It has been pointed out by Gregg et al. (1989) that if the adsorbed P is not readily available to plants, the agronomic effectiveness of PR, measured relative to SSP or TSP, would be lower in a high P-adsorbing soil than in a low P-adsorbing soil (Hammond *et al.,* 1986). This is clearly and sufficiently illustrated by the results obtained in laboratory incubation and glasshouse studies (Hammond *et al.,* 1986; Mackay *et al.,* 1986; Kanabo and Gilkes, 1988; Bolan and Hedley, 1990) and by the crop response in field experiments in Mexico (Guzman *et al.,* 1980), in New Zealand (Sinclair and Dyson, 1988), and in the Philippines and Indonesia (Harris *et al.,* 1984). These findings can be predicted from the model of Kirk and Nye (1986), based on the curvilinear nature of the P-adsorption isotherm (Freundlich type) in which at low P concentrations (C_L), the P-buffering capacity is very high so that a large amount of P must dissolve from the PR in order to satisfy C_L.

Climatic Conditions

Rainfall and temperature are two climatic factors which influence the dissolution of PR in soil. A review by Hammond et al. (1986) of some studies in Africa showed that rainfall increased the effectiveness of PR. They reported that the soil moisture required for dissolution of PR materials can easily be maintained throughout the year in an area with a mean annual rainfall of between 500 and 1500 mm per year. Soil moisture is largely required for the diffusion of the dissolution products, Ca^{2+} and $H_2PO_4^-$, away from, and soil acids to, the reaction surface of apatite (Kanabo and Gilkes, 1988). Furthermore, soil moisture may also affect the rate of Ca and P uptake by plant roots. No significant difference was found in the effectiveness of SPR or TSP applied at annual rates of 30 - 35 kg P ha^{-1} to a soil in the Northland region of New Zealand, where rainfall exceeded 1200 mm per year and was reasonably well distributed throughout the year (Sinclair and Dyson, 1988). However, the low effectiveness of reactive PR in light-textured, lateritic soils in south-western Australia (Bolland *et al.,* 1988) was attributed partly to the short winter `wet season’ and the drying of surface soil between rainfall events (Bolland *et al.,* 1986). In sandy and coarse-textured soils, excessive rainfall may increase the dissolution of reactive PR due to leaching of Ca^{2+} and $H_2PO_4^-$. Leaching of Ca^{2+} and $H_2PO_4^-$ is important in controlling their concentration in soil solution (Ozanne and Shaw, 1961; Bolton, 1977). In cases where the leaching of P from water-soluble fertilisers has been a problem, the effectiveness of Florida PR (Alston and Chin, 1974) and Calciphos and NCPR (Yeates *et al.,* 1986) were found to be equal to or greater than SSP for pasture growth (Bolan *et al.,* 1990a).

For any chemical reaction, temperature is one of the most important variables. The variation of the reaction rate constant is often assumed to be representative of the classical equation proposed by Arrhenius in the form of $k = Ae^{-E_a/RT}$, where, k = reaction rate constant, A = Arrhenius constant, E_a = activation energy, R = molar gas constant, and T = temperature (°K). However, temperature has been found to have no significant effect on the dissolution of North Carolina PR in soil (Chien *et al.,* 1980b). This suggests that the P release from PR is less affected by temperature compared to that from a water-soluble P fertiliser. In another study, the relative agronomic effectiveness of Huila PR (Colombia), evaluated in a number of agroclimatic zones (Pescador, altitude 1000-2000 masl and mean temperature 17.5-23°C; and Ipiales, altitude 2000-3000 masl and mean temperature 12-17.5°C) ranged from 15 to 87% as that of TSP in the Pescador region, whereas there was no significant difference between the two sources in the Ipiales region (Leon and Ashby, 1984). The difference in performance of the two P sources between the two regions was attributed partly to climate. In the colder climate of the highland region, where a good performance of the PR was observed, the growing season was 9 months whereas at the lower altitude the plants were harvested within 3 months (Leon and Ashby, 1984). Thus, the influence of temperature on the agronomic effectiveness of PR is most likely an indirect result of the influence of temperature on the physiological development rate of the crop.

Type of Crop/Pasture Grown

The varying ability of crop species to utilise the P from PR under different soil conditions was first reported by Truog (1916). He attributed this variability to differences in crop demand for Ca. Later on, several detailed studies have attempted to elucidate the differential ability of crops to utilise P from PR (Cook, 1935; Murdock and Seay, 1955; Johnston and Olsen, 1972; Kirk and Nye, 1986b; Nye and Kirk, 1987). The results suggest that the variability among crops is related to their demand for both Ca and P, and the ability of plant roots to acidify the soil solution in the rhizoshpere.

The uptake of the dissolution products, Ca^{2+} and $H_2PO_4^-$ by plant roots also acts as an important sink. The largest effect of Ca removal by plants has been reported by Johnston and Olsen (1972) in a study to evaluate the effects of selected processes at the root surface, such as acidification, CO_2 excretion, and the adsorption or absorption of Ca following the dissolution of fluorapatite. However, calculations based on experimental data indicated that there was insufficient removal of Ca^{2+} by the plant to account for the dissolution of PR, unless the mass-action effect was confined to a microenvironment. Furthermore, plants with high root densities (length of root/volume of soil) and fast-growing plants, which require a high uptake of P to maintain growth rates, should increase the dissolution of PR by a mass-action effect (Khasawneh and Doll, 1978). Crops differ in their rooting habits, which are largely genetically dependent, but they are also significantly modified by subsoil acidity, subsoil compactness, and drainage. This is well illustrated by the effectiveness of reactive PR in supplying P to permanent, white clover-based pasture in New Zealand. A higher root density under permanent pasture, particularly in the top 10 cm, increased the rate of P uptake per unit volume of soil because of the greater chance of a root growing into the sphere of influence of a PR particle (Bolan *et al.,* 1990a). Similarly, mycorrhizal association can extend root ramification into the soil and increase the probability of the root contacting or being physically close to a PR particle. However, Tinker (1975) concluded that the mycorrhizal association alone cannot explain the variability of crop species to utilise PR. An extensive list of crop species which were efficient or the least efficient users of PR were listed by Dean and Fried (1953) and Rogers et al. (1953).

The dissolution of a PR becomes much more significant when plant roots have the ability to acidify the soil solution in the rhizosphere (Kirk and Nye, 1986; Nye and Kirk, 1987). Acid production is particularly important in legumes because legumes can acidify the rhizosphere when they are actively fixing nitrogen. Nitrogen enters the root as uncharged molecules and the excess of cations over anions can be absorbed by the root to balance the negative charge on newly-formed proteins and organic acids. The excess of cation uptake is usually balanced by a net H^+ efflux into the rhizosphere (Nyatsanga and Pierre, 1973; Bolan *et al.,* 1990a). However, acid production can also occur when non-legumes are supplied with NH_4^+ and NO_3^- or with all their N's in the NH_4^+ form (Riley and Barber, 1971). There is an excess of cations over anions when NH_4^+ uptake occurs and a net H^+ efflux from the roots resulting from the deprotonation of NH_4^+ to form amino acids (Haynes and Goh, 1978). For some non-legumes fed N in the NO_3^- form, acid production also occurs when they become severely P deficient (Hedley *et al.,* 1983).

MEASUREMENT OF PHOSPHATE ROCK DISSOLUTION AND ITS PHOSPHORUS AVAILABILITY TO PLANTS

Phosphate rock is essentially insoluble in water. Dissolution and the subsequent plant availability of P from PR in soil occur due to interaction between the factors mentioned earlier. The congruent dissolution of an apatite mineral, the major component of PRs, in soils is in accordance to the ideal reaction (Eqn. [1]). The extent of PR dissolution in soil (i.e. the release of P from PR to soil) has been determined by either measuring the increase in the amounts of soluble and adsorbed P_i (ΔP) or calculated from the increase in the amount of exchangeable calcium (ΔCa). In the later case, congruent dissolution of the PR is assumed. Hence, for soils receiving PR materials, the extractants employed must satisfy the following requirements: (i) it should be able to extract most of the dissolved P or Ca released from a PR and (ii) it should not promote dissolution of PR at any stage of the determination. The increase in the amount of 0.5M NaOH extractable inorganic P (ΔP_i) in a soil to which a PR is added should provide a good estimate of the amount of P dissolved and retained by the soil (Mackay *et al.,* 1986). This method is unlikely to be accurate in soils where there is active net mineralisation or immobilisation of soil P. In the case of measuring the increase in exchangeable Ca (ΔCa), 0.5M $BaCl_2$ buffered at pH 8.1 with triethanolamine ($BaCl_2$/TEA) extracting solution (Bascomb, 1964) has been shown to provide a good estimate of the extent of PR dissolution, provided the soil does not contain naturally high levels of Ca-bearing minerals (Hughes and Gilkes, 1984).

The assessment of plant available P and/or residual P in soil has frequently been evaluated using soil-testing procedures. Most of the extraction methods employed have been developed for use with soil receiving water-soluble P sources, and are categorised into three broad groups: (i) acid extractants- Bray 1 and 2 (Bray *et al.,* 1945), (ii) neutral extractants- water extraction (Sorn-Srivichai *et al.,* 1984), and (iii) alkaline extractants- 0.5M $NaHCO_3$ (Olsen *et al.,* 1954, Colwell, 1963). However, based on the characteristics of the extractants for measuring PR dissolution mentioned earlier, the 0.5M $NaHCO_{3,}$ pH 8.5 (Olsen *et al.,* 1954) is likely the best method for the measurement of plant availability of P from PR.

The most common method to measure the dissolution and subsequent plant availability of P from PR amended soil is by a closed incubation method. In this system, the soil amended with PR is incubated at a specified moisture content and temperature in a plastic bag. The soil-P source mixture was periodically mixed to ensure homogeneity and water was added to maintain the soil moisture content throughout the incubation. The extent of dissolution (ΔP) and amount of Olsen-extractable P (ΔP_b), from the P source is calculated from the changes in 0.5M NaOH-extractable P and 0.5M $NaHCO_3$-extractable P, respectively, compared to the control soil. The ΔP and ΔP_b increased with increasing incubation time but negligible increases are observed after 60 d, at which ΔP and ΔP_b were considered to have reached equilibrium values. Hanafi et al. (1992) suggest that an inadequate sink for Ca^{2+} and $H_2PO_4^-$ may have caused the system to attain equilibrium despite an adequate supply of protons (H^+). This led to an establishment of a new method for measurement of PR dissolution in soil using an open-leaching system (Hanafi and Syers, 1994a). This method simulates field conditions, wherein dissolved P and Ca are removed either by plant uptake or leaching. For the soil amended with PR, this method was successfully used for evaluating water soluble P sources and the release of nutrients by controlled-release fertilisers (Hanafi and Syers, 1993; Hanafi *et al.,* 2002ab).

STRATEGIES FOR IMPROVING PHOSPHATE ROCK DISSOLUTION AND ITS SUBSEQUENT SUPPLY OF PLANT AVAILABLE PHOSPHORUS

Physical Approach

As mentioned earlier, a finely-ground PR material has a higher agronomic potential, at least in the short-term. However, it is rather dusty and difficult to spread on land or from the air. In order to overcome this problem, the PR material is granulated or pelletized to make it commercially-acceptable (Stephen and Lipsett, 1975; Khasawneh and Doll, 1978; Mackay *et al.,* 1980). Granulation of PR to achieve conventional sizes of fertiliser can be performed by wet granulation (Carmon, 1979) or by dry compaction techniques (Lupin and Le, 1983). Through these two techniques, a smaller (2-5%) amount of binder, such as urea or KCl, can be added to improve the physical properties of the granulated product.

Granulation reduces the agronomic effectiveness of a PR, hence the International Fertilizer Development Centre (IFDC) developed a small-sized granule (by mini-granulation) to reduce the dust problem. However, the rate of dissolution decreases markedly as was shown in laboratory, pot, and field experiments in Australia (Kirk and Nye, 1986; Mackay *et al.,* 1984; Bolland *et al.,* 1986; Bolland and Barrow, 1988). This is a result of soil around the particles becoming saturated very quickly with the dissolution products, when PR particles are clumped together.

Chemical Approach

Acidulation

Acidulation is a process of the addition of proton (H^+) mostly from acid to a substance. The most common water soluble P sources, such as single superphosphate (SSP), triple superphosphate (TSP), diammonium phosphate (DAP), and nitrophosphate (NP) are fully acidulated fertilisers. The main component of the fertiliser is a monocalcium phosphate (MCP). These fertilisers are produced by completely (100%) acidulating the PRs with mineral acids, such as sulphuric (H_2SO_4), phosphoric (H_3PO_4), or nitric acid (HNO_3) acids, based on the stoichiometric reaction between apatite in PR and acid.

During the manufacture of fully acidulated phosphate fertilisers, such as SSP or TSP the final product is MCP. In SSP production, H_2SO_4 reacts with parts of the PR component to produce H_3PO_4 Eqn. [2] which subsequently reacts with the remaining PR to produce MCP Eqn. [3]. In the production of TSP, the PR is directly acidulated with H_3PO_4 to produce MCP Eqn. [3].

$$2Ca_{10}(PO_4)_6F_2 + 9H_2SO_4 \rightarrow 9CaSO_4 + 6H_3PO_4 + CaF_2 + Ca_{10}(PO_4)_6F_2 \qquad [2]$$

$$Ca_{10}(PO_4)_6F_2 + 12H_3PO_4 \rightarrow 9Ca(H_2PO_4)_2 + CaF_2 \qquad [3]$$

The main components of SSP fertiliser are 16% water soluble P_2O_5, 12% S, 21% Ca and small proportions of some other essential micronutrients. TSP contains 46% P_2O_5 and DAP contains 46% P_2O_5 and 18% N.

Partial Acidulation

The addition of H^+ from different acid combinations and acid to phosphate rock ratio in amounts less than the stoichiometric reaction for SSP or TSP produces partial acidulated phosphate rock (PAPR). An ideal chemical reaction summarised by Braithwaite (1986) is shown as Eqn. [4].

$$Ca_{10}(PO_4)_6F_2 + y(6\text{-}x)\ H_2SO_4 + 2xy\ H_3PO_4 \xrightarrow{H_2O} y(6\text{-}x)\ CaSO_4$$
$$+\ (3+x)y\ Ca(H_2PO_4)_2H_2O + (1\text{-}y)\ Ca_{10}(PO_4)_6F_2 + y\ CaF_2 \qquad [4]$$

Where, y = acidulation factor
when $y = 1, x = 0$ ≡ SSP
when $y = 1, x = 6$ ≡ TSP
when $0 < y \leq 0.75$ ≡ PAPR
When $0 < y \leq 0.75,\ 6 > x>>$ ≡ Mixed acid PAPR

Partially acidulated phosphate fertilisers contain in parts water soluble MCP and water insoluble form, mainly as un-reacted apatite. These fertilisers can be grouped and produced by two processes, namely (i) Directly acidulated PAPR – this process uses less acid than that required for complete acidulation of PR and (ii) Mixture of SP:PR – this process involves indirectly mixing different proportions of fully acidulated fertilisers and un-acidulated PRs (Bolan *et al.,* 1990b). The most common commercially available PAPR fertilisers are given in Table 4.

Table 4 Phosphorus and sulphur contents of commercially available partially acidulated phosphate fertilisers.

Products	Origin	P	S	Remarks
Directly acidulated PAPRs				
		—— %w/w	——	
ESPARP[2]	Australia	10.1	9.0	Duchess PR + H_2SO_4 + S°
Granphos[1]	UK	16.4	-	Gafsa PR + H_3PO_4 + $NH_4(H_2PO_4)$
Hyphos[1]	New Zealand	16.0	0.6	NCPR + H_3PO_4
Hyphos S[1]	New Zealand	15.0	6.0	NCPR + H_3PO_4 + S°
Novaphos[1]	Germany	-	-	-
SSP:PR mixtures				
Coastal super[1]	Australia	9.5	21.0	SSP + NCPR + S°
Endurophos[1]	New Zealand	10.8	8.0	SSP + NCPR
Longlife[1]	New Zealand	10.8	8.0	SSP + NCPR
Longerlife[1]	New Zealand	10.8	8.0	SSP + NCPR

Source: After Bolan et al. (1990b).

Note: [1] Trade name.

[2] Experimental material.

The use of PAPRs (20-50% nominal acidulation) for direct application improves plant available P in P deficient, high fixation capacity or on acid soils (Bolan *et al.,* 1990b). The PAPRs are able to produce water soluble P when in contact with soil moisture, which provide immediate value to fast growing crops. This translates into an improvement of the agronomic value of the PRs. In SSP:PR mixtures, the fertilisers contain both water soluble and insoluble P and as such are able to maintain higher soil solution P concentrations longer in the soil system near to the fertiliser granule. The improvement of P supply for this type of fertiliser is due to the preferential reaction of acid generated by MCP hydrolysis in soil moisture with the PR residue than that of soil minerals (McLean and Wheeler, 1964).

Biological Approach

Microorganisms

Microorganisms are very important soil components, which directly or indirectly influence soil's health through their numerous activities (Vineela *et al.,* 2008; Zhou *et al.,* 2008). Most microorganisms are living in the soil volume surrounding the rhizoplane (i.e. soil rhizoshpere). Rhizospheric microorganisms involve in decomposition, nutrient mobilization and mineralization, release of stored nutrients and water, nitrogen fixation, denitrification, and solubilisation of phosphate. However, their compositions in soil rhizosphere are affected by rhizodeposition, a substance released from roots to soil (Nannipieri *et al.,* 2007). Phosphate-solubilising ability of microorganisms can convert the insoluble phosphate into soluble forms in soil and make them available to plants (plant available-P) (Kang *et al.,* 2002; Pradhan and Sukla, 2005).

Phosphate-solubilising microorganisms (PSM) can be found everywhere but the numbers vary from soil to soil. The relative proportions of PSM to total populations in soil are 1-50% (bacteria) and 0.1-0.5% (fungus) (Kucey, 1983). A high proportion of PSM is concentrated in the rhizosphere and more active than those isolated from non-rhizosphere soil. Phosphate-solubilising microorganisms can be classified into (i) phosphate solubilising fungi (PSF) and actinomycetes (PSA) and (ii) phosphate solubilising bacteria (PSB). Most of the investigations on using PSM to solubilise phosphate from insoluble phosphate were in pure liquid culture medium (Whitelaw, 2000; Narula *et al.,* 2000). In this condition, the solubility of phosphate is attributed to excretion of organic acids. The excretion of organic acids by selected PSM is shown in Table 5. Although mineral acids, such hydrochloric acid have frequently been used in acidulation of PR, they are less effective than organic acids to solubilise the phosphate under similar pH conditions (Kim *et al.,* 1997). The role of organic acids to solubilise phosphate is due to the acidification by lowering the pH, chelation of cations (Al and Fe), and by competing with phosphate for the adsorption sites in soil (Nahas, 1996). However, in some cases there was no definite relationship between the organic acids produced by PSM and the amounts of phosphate solubilised (Subha Rao, 1982; Asea *et al.,* 1988).

Although the numbers of PSB are 1-150 times greater than that of PSF, the activity of PSBs to solubilise phosphate decreases substantially upon repeated sub-culturing (Kucey, 1983). In contrast, PSF produce more acids and consequently exhibit greater phosphate solubilising activity than that of PSBs in liquid and solid media (Venkateswarlu *et al.,* 1984). The phosphate solubilising activity of PSM also depends on the nature of the nitrogen source in the media used. Greater solubilisation of phosphate is obtained when NH_4^+-N is used compared to NO_3^--N as the source of nitrogen. This has been attributed to exudation of H^+ ion to compensate for NH_4^+ uptake, thus lowering the extra-cellular pH (Roos and Luckner, 1984). In some cases, however, addition of NH_4^+-N in media can lead to a decrease in phosphate solubilising activity by PSF, *Penicilium rogulusum* IR-94MF1 and its mutants (Reyes *et al.,* 1999). They attributed this to the insufficient CO_2 fixation at the level of the recharge reaction of the Krebs cycle (anaplerotic reactions), which in turn could affect the production of citric acid.

Table 5 A brief summary of production of principal organic acids by phosphate-solubilizing microorganisms.

Organism	**Predominant acids**
Phosphate-solubilizing fungi and actinomycetes	
Aspergillus flavus, *A. niger*, *Penicillium canescens*	Oxalic, citric, gluconic succinic
A. niger	Succinic
Penicillium rugulosum	Gluconic
Penicillium radicum	Gluconic
Penicillium variable	Gluconic
A. niger	Citric, oxalic, gluconic
A. awamori, *A. foetidus*, *A. terricola*, *A. amstelodemi*, *A. tamari*	Oxalic, citric
A. japonicus, *A. foetidus*	Oxalic, citric, gluconic succinic, tartaric
Penicillium bilaji	Citric, oxalic
A. niger, *P. simplicissimum*	Citric
A. awamori, *P. digitatum*	Succinic, citric, tartaric
Penicillium sp.	Oxalic, itaconic
Scwaniomyces occidentalis	Succinic, fumaric, citric, tartaric, α-ketbutyric

A. niger	Succinic
Aspergillus sp., *Penicillium* sp., *Chaetomium nigricoler*	Oxalic, succinic, citric, 2-ketogluconic
Streptomyces	Lactic, 2-ketogluconic
A. fumigatus, *A. candidus*	Oxalic, tartaric, citric
Phosphate solubilizing bacteria	
Enterobacter intermedium	2-ketogluconic
Bacillus amyloliquefaciens, *B. licheniformis*, *B. atrophaeus*, *Penibacillus macerans*, *Vibrio proteolyticus*, *xanthobacter agilis*, *Enterobacter aerogenes*, *E. taylorae*, *E. asburiae*, *Kluyvera cryocrescens*, *Pseudomonas aerogenes*, *Chryseomonas luteola*	Lactic, itaconic, isovaleric, isobutyric, acetic
Pseudomonas cepacia	Gluconic, 2-ketgluconic
Bacillus polymyxa, *B. licheniformis*, *Bacillus* spp.	Oxalic, citric
Pseudomonas striata	Malic, glyoxalic, succinic, fumaric, tartaric, α-ketobutyric
Arthrobacter sp.	Oxalic, malonic
Bacillus firmus	2-ketogluconic, succinic
Micrococcus spp.	Oxalic
Bacillus subtilis, *Bacillus* spp.	Oxalic, succinic, citric, 2-ketgluconic

Source : Adapted after Khan et al. (2006).

Mixing of PR materials with specific PSM promotes the dissolution and plant availability of PR through acidification and its enzyme production by microorganisms. Organic matter is utilised by PSM as food and oxidation of this substrate produces organic acids for solubilisation of phosphorus from PR (Asea *et al.,* 1988; Kiani Rad, 1995;Nahas, 1996). Furthermore, the organic acids and organic residue would increase the size of Ca-sink sites. The acidity and size of Ca-sink sites depend on the types of organic matter and species of PSM used. A laboratory study using peat material, oil palm leaves, rubber leaves, and palm oil mill effluents (POME) previously inoculated with *Bacillus pumilis* PJ19 or UPMB 001 and incubated with gafsa phosphate rock (GPR) using Bungor soil (Typic Paleudults) in a closed incubation system showed an increasing trend in the dissolution of GPR as measured by $BaCl_2$-TEA pH 8.1 exchangeable Ca (ΔCa) with time (Figure 3). The dissolution of GPR related with the amounts of the carboxylic functional groups, an indication of greater Ca-sink sizes and acidity (Hanafi and Shamsuddin, 1996; Pozan *et al.,* 1997). Hence, the selection of organic matter as a carrier is very important for mass-production of efficient PSM cultures (microphos) for distribution to farmers. Peat, farmyard manure (FYM), soil, and cow dung cake powder are commonly used for production of microphos (Kundu and Gaur, 1981).

Acidity produced by sulphur (S) oxidizing bacteria through oxidation of elemental S has been used for enhancing dissolution and subsequent plant availability of PR. *Thiobacillus*, especially from the chemolithotrophs group, is the most important S oxidizing bacteria found in soils, which can oxidize S and fix CO_2. Twenty of such strains have been identified and they were grouped as acidophilus and neutrophiles (Besharati *et al.,* 2003). The well known strain is *Thiobacillus thiooxidans* which is an aerobe that survives at pH range of 2 to 5. The performance of PR materials has been shown to be similar to water soluble P, such as TSP, causing the production of better yields by various crops when used in combination with S + *Thiobacillus* + P-solubilizing bacillus for corn (Noorgholipour, 2000) and for Sorghum (Rosa *et al.,* 1989); *Thiobacillus* inoculant + S+ nutrient elements (Ghani *et al.,* 1994); S + *Thiobacillus* for ryegrass (Kittams and Attoe, 1965); and S

+ organic matter + the *Thiobacillus* bacteria (Lotfollahi *et al.,* 2000).

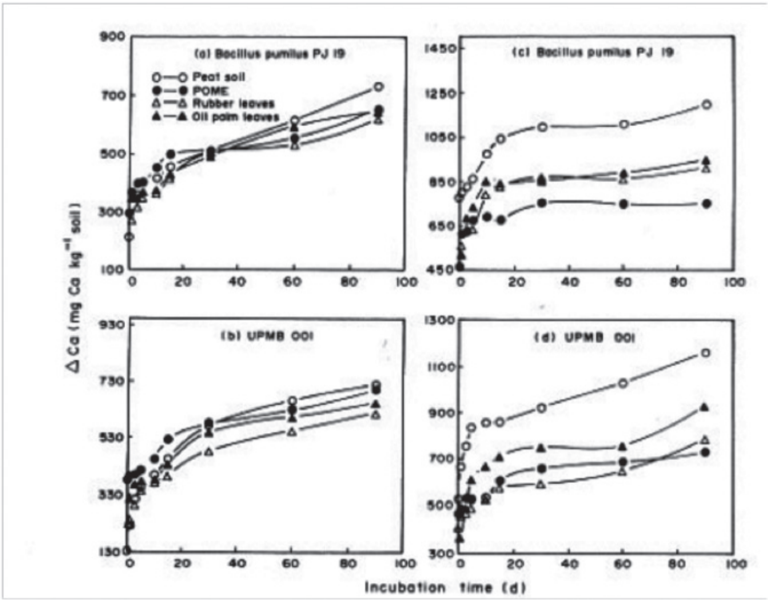


Figure 3 Changes in ΔCa for organic matter inoculated with *Bacillus pumillus* PJ19 or UPMB 001 (a and b) and for organic matter + Bungor soil in the presence of either bacteria (c and d) following the addition of GPR at 500 mg P kg^{-1} soil during 90 d incubation (LSD0.05 = 3.51).

Mutualistic symbiosis between plant and 'fungus-root' called mycorrhiza, localised in roots or root-like structures are known to be of fundamental importance in soil ecosystems. They are classified as ecto- and endo-mycorrhizas. The fungus that normally grows inner-cellularly in the cortex of plant's roots is for the former and form external hyphal networks in the soil and grow extensively within the cortical cells of plant roots is for the latter. Endomycorrhiza fungus is an obligate symbiont and produces arbuscules within root cortical cells, vesicles in the inter-cellular spaces, and auxiliary cells (coiled or knobby) in the soil. The hyphae are aseptated and multinucleated. The asexual reproductive spores are formed either in root or more commonly in soil. Arbuscules are highly branched, haustoria – like structures and function as an exchange organ for nutrients, water, and photosynthates between the symbionts. The vesicles are thin-walled lipid filled swollen structures which primarily function as a storage organ. The extraradical phase or external structures of the mycorrhizal system comprise an extensive network of fungal hyphae and spores. The external hyphae are the functional organs for nutrient and water uptake and translocation into the host plants. They are also the link between the internal phase and the spores (Azizah, 1999). The most important and most widely distributed (geographically as well as in the plant kingdom) type of endomycorrhiza is the arbuscular mycorrhiza (AM). This type of mycorrhiza is found under natural conditions in almost all tropical and subtropical agronomic crops. A vast majority of tropical trees are also endomycorrhizal of the AM type (Azizah and Rosenani, 1985; Sieverding, 1991; Azizah and Mokhtar, 1992).

The role of AM in increasing P nutrition of plants is thought to be through the large surface area of fungi hyphae scavenging for plant available P in soil and their high-affinity P uptake mechanisms (Hayman, 1983). However, there are reports that organic acid production by AM could solubilise insoluble P in soil (Lapeyrie, 1988). In some cases, AM fungi could exert a selective influence on soil microbial communities by increasing the population of α-ketoglutarate catabolising microorganisms (Duponnois *et al.,* 2005). However, the influence of AM fungi in colonisation of plant roots is severely reduced under sufficient or high plant available P conditions in soil (Son and Smith, 1995). In highly weathered acid soils, including degraded ex-mining tin soils (tin tailings), P is deficient due to transformation of water soluble P to low-soluble Al- or Fe-bound forms. Biomass yield and plant maturity of AM-inoculated *Acacia mangium* seedlings planted on tin tailing soils using different sources and rates of P were significantly higher compared to the control (Satter *et al.,* 2004a; 2006) (Figure 4). Non-mycorrhizal seedlings required 15 to 20 more days to produce equivalent biomass yield to that of mycorrhizal seedlings. Improvement of biomass yield has been attributed to increase in shoot development (Satter *et al.,* 2005) and root development and nodulation of mycorrhizal inoculated seedlings (Satter *et al.,* 2004b). Uptake of N, P, K, Ca, and Mg were significantly higher compared to non-mycorrhizal seedlings. Inoculation with AM fungi have been shown to improve nutrient use efficiency (represents the production of plant biomass per unit of nutrient uptake), especially for N and P as compared to non-mycorrhizal seedlings (Figure 5).

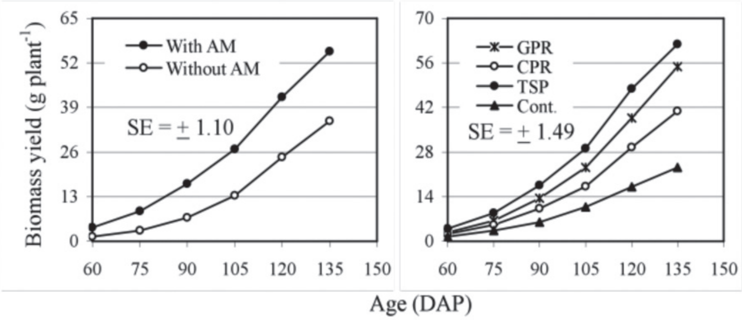


Figure 4 Effect of (a) AM and (b) P source on biomass yield of *A. mangium* seedlings over time in the glasshouse.

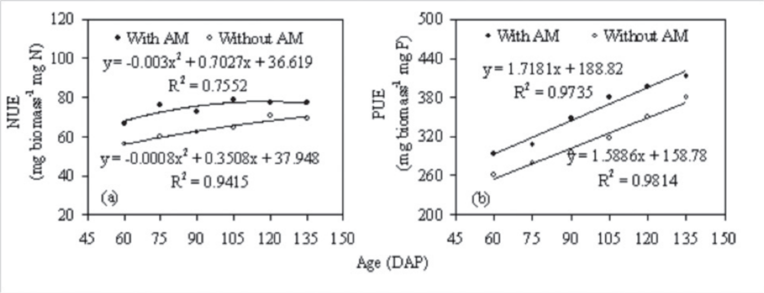


Figure 5 Effect of AM on (a) N (NUE) and (b) P use efficiency (PUE) by *A. mangium* seedlings over time.

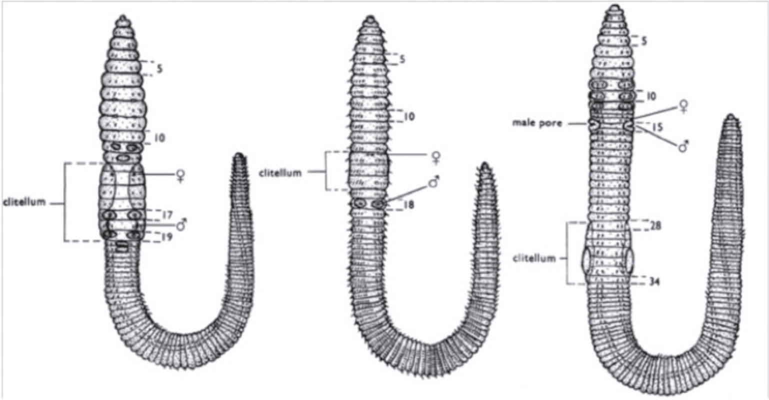
Interaction between PSM and N fixers may benefit plants inoculated with these organisms in combination better than individual inoculation. Colonisation of the rhizosphere with mixed culture or co-inoculation of these organisms together may enhance growth of legumes by providing P and N concurrently. The potential of PSM and N fixers to be used in mixed culture has been done *in-vitro* and *in-vivo* (Sarojini *et al.,* 1989). They were tried for solubilisation of tricalcium phosphate using mixed and individual cultures of *Pseudomonas striata, Bradyrhizobium* sp. or *Mesorhizobium ciceri* with no antagonistic behaviour between organisms. By mixing N-fixers with PSM organisms, the organisms provided the plant with sufficient amount of N and also improved the N fertility status of soil. A beneficial effect of PSM alone or in combination with N-fixers in field experiments has been reported by several researchers using many type of crops, such as green gram, chickpea, *vicia faba* (broad bean), soyabean, cotton, lentil, groundnut, mungbean, black gram, moonbean (Khan *et al.,* 2007).

Symbioses between PSM and AM fungi increase N and P nutrients of plants, especially in P-deficient soils (Cruz *et al.,* 1988). The interaction between PSM and AM fungi in P-deficient soil or soil fertilised with PR can release ion P from sparingly soluble P, which are tapped and translocated by AM fungi hyphae from soil to the plant (Azcon-Aguilar *et al.,* 1986). Thus, the dual inoculation with PSM and AM fungi stimulates plant growth more than inoculation with the individual microorganisms in certain situations when the soil is P-deficient. The survival rate of microrhizal endophyte could be improved greatly under these conditions, thus increasing plant growth in P-deficient soil. The improvement of P nutrients is due to exploration by external hyphae beyond the root-hair zone in P depleted soil. The PSM inoculation might influence the development of AM fungi by modification of root exudation and plasticity. In addition, the AM fungi could improve the activity of N-fixers in the root zone by producing plant hormones. Improvement in either plant growth or nutrient uptake by plant or yield of wheat, clover, and pasture (C*entrosema macrocarpum*) has been reported by several researchers, when PSM and AM fungi are inoculated together (Khan *et al.,* 2007).

Tripartite symbioses between N-fixers, PSM, and AM fungi in N and P limiting soil may improve P uptake by plants through AM fungi activity. Higher P concentrations in the plant benefit the N-fixers and increase the nitrogenase activity leading to increased N fixation resulting in the promotion of root and mycorrhizal development. There are several reports to illustrate the beneficial effects of tripartite association in improving plant growth and soil fertility status. The interaction of *Bradyrhizobium japonicum*, AM fungi, and PSM in Mollisol significantly increased, the grain yield of soybean, nodulation, nitrogen uptake, and available soil P (Singh and Singh, 1993). The complex interaction between *Glomus mossease*, *Bacillus* sp, and *Rhizobium* sp, dramatically improved *Pisum sativum* plant growth and soil aggregation (Bethlenfalvay, 1994). It has also been shown that inoculation of *Rhizobium*, *Bacillus polymyxa*, and *Glomus faciculatiom* resulted in significantly greater dry matter production and uptake of P by chickpea in comparison to single or double inoculation (Poi *et al.,* 1989).

Macroorganisms

One of the most important macroorganisms in soil ecosystems is earthworms. Earthworm is the common name for the largest members of Oligochaeta, subclass in the biological phylum Annelida. Oligochaetes are well-segmented worms and most have a spacious body cavity (coelom) that is used as a hydroskeleton. They range in length from less than 0.5 millimetres (0.020 in) up to 2 to 3 metres (6.6 to 9.8 ft), for the giant Gippsland earthworm species. The internal and external segmentation is a special feature of earthworms (Figure 6). The earthworm's alimentary canal is the central feature of its body cavity. The alimentary canal or gut of earthworms is basically a tube extending from mouth to anus, although it is differentiated into buccal cavity, pharynx, oesophagus, crop, gizzard, and intestine (Figure 7).



(a) (b) (c)

Figure 6 Typical example of clitellum arrangement of the different earthworm species: (a) acanthodrilid (e.g. ACANTHODRILIDAE), (b) megascolecid (MEGASCOLECIDAE), and (c) lumbricidae (LUMBRICIDAE); (d) The only species, *Pontoscolex corethrurus,* found in oil palm plantations in Malaysia.

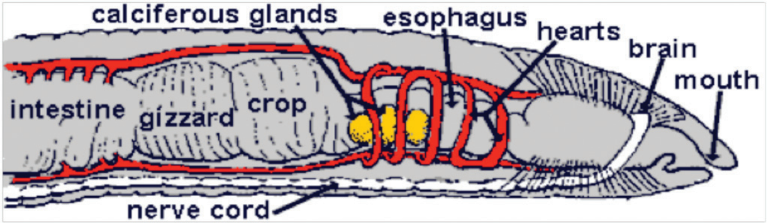


Figure 7 The alimentary canal of earthworms (After J. Conrad, 2009).

Earthworms are classified into three main ecophysiological categories: (i) Epigeic - leaf litter/compost dwelling worms, (ii) Endogeic - topsoil or subsoil dwelling worms and (iii) Anecic - worms that construct permanent deep burrows through which they visit the surface to obtain plant materials for food, such as leaves. Soil dwelling (endogeic and anecic) worms known as "earthworker" include *Aporrectodea calliginosa, A. trapezoids, A. rosea, A. longa,* *Microscolex dubius, Octolasion cyaneum*, and *Lumbricus terrestris* (Appelhof *et al.,* 1996). The other species are composters, such as *Eisenia fetid*a (commonly called "tiger worm" because of its stripes, but also known as the brandling or manure worm); *E. andrei* ("red tiger", a close and nonstriped relative of *E. fetida*); *Perionyx excavatus* (the Indian blue worm, a tropical species); and *Eudrillus eugeniae* (African night crawler, another tropical species). *Lumbricus rubellus* (red worm or dung worm) seems to be one of the few worms that can be classified as both a soil dwelling worm and a composting worm (Appelhof *et al.,* 1996).

Earthworms feed on organic matter and convert these materials into casting (ejected matter) rich in plant nutrients called "vermicompost". The process of producing vermicompost using earthworms is called "vermicomposting". Inoculation of earthworms into the organic wastes during composting helps to enhance the transformation of organic P into mineral forms. In addition, they also keep the magnitude of fixation of released P into insoluble inorganic forms at low levels, thus increasing the availability of P in these compounds. The amount of plant available P in the earthworm casts was 5-fold more than surrounding soils (Sabrina *et al.,* 2009a). Moreover, most of the additional P present in casts is held in more physically sorbed than chemisorbed forms and a reduction in P sorption capacity of soil by organic matter blockage. At the same time, the presence of earthworm will enlarge the microorganism's population in the soil. Thus, activity of earthworms in soil contributes to soil turnover, structure formation, and fertility enhancer in various ways. Earthworms and their casts are useful in land improvement, reclamation, and in organic waste management (Edwards and Baker, 1992; Lavelle and Martin, 1992; Johnson, 1997; Villenave *et al.,* 1999). Soil productivity can be improved by manipulating the community of earthworms in soil (Brown *et al.,* 1999).

During vermicomposting, earthworms digest the decaying organic materials through physical and biochemical processes in their digestion organ. It macerates the organic materials through its grinding gizzard, and produces the widest exposed surface area for beneficial microorganisms to live. The biochemical processes in an earthworm's intestine generates available nutrients for earthworms to absorb and cast with high nutrients content. Earthworm digestion systems are akin to a compost grinder machine and also produce energy for microbes, and an environmental friendly system. Moreover, vermicompost is well known for its good water-holding capacity, hence the soil's need of water for solubilisation of PR could be supplemented. Earthworms also release enzymes to digest its food, which may optimize solubility of PR. Addition of PR to the organic materials would be able to produce vermicompost enriched with water soluble P, a product that can be named "vermiphosphocompost".

Successful production of vermiphosphocompost requires some basic information about availability and suitability of organic materials as a feedstock for earthworms. Oil palm plantations in Malaysia generate a large quantity of oil palm by-products, such as empty fruit bunch (EFB), palm oil mill effluent (POME), trunk, and frond (Chan, 2000). Two of the oil palm by-products, EFB and oil palm frond, are easily available in every oil palm estate. The EFB is produced in the oil palm mill at the beginning of oil extraction process whereas frond is produced during oil palm pruning in the estate. About 6-7 tonnes of EFB are generated for every 10 tonnes of fresh fruit bunch (FFB) of oil palm. Annually, an average of 24 fronds is pruned per plant per year and this is equivalent to 11.7 tonnes ha^{-1} year^{-1} (Chan, 2000). Bearing in mind the projected total oil palm cultivation area to reach 5.10 million ha in 2020 (Anonymous, 2005), these oil palm by-products are a potential source of feedstock for 'vermiphosphocompost'.

Our initial study to evaluate the ability of earthworms in vermicomposting of oil palm by-products showed that only one species of earthworm, *E fetida,* was able to survive in these by-products (Sabrina *et al.,* 2009b). One month pre-composting and the addition of cow dung as food supplement to earthworm would be able to reduce the mortality rate and maintaining the growth of earthworms. The ratio of 1:10 (earthworm/media) was the most appropriate for the earthworm to survive in EFB culture. Vermicomposting of EFB was able to provide beneficial nutrients, such as N, K, and Mg to the test crop, *Setaria splendida* L. in a glasshouse experiment (Sabrina *et al.,* 2009b).

Vermiphosphocompost was produced using two oil palm by-products, EFB and oil palm frond, a worm composter, *E. Fetida,* and selected PRs with variable reactivity in a 9-week laboratory study. The dissolution of PR as measured by ΔP and ΔCa, plant availability of P (ΔP_b), pH, bacteria, humic acid, acid- and alkaline-phosphomonoesterase, and organic C content were measured at the end of the experiment in the vermiphosphocompost. The ΔP and ΔP_b were 60 and 137% significantly higher than that without worms (normal composting) (Table 6). The increase in ΔP and ΔP_b might be due to significant amounts of ammonium and urea released by earthworms during their excretion process. The fate of these compounds in the soil or compost system is firstly the uptake by plant or microbes, denitrification producing N_2, or nitrification producing NO_3^- and releases ion H^+. The possibility of ammonium production is a major reason why earthworms are able to dissolve PR. Ammonium released by earthworms enhances microorganisms growth.

Table 6 The effect of earthworm, PRs, and oil palm by-products on ΔP, ΔCa, ΔP_b, pH, bacteria, humic acid, acid PME, Alkaline PME, and organic C.

Treatment	ΔP	ΔCa	ΔP_b	pH	Bacteria	Humic acid	Phosphomonoesterase		Organic C
							Acid	Alkaline	
	———	mg kg^{-1}	———		cells*10^6	g g^{-1}	µg ρ-nitrophenol h^{-1}		—%—
Earthworm									
+ W	265.6a	3563.9a	227.2a	7.48a	31a	0.074a	103.77a	132.74a	23.96a
- W	160.5b	3472.2a	95.6b	7.38b	24b	0.043b	68.23b	110.58b	23.88b
Oil palm by products									
EFB	240.7a	1763.9b	164a	8.45a	26a	0.080a	91.15a	126.92a	23.95a
Frond	185.4b	5272.2a	158.9a	6.41b	29a	0.036b	80.86b	116.39b	23.90a
Phosphate sources									
GPR	253.2a	3141.7a	165.2a	7.34b	27b	0.094a	79.43a	109.37a	23.93a
MPR	172.1ab	3316.7a	153.9a	7.49a	35a	0.049b	91.48a	123.77a	23.93a
TPR	213.8b	4095.8a	165.2a	7.54a	24b	0.058b	83.57a	122.45a	23.88a
TSP	—	—	—	7.26b	23b	0.042b	87.84a	124.08a	23.91a
No-P	—	—	—	7.52a	29ab	0.047b	87.71a	128.62a	23.97a

Means with the same letters of each factors of each columns and of each parameters are not significantly different at $\alpha \le 0.05$.

During their biochemical process, microorganisms will release more H^+ ions and organic acids and consequently increase ΔP and plant availability of P (ΔP_b) from PRs. The pH of both vermiphosphocompost and normal compost was neutral, but the pH of the former was significantly higher than the later (Table 6). Significantly higher humic acid content in vermiphosphocompost than normal compost (Table 6) indicates that the degree of organic matter decomposition has reached stability for the former than the latter. The pH of the compost indicates that the vermiphosphocompost could contain more humic acid derived from phenolic than that from carboxylic fuctional groups. Since the acidity of many carboxylic acids (pKa 15.7 to -1.7) are stronger than phenol (pK_a 9.95). Humification processes are accelerated and enhanced not only by the fragmentation and size reduction of the organic matter, but also by greatly increasing the microbial activity within the intestines of the earthworms and by aeration and turnover of the organic matter through earthworm movement and feeding (Dominguez, 2004). Vermiphosphocompost showed significantly higher numbers of bacteria compared to normal compost (Table 6). Most of these bacteria could produce acid- and alkaline-phosphomonoesterase. However, a higher content of alkaline- than acid-phosphomonoesterase suggests that this enzyme is capable of removing phosphate groups in many molecules, such as nucleotides, proteins, and alkaloids, through the dephosphorylation process in alkaline environment. Dephosphorylation of phosphate by the bacteria is a means of utilizing phosphate during phosphate starvation or for uptake of organic molecules by passing through the membrane of bacteria in the presence of high phosphate groups in organic compounds in the environment. Earthworms may facilitate significant change in the biogeochemical status of P (availability, organic phosphorus pool, and acid phosphatase activity) in certain hot spots, such as casts and burrow-lining (Le Bayon and Binet, 2006). Vinotha et al. (2000) concluded that the micro flora in worm casts plays an important role in enhanced phosphatase activity. Therefore, the products (vermicompost) released from earthworm contain high concentration of plant metabolites, due to enhanced microbial activity during the vermicomposting process.

The type of bacteria present in PRs treatment was similar, but differed with oil palm by-products. Using Biolog micro plate bacteria identification, the bacteria present in the intestines of the earthworms cultured in EFB were *Brevundimonas vesicularis*, *Pseudomonas citronellolis*, and *Pseudomonas nitroreducens*. *Brevundimonas vesicularis* which produces yellow or orange colonies has been associated with slime deposits on machines in paper mills. *Pseudomonas vesicularis* is a synonym for *Brevundimonas vesicularis*. The bacteria of earthworm intestines cultured in frond and not found in EFB cultured earthworms intestine was *Cellulomonas flavigena*. *Brevundimonas vesicularis*, *Clavibacter agropyri*, and *Acinetobacter calcoaceticus* D were found in the intestines of earthworms cultured in both oil palm residues.

The microbial composition of the earthworm intestine contents has been considered to reflect that of the soil or ingested plant remains (Brown, 1995). The EFB contains high amount of lignin (Chan, 1999). Ligneous materials commonly contain phenolic compounds (Elder and Kelly, 1994). *Pseudomonas nitroreducens* is able to degrade alkylphenolpolyethoxylates (Chen, 2006). *Pseudomonas citronellolis* contain a pyruvate carboxylase with a $\alpha_4\beta_4$ composition and a biotin, and is able to increase anthracene degradation (Jacques *et al.,* 2005). *Clavibacter agropyri* produces amino acids, L-glutamate and L-lysine. *Cellulomonas flavigena* can be used for protein enrichment of cellulotic residues in solid state fermentation (Xu *et al.,* 2005). No information is available on the role of *Burkholderia glumae* in the agricultural sector. *Acinetobacter calcoaceticus* is a gram negative, aerobic, and non motile. *Acinetobacter calcoaceticus* has been investigated for use in crude oil cleanup.

Interactions of organic matter, AM, and earthworm under natural field conditions may influence P utilisation and uptake of P by plants. However, the effectiveness of each factor in influencing plant growth and uptake of P is not yet fully understood. A glasshouse pot experiment was done to evaluate these interactions on the growth and uptake of P by a test crop, *Setaria splendida*, L. on Bungor soil (Typic Paleudult). The experimental pots used were a modification of growth chambers design for earthworms by Tuffen et al. (2002). The inside (ø rim = 12.7 cm, ø bare = 9.2 cm, and height = 7.6 cm). The pot was separated into two parts with a 0.5 mm pore size nylon cloth, which allowed fungal hyphae and roots to pass through (Figure 8).

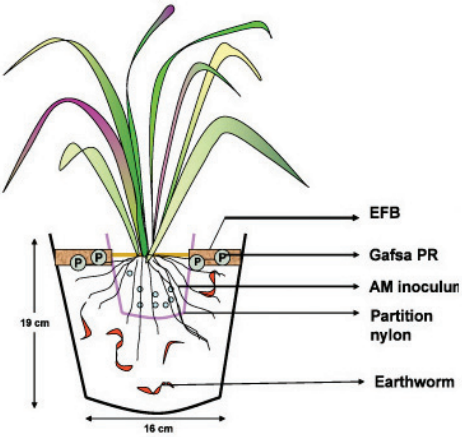


Figure 8 Growing of the grass, *Setaria splendida*, in the experimental pot containing AM, earthworm, and EFB.

The outer part of the pot was filled with soil to about 1/3 of the pot volume, then the inside part of pot was placed on it. Then, both pots were filled with soil up to about 5 cm from the top of the pot. The GPR (150 kg P_2O_5 ha^{-1}) was mixed with EFB (36.5 ton ha^{-1}) and placed on the soil surface of outer part. Meanwhile, AM inoculum was inoculated in the inside pot under the *Setaria* cutting. Nitrogen and potassium fertiliser application and plant watering was similar as described elsewhere (Sabrina *et al.,* 2009c). The treatments comprise: (i) –PR, +PR (GPR), (iii) –PR + EFB, (iv) +PR + EFB, (v) 'Vermiphosphocompost' (VPC), (vi) Worm + AM + EFB, and (vii) Worm + AM + EFB + PR. The dry matter yield, root volume, and P uptake by *S. splendida* were significantly influenced by the technique of applying PR (Table 7). The DM yield of treatments without PR (-PR, EFB–PR, W+AM+EFB-PR) were lower compared to that treated with PR (+PR, EFB+PR, W+AM+EFB+PR). Among the treatments, VPC gave the highest cumulative DM yield (29.07 g pot^{-1}) and differed significantly compared to other treatments except for the treatment +worm +AM + EFB +PR (26.03 g pot^{-1}). The PR mixed with organic matter treatment significantly increased DM yield of grass compared to the DM yield of treatment with (+PR), except for treatment +PR+EFB. Better growth performance of the grass was attributed to more root proliferation as shown by root volume of VPC treated plants compared to other treatments (Table 7). Consequently, the uptake of P and the other nutrients are greater (Table 7). Cumulative P uptake by grass for VPC (79.39 mg P pot^{-1}) was significantly higher than that of 37.38 mg P pot^{-1} for (+PR) treatment. The concentration of P in soluble form for VPC was high and readily taken up by the grass. Similar results were reported for Pepper treated with VPC (Arancon *et al.,* 2005). The significant growth of plant is caused by the presence of plant growth hormones and humic acid (Arancon *et al.,* 2006).

Table 7 Effect of different P treatments on cumulative dry matter yield, root volume, and P uptake by the grass, setaria after 5 months harvest.

Treatment	Dry matter yield	Root volume	P uptake
	g pot^{-1}	cm^{3}	mg P pot^{-1}
– PR	11.58c	25.62d	23c
+ PR	16.24bc	37.38cd	28c
– PR + EFB	16.55bc	37.74cd	67bc
+ PR + EFB	19.34b	53.80b	157a
VPC	29.07a	79.39a	163a
Worm+AM+EFB	19.82b	44.14bc	107ab
Worm+AM+EFB+PR	26.03a	52.57b	150a

Means with the same letters are not significantly different at $\alpha \leq 0.05$.

Crop/Pasture Improvement

One of the mechanisms suggested for the differences in ability of various crop species to utilise PR is through the acidification in the plant's rhizosphere environment (Bekele *et al.,* 1983; Van Ray and Van Diest, 1979). Using six plant species, such as wheat, paspalum grass, maize, molasses grass, soybean, and buckwheat, Van Ray and Van Diest (1979) found that Gafsa PR (Tunisia) was as good as TSP for buckwheat, which produced much lower soil pH than did other plant species through imbalance of cation and anion absorption by the roots.

The effectiveness of Sechura PR (SPR) from Peru relative to TSP on the same soil (Mountview silt loam, pH 4.8) was observed using five different crops (Chien *et al.,* 1990). The SPR was less effective than TSP for wheat, maize, and flooded rice but was as good as TSP for upland rice and ryegrass. They attributed this to the efficient use of PR by ryegrass probably due to its high rooting density. Upland rice was more effective than flooded rice in using PR, probably because of the soil pH effect as discussed previously.

Published results by the International Fertilizer Development Corporation (IFDC) have shown that rapeseed (canola) is able to utilize PR in alkaline soils while other crops, such as maize, cowpea, and cotton failed. Under this situation, organic acids exudation, such as malic and citric acids by the rapeseed roots is the main factor for PR dissolution **(**Hoffland *et al.,* 1989). Using a medium reactive Syrian PR, Habib et al. (1999) found that the relative agronomic effectiveness (RAE) was 55% of the TSP for rapeseed grown on an alkaline soil (pH 7.8). Using PR with different reactivity on the same soil, the RAE for increasing rapeseed yield ranged from 0 to 80% of TSP (Table 8). Thus, a high reactivity of the PR may also have potential for a direct application to high pH soils with efficient crops, such as rapeseed.

Table 8 Relative agronomic effectiveness of various PR sources in alkaline soil (pH 7.8) as measured by rapeseed yield.

PR Source	**Reactivity**	**RAE[a] (%)**
Gafsa, Tunisia	High	81
Eshidiya, Jordan	Medium high	70
Ain Laylous, Syria	Medium	64
Chelesia, Kazakstan	Medium	63
Kengesepp, Russia	Medium low	60
Kodjari, Burkina Faso	Low	53
Kaiyang, China	Low	30
Panda Hills, Tanzania	Very low	0

Note : [a]Relative agronomic effectiveness (RAE); RAE of TSP=100%.
Source : Adapted after Chien (2003).

Removal of the products of PR dissolution, such as Ca^{2+} ions from the sites of reaction is one of the methods for promoting the dissolution of PR in soil environment. A high exchange Ca-capacity (Mackay *et al.,* 1986; Hanafi *et al.,* 1992) and organic matter content (Khasawaneh and Doll, 1978; Chien, 1979) of soil have been shown to provide a sink for Ca^{2+}, thereby promoting the dissolution of PR in soil. Apart from supporting and enhancing the development of plants, the main functions of plant roots are for nutrients absorption and water transport. Plant roots have fixed negative electrical charges within the root cell walls which are used for nutrients absorption (Briggs, 1957). The root cell walls act as a cation exchanger (Devaux, 1916; Ledin and Wiklander, 1974). The origin of cation exchange properties of plant roots is generally assumed to be carboxylic (-COOH) and phenolic (-OH) functional groups from cellulose, hemicelluloses, and lignin materials of the cell wall (Ledin and Wiklander, 1974). Based on this assumption, the root cell walls can be assumed to behave in a similar way to soil, which posses 'Ca-sink'. Hence, the differences in capacity for Ca uptake (sink size) by plants can be used as an index to indicate the ability of crop species to utilise P from PRs. Using Ca^{2+} adsorption isotherms study of several tropical fruits, duku terengganu (*Lansium domesticum* Jack), belimbing manis (*Averrhoa carambola* L.) cempedak (*Artcocapus champeden* Spreng.), papaya (*Carica papaya* L.), durian (*Durian zibenthinus* L.), mango (*Magifera indica* L.) and mangosteen (*Garcinia mangostana* L.) and bristle grass (*Setaria splendida* L.) roots (Hanafi, unpublished data) showed that the plants affinity for Ca^{2+} differed widely (Figure 9). For example, at the highest concentration of Ca added (100 mg Ca^{2+} L^{-1}), papaya adsorbed the most (1708.3 mg Ca^{2+} kg^{-1} root) compared to setaria grass (679.3 mg Ca^{2+} kg^{-1} root). For every additional increments of Ca^{2+} in solution, the amounts of Ca^{2+} ion adsorbed by plant roots increases. Further examination using Freundlich and Langmuir equations showed that the former is better the latter in estimating the adsorption of Ca^{2+} by plant roots.

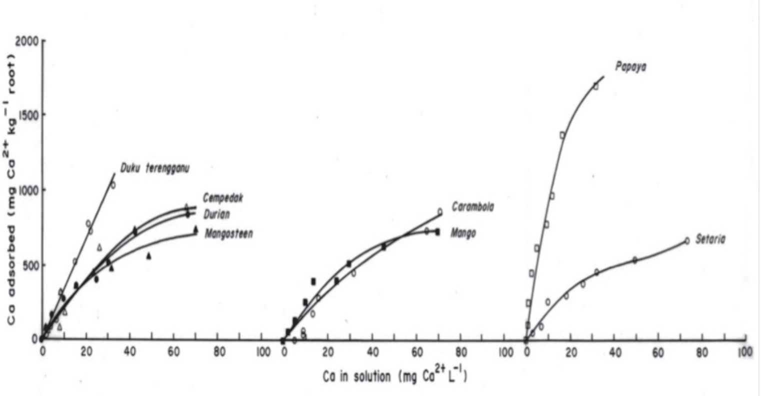


Figure 9 Calcium adsorption isotherms of several tropical fruit and setaria grass roots using $CaCl_2$ as supporting electrolytes.

Equilibrium constant (k) for the Freundlich equation differ vary greatly for the different types of plant roots used in this experiment (Table 9). For example, it ranges from 1.028 mg Ca^{2+} kg^{-1} root for carambola to 173.78 mg Ca^{2+} kg^{-1} root for papaya. This indicates that the degree of Ca^{2+} adsorption by plant root of papaya was greater than that of carambola. Differences in the genetic variability of plant types may be responsible for the different in root capacity to adsorb Ca^{2+} in solution. Based on the k values, the types of plant used can be divided into four groups: very low (carambola, duku terengganu, cempedak, and setaria), low (mango and durian), medium (mangosteen), and very high (papaya) Ca^{2+}-adsorbing plant. Crops with high affinity for Ca^{2+} would be able to promote the dissolution of PRs in soil, hence increasing P utilisation efficiency.

Table 9 Constants and correlation coefficients (r) for Freundlich and Langmuir equations following Ca^{2+} adsorption using $CaCl_2$ as supporting electrolyte by plant roots.

Plant root	**Freundlich**			**Langmuir**		
	k	**n**	**r**	**k**	**b**	**r**
Duku terengganu	3.95	0.774	0.990^{**}	-0.006	-1159.9	0.756^{*}
Cempedak	7.78	0.953	0.990^{**}	0.000	-97336	0.021^{ns}
Durian	45.60	1.390	0.976^{**}	0.021	1428.6	0.935^{**}
Mangosteen	72.11	1.780	0.982^{**}	0.046	909.1	0.974^{**}
Carambola	1.03	0.656	0.988^{**}	0.009	-331.4	0.663^{**}
Mango	44.16	1.400	0.970^{**}	0.029	1111.1	0.974^{**}
Papaya	173.78	1.420	0.961^{**}	0.060	2564.1	0.918^{**}
Setaria	15.49	1.168	0.973^{**}	0.008	1605.7	0.880^{**}

Note : ** Significant at 1% level
* Significant at 5% level
^{ns} Not Significant

Within the same variety of crop (for example Corn, *Zea mays* L.), differences in the ability of roots to adsorb Ca^{2+} in limed soil using ground magnesium limestone and a control (Table 10) was observed. Addition of Ca^{2+} from lime reduces the amount of Ca^{2+} adsorbed by the root when compared to the control due to the saturation of Ca^{2+} at the Ca-sink sites. The ability of corn roots to adsorb Ca^{2+} decreases in the following order: double-cross hybrid > single-cross hybrid > Suwan > Metro (Govindaraju, 1995). Hence, the Ca-sink size of plant roots, genotype, and mechanisms involved can be used to evaluate suitable genotypes to be fertilised with PR materials.

Table 10 Constants and correlation coefficients (r) for Freundlich equation following Ca^{2+} adsorption using $CaCl_2$ as supporting electrolyte by plant roots grown on limed- and unlimed-soil.

Genotype		Limed			Unlimed		
		k	**n**	**r**	**k**	**n**	**r**
Metro		1.874	0.732	0.9841^{**}	1.324	0.804	0.9788^{**}
Suwan		4.341	0.849	0.9264^{**}	3.289	0.823	0.9652^{**}
G3	Hybrid	4.087	0.890	0.9632^{**}	5.406	1.000	0.9463^{**}
G4	(Single-cross)	2.442	0.848	0.9831^{**}	1.507	0.897	0.9077^{**}
G5		0.572	0.562	0.9597^{**}	1.152	0.683	0.8963^{**}
G6		2.506	1.477	0.9774^{**}	2.506	0.978	0.9572^{**}
G7		2.065	0.944	0.8751^{**}	13.200	1.392	0.9638^{**}
G8		2.335	0.842	0.8744^{**}	10.051	1.245	0.9802^{**}
G9		5.509	0.834	0.9390^{**}	8.057	1.066	0.9699^{**}
G10		3.466	0.843	0.9023^{**}	4.249	0.890	0.9675^{**}

G11	Hybrid	7.060	1.009	0.9061**	19.536	1.933	0.9902**
G12	(double-cross)	5.136	1.180	0.9098**	19.704	1.942	0.9886**
G13		3.481	0.797	0.9660**	11.423	1.570	0.9849**
G14		6.763	1.009	0.9537**	6.936	1.422	0.8939**
G15	Inbreed lines	8.374	1.053	0.9610**			
G16		2.163	0.870	0.9714**			
G17		8.797	1.383	0.9793**			
G18		6.462	1.111	0.9784**			
G19		2.657	0.868	0.9776**			
G20		8.917	1.305	0.9761**			

Note : ** Significant at 1% level.

Crop Mixtures

Crop mixtures or intercropping system is the growing of two or more crops with different characteristics and requirements at the same time on the same plot of land (Andrews and Kassam 1976). In this system, crop productivity may be increased or decreased depending on the inhibitor or stimulator effects of components crops on each other under non-limiting growth resources, such as light, water, nutrients, and space (Narwal, 2000). This practise is very common in all tropical and sub-tropical areas for increased crop yield, management of pests and diseases, and other agronomic benefits. However, in some areas in Africa, the order of importance for crop mixtures is for food security followed by soil conservation, crop compatibility, crop insurance, and other preferences (Fawole and Oladele, 2007).

In this system, the growth and yield of component crops increases due to better nutrient absorption and weed control compared to monocrop. Root exudates and volatile substances in shoots have been identified as major role players in increasing plant productivity through improved ion exchange, greater nutrient uptake, and better weed control (Narwal, 2000). Thus, the most common goal of crop mixtures is to produce a greater yield on a given piece of land by making use of resources that would otherwise not be utilized by a single crop. However, in Malaysia crop mixture systems are used only for better nutrient management during the establishment and initial 1-4 years of oil palm growth to maintain good ground cover for good agricultural practices and also for rejuvenation of marginal soil for tree crops planting. Several legume species have been used for this purpose, such as groundnut (*Arachis hypogaea* L.), tropical kudzu (*Pueraria javanica*), and ox-eye bean (*Mucuna bracteata*).

A joint-research project involving Universiti Putra Malaysia (UPM), Sime Darby Research Centre (SDRC), FELDA Agricultural

Services Sdn. Bhd. (FELDA), Tradewinds Research and Development Centre (TRDC), Malaysian Palm Oil Board (MPOB), and Advanced Agriecological Research (AAR) Sdn. Bhd. was commissioned by the World Phosphate Institute (IMPHOS) to examine the long-term effects of the use of phosphate rocks in oil palm plantations. The project was funded for 6 years (2004-2010) with a total cost of USD 360,000. Crop mixtures between the major crop (oil palm) and minor crop (legume) was established in two agroclimatic zones on (i) Bungor soil (Typic Paleudults) in Batu Lintang Estate, Kedah (AAR) and (ii) Basaltic (Mostyn) soil in Mostyn estate, in Kunak, Sabah (SDRC). The effect of P immobilisation of medium reactive, JPR on P uptake and dry matter production of sole *Mucuna bracteata* (MB) and MB mixed with *Pueraria javanica* (JP) in immature oil palm showed that within six months, P concentration of MB in pure MB plot increased linearly with increasing PR rates up to 80 kg P ha^{-1}, whereas no response was obtained for PJ (Ng *et al.,* 2005). Significantly higher mean P concentration in MB was obtained in mixed planting of MB and PJ (0.133%) than that of sole MB (0.117%). They attributed this to symbiotic effects between these two legumes which might have contributed to the rapid ground coverage of PJ thereby reducing erosion, improve soil moisture, and slow down run-off losses of applied PR. Thus, P solubilised from PR is readily available for uptake by plant. The amount of P immobilised by the MB and PJ mixture from the soil and PR was 2.92 kg P ha^{-1} within 6 months. This study showed that medium reactive Jordanian PR (JPR) can supply sufficient amount of P to the legumes and later remobilised to oil palm through leaf litter when the legumes die. However, no oil palm yield was harvested during this period. Conversely, the results recorded for total biomass (green and leaf litter) and P and other nutrients immobilised by MB for Mostyn soil following the addition of P (15-282 kg P_2O_5 ha^{-1}) as Algerian PR (APR), Morocco PR (MPR), Christmas Island PR (CIPR), China PR (CPR), triple superphosphate (TSP) and control during one year did not show any significant difference on all variables measured (Shaharudin *et al.,* 2006). However, the amount of total biomass of MB recorded was substantially higher compared to the yield reported on Bungor soil (Table 11). Hence, subsequent P and other nutrients immobilised by the MB (Table 11) on this soil were also very much higher than that obtained by Ng *et al.,* (2005; 2006). Preliminary results from these two experiments show a very high potential in immobilisation of P from PRs to supply P when the litter decompose in soil. This P is available to be taken up by oil palm. However, the rate of P added to MB must be sufficient in order to provide a better growth performance and high biomass content to soil when the MB decomposes. Goh et al. (2009) have shown that the rate of P added to MB at 80 kg P ha^{-1} as JPR (13.2% P) significantly improved the FFB yield of oil palm for 3 to 5 yrs palms with mean FFB of 19.8 tonne ha^{-1} y^{-1} (Table 12).

Continuous tin mining operations in Malaysia started in the late nineteenth century and ceased about 100 years later leaving more than 200,000 hectares of abandoned barren land (Azizah *et al.,* 1989). Absence of organic matter and predominance of coarser materials mainly sand, resulting in very low nutrient contents, water holding capacity and microbial activity have made these areas unsuitable for agriculture and forestry (Azizah *et al.,* 1989; Vimala *et al.,* 1990). A short-term experiment was conducted to investigate the potential of a mixed *Acacia mangium* and groundnut agroforestry system for rejuvenating of tin tailings (Satter *et al.,* 2006). The experiment was laid out in split plot design with three replications. Treatments with and without AM inoculation were assigned to the main plot and P rate to the subplot.

Table 11 Dry matter yield of MB treated with different sources of P planted on Bungor and Mostyn soils at various harvest time.

Soil	Legume age	Rep.	Sample	Dry matter			Reference
				Shoot	Litter	Total	
	month				tonne ha^{-1}		
Bungor[1]	6	2	4	1.51	0.05	1.56	Ng et al. (2006)
Bungor[1]	12	2	4	2.28	0.13	2.41	Ng et al. (2006)
Bungor[1]	24	2	4	7.80	9.17	16.96	Ng et al. (2006)
Mostyn[2]	18	4	3	10.90	8.22	19.12	Shaharudin et al. (2006)

Note: [1] Jordan phosphate rock (0-160 kg P ha^{-1}.)

[2] Algerian PR, Morocco PR, Christmas Island PR, China PR, and triple superphosphate (0-600 kg P ha^{-1}.)

Source: After Zaharah et al. (2009).

Table 12 Effect of JPR addition to MB plots on subsequent oil palm FFB yield planted on Bungor soil for several harvests.

P rates to legume	**FFB yield**[1]			
	2006 **Year 3** **25th – 36th mth**	**2007** **Year 4** **37th – 48th mth**	**2008** **Year 5** **49th – 60th mth**	**Mean** **Year 3 – 5** **25th – 60th mth**
kg P ha^{-1}		tonne ha^{-1} y^{-1}		
27	13.0	18.7	22.4	18.0
80	14.5	20.7	24.1	19.8
160	12.9	18.7	23.7	18.4
p-value	0.03	0.01	0.23	0.03 (quad)
0[2]	13.0	19.1	22.2	18.1

Note: [1] Split-plot design with P rates 0-67.5 kg P ha^{-1} y^{-1} to oil palm (sub-plots) and 0-160 kg P ha^{-1} to MB (main plots) and 4 replications.

[2] Only 4 plots (L0P0) compared to others where there are 16 plots.

Source : After Goh et al. (2009)

Phosphorus rates were 0, 50 and 100 g GPR (13.5% P) plant^{-1}. The unit plots measured 8 m × 10 m. Three months old *A. mangium* seedlings were planted to the field at 2 m × 2 m spacing. Groundnut (var. Matjam) was planted at 40 cm × 15 cm spacing in 185-day old *A. mangium* plantation. Three P rates 0, 50 and 100 kg P ha^{-1} (from GPR) in combination with AM and without AM were studied using groundnut. Mycorrhiza inoculation was allocated to the main plot and P dose to the sub-plot. The AM treatment and 0, 50 and 100 kg P ha^{-1} treatments of groundnut were respectively allocated to the plots of AM treatment and 0, 50 and 100 g GPR plant^{-1} treatments of *A. mangium*. Growth parameters for *A. mangium* were measured at several times up to harvesting time for groundnut (100 DAP). Yield components, root nodulation of groundnut, and soil characteristics were determined at harvest. Results showed that with the exception of effect of P dose on plant available P in soil, inoculation of groundnut with AM and P treatments did not show any significant effect on all soil parameters measured at harvest (Table 13). The addition of different amounts of P increased P content in treatment plots. The soil P content increased to about 27.2% from 7.9 for control plots to 10.1 mg P kg^{-1} soil for soils treated with 100 kg P ha^{-1} plot. Generally, the AM and P rates for the whole treatment plots resulted in the following soil chemical characteristics after harvest: 0.83% for organic-C, 0.14% for total N, and 8.9 mg kg^{-1} soil for P; and 0.15, 3.0, and 0.23 meq 100 g^{-1} soil, for K, Ca, and Mg, respectively. Some improvements were observed in soil organic matter (SOM) as measured by organic-C content in soil (15.3%) and nutrient content (from 15% for K to 100% for N) due to growing *A. mangium* and groundnut agroforestry system. This indicates the potential of this agroforestry system for building up of soil fertility. Even though, the duration of the experiment was short (only nine months) there were notable significant treatment effects on soil properties. There was an increase in SOM and fertility status indicating improvements under this agroforestry system compared to the inherent soil properties or the control.

Table 13 Changes in the selected properties of tin tailings after planting with *A. mangium* and groundnut agroforestry system for 9 months.

Soil variable	Content		Soil variable	Content	
	Initial	**After harvest**[1]		**Initial**	**After harvest**
Sand (%)	83.80	-	K (cmol$_c$ kg^{-1} soil)	0.10	0.15
Silt (%)	11.90	-	Ca (cmol$_c$ kg^{-1} soil	2.51	3.0
Clay (%)	4.30	-	Mg (cmol$_c$ kg^{-1} soil)	0.19	0.23
pH (H_2O)	5.60	-	CEC (cmol$_c$ kg^{-1} soil)	3.28	-
Organic C (%)	0.72	0.83	Zn (mg kg^{-1} soil)	15.53	-
N (%)	0.07	0.14	Cu (mg kg^{-1} soil)	34.69	-
P (mg kg^{-1} soil)	6.76	8.9	Mn (mg kg^{-1} soil)	20.30	-

Note: [1] Average value across AM and P treatment plot.
[2] Bray II-P.
- Not determined.

CONCLUSIONS

Most Malaysian soils are acidic and low in P status and therefore all crops require an addition of P fertiliser to achieve a reasonably good yield target. Since no phosphate mineral deposits are found in Malaysia, the P sources are mostly imported from various countries. Imports will continue to rise in the future due to an expansion of the agriculture sector and the sector's status as the third engine economic growth. A majority of the P sources imported are in the form of ground PR. This PR is used as direct application fertiliser for perennial and annual crops production because it is cheaper source of P per unit compared to the water soluble P sources. The performance of various PR sources depends on the characteristics of PR and soil, types of crops, and environmental conditions. Thus, evaluation of P sources in a real field situation is very important to determine the best source of PR for any soil-crop-environmental combination. Judicious selection of P sources should be based on the most cost effective using RAE in that particular situation. However, directly applied PR sources are not effective at all in some situations. Then, there is a need to improve their agronomic effectiveness which would make the PR sources more economically attractive to farmers. Among the strategies *viz.* physical, chemical (acidulation and partial acidulation), and biological approaches (microorganisms, macroorganisms, crop/pasture improvement, and crop mixtures) can be used individually and/or in combination.

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Thank you

BIOGRAPHY

Dr. Mohamed Hanafi Musa (M.M. Hanafi) was born on June 12, 1955 in Tanah Merah, Kelantan. His early education was in Tanah Merah (primary and lower secondary), Pasir Mas (middle secondary), Kelantan, and Jitra (upper secondary), Kedah. He subsequently enrolled at Universiti Pertanian Malaysia in 1975 and received a Bachelor of Science cum Education (Honours) in Chemistry in the Faculty of Science and Environmental Studies in 1979. He became a part–time tutor at the Science Matriculation Centre, Universiti Malaya before joining as tutor at the Department of Soil Science, Faculty of Agriculture in 1980. He obtained a Masters in Soil Science (Soil Chemistry) from the State University of Ghent, Belgium in 1982. He served initially as a lecturer at the Department of Soil Science, Universiti Pertanian Malaysia, and later volunteered to serve the UPM Sarawak Branch in Semengok for three and half years (1983–1987). In September 1988, he was awarded a scholarship by the Public Services Department (JPA) to pursue a PhD program at the University of Newcastle upon Tyne, United Kingdom. He submitted a PhD thesis on "Dissolution and plant availability of phosphate rock in acid Malaysian Soils" in June 1992, and was awarded a PhD degree in May 1993.

After serving as lecturer for 17 years, Dr. M.M. Hanafi was promoted to associate professor in 2000 and professor in 2006. Following the outcome of the restructuring and rationalization process of the Institutes, Academies, and Centres in Universiti Putra Malaysia (UPM), he was seconded and appointed as the Deputy Director of the interim Institute of Tropical Agriculture (ITA) in June 2006 , a position he now holds till 2010.

Dr. M.M. Hanafi truly enjoys teaching and supervising students. He was assigned to give lectures to Diploma and Undergraduate students in the following courses: Basic Soil Science, Forest Soil,

Soil Resource and Ecosystem, Soil Fertility, Water Resources and Climate, Agriculture and Man, and Agriculture Chemistry. He is also actively involved in students' supervision not only from Faculty of Agriculture but from other faculties, such as Engineering. To date, he has supervised 5 Post–doctoral fellows, 26 PhD's and 18 MSc/M. Agric. Sc. degree candidates. Since 1982 until now, he has successfully supervised 71 final year students projects in the Faculty of Agriculture and Faculty of Science (as co–supervisor in Chemistry and/or Biology project).

Dr. M.M. Hanafi's research activities at UPM first gained momentum in early 1983 when he was awarded RM 10,400 research grant by UPM Sarawak branch campus to conduct three projects on: (i) Distribution of micronutrients in soil under different plants/crops species (1983–1985), (ii) Rice production on different soil types in Sarawak (1984–1986), and (iii) Integrated research on pepper (*Piper nigrum* L.) in Sarawak (1984–1986). By the end of 1987, he was introduced to the use of phosphate rock materials for direct application as fertiliser in acid tropical soils. He managed to secure RM 3,000 research grant from UPM and also from the Intensification of Research in Priority Areas (IRPA) to do two research projects on phosphate rock materials. His keen interest on phosphate rock chemistry and its reaction in acid tropical soils caught the interest of Prof. J.K. Syers from the University of Newcastle upon Tyne, UK, who subsequently, offered to be his supervisor for a PhD program. His work on phosphate rock chemistry was soon recognized by other Universities locally and abroad as well as by the Private Sectors in Malaysia. Subsequently in January 1988, he was appointed as Co–Supervisor to a PhD student registered at the University of Newcastle upon Tyne, United Kingdom. He was also offered a scholarship under the German Academic Exchange Service (DAAD) for collaboration with Prof.

Dr. Dr. Ewald Schnug, the Director of the Institute of Soil Science and Plant Nutrition, Federal Agricultural Research Centre (FAL), Braunschweig, Germany for 2 months (15 Nov. – 27 Dec. 1998). Subsequently, he has been invited to co-supervise a PhD candidate from UPM to undertake a research on 'The coincidental spatial pattern of the nitrogen fertilisation requirement of winter wheat' on scholarship provided by the FAL. In due recognition for his work on the phosphate rock chemistry, he was also invited to participate in the workshop in Bali, organized by the Institut Mondial du Phospahate (IMPHOS), whose H.Q. is in Casablanca, Morocco. Private Sectors, such as Peninsula Plantations Sdn. Bhd., Indah Water Konsortium (IWK) Bhd., and IMPHOS also seek his services as their consultant on this branch of science. Among the consultancy he has been engaged in up to now are: (i) Undertake a long−term study on P status, residual effect, and rice yield following direct application of phosphate rock on acid sulphate soil in Malaysia (USD 50, 715.00, IMPHOS (1998−2000), (ii) Phosphate fertiliser management in oil palm plantations in Malaysia (USD 60,000.00, IMPHO (2004−2010) as co−worker in some part of the projects), (iii) Agronomic validation of a phosphate rock decision support system (PRDSS) for PR direct application in crop production in Malaysia (USD 5,000.00, FAO/IAEA/IFDC (2004−2005), and (iv) Effects of direct biosolid application on landscape plants (RM 115,000, IWK/MAB/UPM).

In 1990, the Malaysian Government introduced a research grant to scientists at the local Universities. Under the Intensification of Research in Priority Areas (IRPA) program, he received several research grants including on: (i) Organic matter recycling in sandy soil (RM 29, 500), (ii) Production of tropical fruit (*Averrhoa carambola* L.) (RM 10,000), (iii) Improvement of pineapple production through mechanisation (RM 313,000), (iv) Development of fertilisation program for sago on tropical deep peat (RM 190,000) (co−researcher with the Department of Agriculture, Sarawak), (v) Improvement of phosphate rock dissolution using products from the decomposition of organic matter (RM 15,000), (vi) Bioconversion of palm kernel cake for fish feed production (RM 108,000), (vii) Development of a fertigation technique for pineapple production on sandy soil (RM199,500.00), (viii) Identification and evaluation of upland rice varieties for cultivation on selected idle land (RM 185,000).

Beginning in 2007, his research interest was more diverse in line with the mission and vision of the ITA to become 'A centre of excellence in tropical agriculture research for sustainable development'. Among the grants he received in ITA from 2007 – present: (i) Development of good agriculture practice for soil, water, and pest disease management for kenaf production on BRIS soils (RM 150,000, top−down MOHE), (ii) Improvement of non−starch polysaccharide and vitamin A nutrition in upland rice through marker assisted backcross breeding (RM 115,000, RUGS), (iii) Selecting plant traits that enhance nitrogen acquisition in upland rice in Malaysia (USD 30,000, IAEA), and (iii) Silicon nutrition and resistance against *Ganoderma boninense* basal stem rot of oil palm (RM 275,000, MPOB).

As an outcome of his research activity and student supervision, a total of more than 100 research papers have been published in various International Journals and Proceedings as well as several Technical papers. A total of more than 50 papers have been presented both at the National and International Seminars, and Workshops. At present Dr. M.M. Hanafi is a member and immediate past president of the Malaysian Society of Soil Science (MSSS), member of British Society of Soil Science (BSSS), member of the International Society for Southeast Asian Agricultural Sciences

(ISSAAS, Malaysian Chapter), and associate member Malaysian Institute of Chemistry (AMIC). He has served as a referee for local and international journals. Among the journals are (i) Local – Pertanika Journal of Tropical Agriculture Science, Pertanika Journal of Science and Technology, Journal of Tropical Agriculture and Food Science, and Malaysian Journal of Soil Science and (ii) International – Chemical Engineering Research and Design (UK), Water, Air & Soil Pollution (US), Biology and Fertility of Soil (UK), African Journal of Agricultural Research, Sarhad Journal of Agriculture (Pakistan), Journal of the Science of Food and Agriculture (UK), and Waste Management (US). He has served as an academic assessor for promotion to associate professor for King Saud University, Saudi Arabia and Universiti Putra Malaysia and professor to Universiti Teknologi Malaysia. At present, he is also serving as the editorial board of the Malaysian Journal of Soil Science.

Dr. M.M. Hanafi has also contributed to the society through Malaysian Professional Centre (BIM). He served as an EXCO member BIM for two terms (2007/08–2008/09). He has also been invited by the Standards and Industrial Research Institute of Malaysia (SIRIM) to be an auditor for laboratory accreditation scheme and a member of the technical committee on 'Soil Quality' of the National Standards Development Agency, and a technical expert in Agriculture under the scheme of the certificate accreditation agencies, Department of Standard, Ministry of Science, Technology, and Environment Malaysia.

Dr. M.M. Hanafi truly enjoys seeking new research areas and will continue to do so in future, insyaalah!

LIST OF INAUGURAL LECTURES

1. Prof. Dr. Sulaiman M. Yassin
   The Challenge to Communication Research in Extension
   22 July 1989

2. Prof. Ir. Abang Abdullah Abang Ali
   Indigenous Materials and Technology for Low Cost Housing
   30 August 1990

3. Prof. Dr. Abdul Rahman Abdul Razak
   Plant Parasitic Nematodes, Lesser Known Pests of Agricultural Crops
   30 January 1993

4. Prof. Dr. Mohamed Suleiman
   Numerical Solution of Ordinary Differential Equations: A Historical Perspective
   11 December 1993

5. Prof. Dr. Mohd. Ariff Hussein
   Changing Roles of Agricultural Economics
   5 March 1994

6. Prof. Dr. Mohd. Ismail Ahmad
   Marketing Management: Prospects and Challenges for Agriculture
   6 April 1994

7. Prof. Dr. Mohamed Mahyuddin Mohd. Dahan
   The Changing Demand for Livestock Products
   20 April 1994

8. Prof. Dr. Ruth Kiew
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   11 May 1994

9. Prof. Ir. Dr. Mohd. Zohadie Bardaie
   Engineering Technological Developments Propelling Agriculture into the 21st Century
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10. Prof. Dr. Shamsuddin Jusop
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11. Prof. Dr. Abdul Salam Abdullah
    Natural Toxicants Affecting Animal Health and Production
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12. Prof. Dr. Mohd. Yusof Hussein
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    9 July 1994

13. Prof. Dr. Kapt. Mohd. Ibrahim Haji Mohamed
    Managing Challenges in Fisheries Development through Science and Technology
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14. Prof. Dr. Hj. Amat Juhari Moain
    Sejarah Keagungan Bahasa Melayu
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15. Prof. Dr. Law Ah Theem
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16. Prof. Dr. Md. Nordin Hj. Lajis
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17. Prof. Dr. Sheikh Omar Abdul Rahman
    Health, Disease and Death in Creatures Great and Small
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18. Prof. Dr. Mohamed Shariff Mohamed Din
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19. Prof. Dr. Tengku Azmi Tengku Ibrahim
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20. Prof. Dr. Abdul Hamid Mahmood
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21. Prof. Dr. Rahim Md. Sail
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22. Prof. Dr. Nik Muhammad Nik Abd. Majid
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24. Prof. Dr. Sharifuddin Haji Abdul Hamid
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28. Prof. Dr. Wan Sulaiman Wan Harun
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