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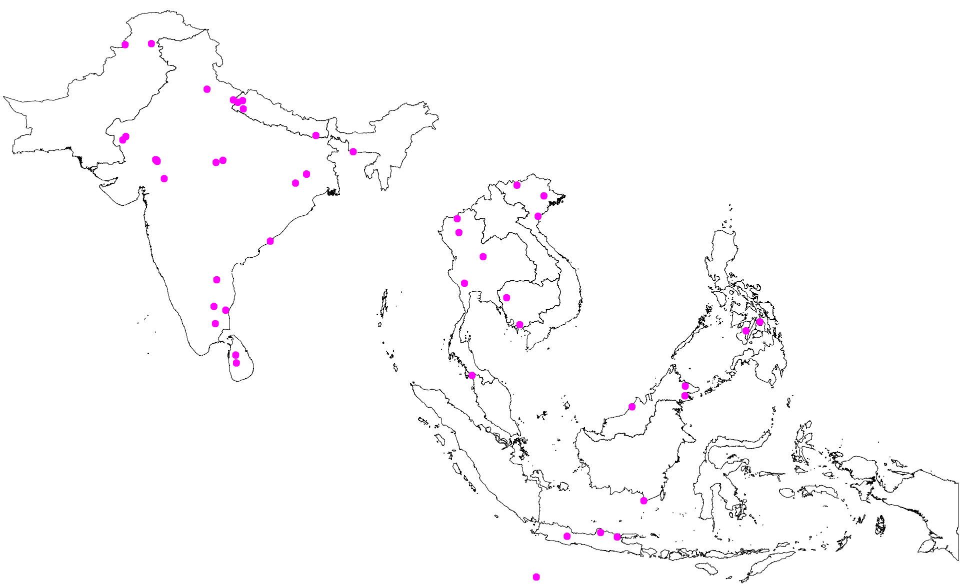
Local phosphate resources for sustainable development in India, Nepal, Pakistan and southeast Asia

Economic Minerals and Geochemical Baseline Programme

Report CR/02/123/N



BRITISH GEOLOGICAL SURVEY

REPORT CR/02/123

Local phosphate resources for sustainable development in India, Nepal, Pakistan and southeast Asia

J D Appleton and A J G Notholt

Key words

phosphate, resources, Central and South America, agronomic, fertilizer, direct application.

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Distribution of phosphate mineral resources in Central and South America

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Foreword

This report is an output for the Department for International Development (DFID) funded research project R7370 *Local Phosphate Resources for Sustainable Development* and is a contribution towards DFID Infrastructure and Urban Development Department's Goal G1: *Environmental Mineral Resource Development*. It was compiled and collated from readily available existing information including archive material held by the BGS; digital bibliographic data bases; IFDC reports; and through contacts with mineral resources and agricultural organisations including FAO, IFDC, ICRAF, UNIP, UNIDO, IFA. An *Endnote* database was compiled of bibliographic references and abstracts together with information from web sites and this now includes over 2400 records.

This report was commissioned by the UK Department for International Development (Contract R7370) but the views in it are not necessarily those of the Department.

Acknowledgements

Arthur Notholt, the renowned phosphate mineral resource expert, who died suddenly in 1995, had been working for many years on a comprehensive review of world phosphate deposits and the international phosphate mining industry. Arthur's widow, Agnes, kindly gave permission for the compiler of this report to make extensive use of information from Arthur's unpublished papers (Notholt, 1999). In some cases it was appropriate to include text written by Arthur. It is for this reason, and with the full approval of Agnes, that Arthur is named as joint author of this report.

Maps illustrating the location of phosphate resources in each country were complied using coastlines, international boundaries and the gazetteer from Edition 1 of the Digital Chart of the World (DCW) July 1992.

Summary

Soil degradation and infertility are major constraints to the sustainability of agricultural systems in many developing countries, particularly those located in the tropical humid lowlands of Asia where phosphorus (P) deficiency is recognised as a major constraint to sustainable agricultural productivity. Whereas nitrogen deficits can be restored, at least in part, through the application of organic crop residues and manure or by the use of cover crops, the restoration of soil P-status can only be achieved by the use of phosphate fertilisers. The socio-economic situation for many farmers is, however, such that they are unlikely to be able to afford to purchase manufactured mineral fertilizers required to replenish this deficit. The most vulnerable groups of subsistence farmers, such as those practising shifting cultivation or cultivating marginal lands are already seeing production levels fall as soil fertility declines. Most developing countries in Asia need to meet the needs of growing populations without damaging the resource base. DFID's *Sustainable Agriculture Strategy* (1995) clearly identifies the need to increase crop yields through the prevention of erosion, the introduction of stable farming systems, improving genetic material, and the use of organic and, inorganic fertilisers.

Agronomists, agricultural economists, renewable natural resources and mineral resources advisers in local and national governments, international bodies including development agencies, and NGOs working with poor farmers, may not be adequately aware of locally available phosphate rock resources and their agronomic potential, as a low-cost source of phosphate, for the enhancement of soil fertility and productive capacity of relatively poor, smallholder farmers. There is a need to ensure that the use and development of local resources is considered as an option for restoring the P-status and productive capacity of degraded soils. Unfortunately, much of the information required to inform the consideration of this option is widely dispersed in reports, scientific publications, symposia and workshop proceedings that may not be readily available to advisers working in the developing countries of Asia. This report presents the third of a series of three regional reviews (covering sub-Saharan Africa, Central and South America and selected countries in Asia) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with the following countries: Cambodia, India, Indonesia, Malaysia, Nepal, Pakistan, Philippines, Sri Lanka, Thailand and Vietnam.

The report contains a brief regional review of the phosphate mineral resources of the selected countries including information on phosphate rock and phosphate fertilizer production, consumption, and export.

Eleven country profiles contain summaries of:

- Quantity, quality and location of local phosphate rock deposits/sources in each country. Maps indicate the location of the phosphate resources.
- Past and current phosphate rock production including export as intermediate/raw materials and local use in agriculture
- Agronomic and agro-economic assessments of rock phosphates and associated phosphate fertilizer products, including information on the soil types and crops likely to show a positive response to direct application of rock phosphate fertilisers.

A summary of the quantity, quality, production, agronomic testing, use and development potential of the phosphate resources, together with their geological type and age is provided in the final section of the report.

The first volume of the series, covering Sub-Saharan Africa, contains generic reviews of:

- Phosphate rock products and processing options
- Estimated investment required for mining, infrastructure and processing options
- Constraints for utilisation of phosphate rock resources
- Environmental constraints related to heavy/hazardous elements contained in the rock phosphates or their by-products.
- Existing or anticipated direct use of phosphate rock in agriculture including general results of agronomic and economic assessments.
- Role of phosphate rock in strategies for dealing with soil fertility.

Local Phosphate Resources for Sustainable Development is an 'enabling project' which aims to support the context for poverty reduction and elimination. In order to enable poverty alleviation, the project focuses on opportunities for the promotion of local use rather than the export of phosphate. The project cannot ensure that poor communities and farmers will not be adversely affected, for example, by ensuring that areas that are currently used, for whatever purpose, by poor people are not recommended as areas for phosphate rock extraction. Only the appropriate advisers and local authorities can achieve this so the report is directed at these advisers, who work with and on behalf of the poor.

CONTENTS

INTRODUCTION

Soil degradation and infertility are major constraints to the sustainability of agricultural systems in many developing countries, particularly those located in the tropical humid lowlands of Asia where phosphorus (P) deficiency is recognised as a major constraint to sustainable agricultural productivity. Whereas nitrogen deficits can be restored, at least in part, through the application of organic crop residues and manure or by the use of cover crops, the restoration of soil P-status can only be achieved by the use of phosphate fertilisers. The socio-economic situation for many farmers is, however, such that they are unlikely to be able to afford to purchase manufactured mineral fertilizers required to replenish this deficit. The most vulnerable groups of subsistence farmers, such as those practising shifting cultivation or cultivating marginal lands are already seeing production levels fall as soil fertility declines. Many developing countries in Asia need to meet the needs of growing populations without damaging the resource base. DFID's *Sustainable Agriculture Strategy* (1995) clearly identifies the need to increase crop yields through the prevention of erosion, the introduction of stable farming systems, improving genetic material, and the use of organic and, inorganic fertilisers.

A recent DFID overview of thirteen soil fertility reviews highlighted the inherent low nutrient status of weathered tropical soils as well as the losses of nutrients through erosion and leaching (Pound, 1997). The reviews recognised that phosphorus is a key element in many situations and several reviews suggested further study and exploitation of phosphate rock deposits together with the increased use of mineral fertilisers. The overview identified a number of development issues including (a) the urgent need to rebuild soil fertility and maintain increased levels of productivity, and (b) that farmer financial resources and poor distribution systems limit fertiliser use to a very low level. Low soil nutrient status could be resolved by increasing inorganic fertiliser use although this would be constrained by the lack of adequate knowledge regarding, amongst other things, (a) the potential for the production of fertiliser materials from local phosphate rock resources and (b) non-industrial techniques for increasing the solubilities of native phosphate rock. For Forest/Agriculture Interface Production Systems, it was recommended that the application of a wide range of rock based phosphate sources should be considered as a method of dealing with the degradation of natural resources at the forest margin.

Agronomists, agricultural economists, renewable natural resources and mineral resources advisers in local and national governments, international bodies including development agencies, and NGOs working with poor farmers, may not be adequately aware of locally available phosphate rock resources and their agronomic potential, as a low-cost source of phosphate, for the enhancement of soil fertility and productive capacity of relatively poor, smallholder farmers. There is a need to ensure that the use and development of local resources is considered as an option for restoring the P-status and productive capacity of degraded soils. Unfortunately, much of the information required to inform the consideration of this option is widely dispersed in reports, scientific publications, symposia and workshop proceedings that may not be readily available to advisers working in developing countries. This report presents the third of a series of three regional reviews (covering sub-Saharan Africa, Latin America and selected countries in Asia) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with the following countries: Cambodia, India, Indonesia, Malaysia, Nepal, Pakistan, Philippines, Sri Lanka, Thailand and Vietnam, together with the Territory of Christmas Island.

This report is an output for the DFID funded research project R7370 *Local Phosphate Resources for Sustainable Development* and is a contribution towards DFID IUD's Goal G1: *Environmental Mineral Resource Development*. It was compiled and collated from readily available existing information including archive material held by the BGS; digital bibliographic data bases; IFDC reports; and through contacts with relevant mineral resources and agricultural organisations (e.g. FAO, IFDC, ICRAF, UNIP, UNIDO, IFA, Potash & Phosphate Institute). An *Endnote* database was compiled of bibliographic references and abstracts together with information from web sites and this now includes more than 2400 records. Internet searches alone revealed over 3500 sites with information on 'rock phosphate' and another 5600 with information on 'phosphate rock'.

The report contains a brief regional review of the phosphate mineral resources of the selected countries including information on phosphate rock and phosphate fertilizer production, consumption, and export.

Eleven country profiles contain summaries of:

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RESOURCES & PRODUCTION

Phosphate rocks in the selected countries of Asia covered in this report are of three main types. Sedimentary deposits of phosphate rock, formed in coastal marine or lacustrine environments as the result of biogenic activity, are predominant in Cambodia, India, Nepal, Pakistan, and Vietnam. Phosphate deposits associated with igneous carbonatite complexes and metamorphic rocks occur in India, Pakistan and Sri Lanka. Some of the igneous and metamorphic deposits are hard rock, for example the Loe-Shilman deposit in Pakistan, whilst in other cases weathering has led to the concentration of phosphate in residual deposits (e.g. Eppawala in Sri Lanka). Historically important guano deposits and phosphatised limestones derived from guano occur at a number of localities on Christmas Island as well as in Indonesia, Malaysia, the Philippines, Thailand and Vietnam (Notholt, 1994; Notholt, 1999).

The distinction between sedimentary and igneous-metamorphic phosphate rocks may not be of major importance if these are beneficiated and used for manufacturing chemical fertilizers. However, the low reactivity of igneous and metamorphic phosphate rock generally makes it unsuitable for use as direct application fertilizer apart from in special circumstances such as for perennial crops grown on very acid soils in areas with high rainfall.

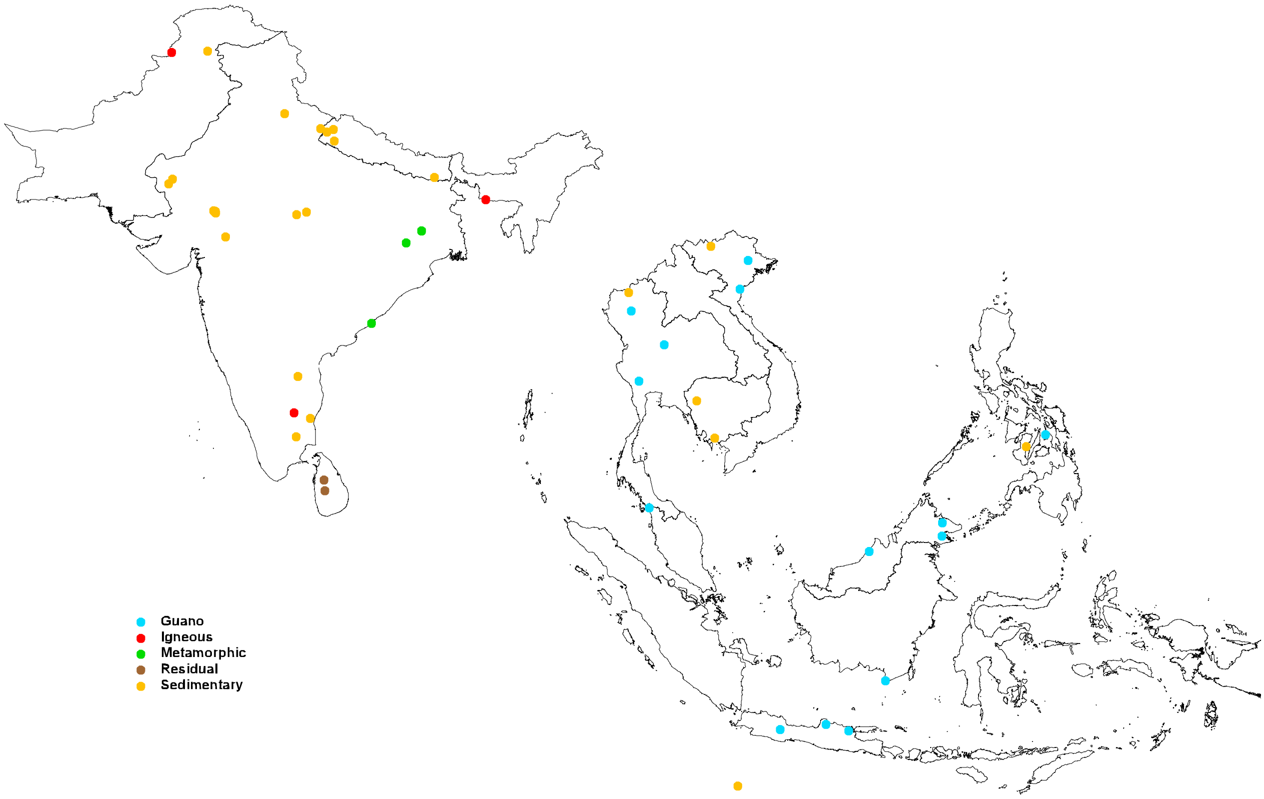
Detailed information on the geology, resources and characteristics of the phosphate deposits of Asia is available in a number of key sources (Anon., 1989; Cook et al., 1990; Dahanayake et al., 1995b; ESCAP, 1986; Notholt, 1980; Notholt, 1994; Notholt, 1999; Notholt and Hartley, 1983; Notholt et al., 1989; Savage, 1987; Van Kauwenbergh, 1995a; Van Kauwenbergh, 1995b; Van Kauwenbergh, 1995d; Van Kauwenbergh, 2001) as well as in hundreds of scientific papers, and reports produced by Geological Surveys and mining companies. Only a very brief summary of the quantity, quality and location of the main phosphate rock deposits in the selected countries of Asia is given in this report. The interested reader should refer to the sources listed above for greater detail. It is important to note that the information available on individual phosphate rock occurrences or deposits may be inaccurate, out of date, or insufficient for their quantity and quantity to be assessed. Thus the potential use as fertilizer raw material of phosphate rock from some of the occurrences cannot be assessed accurately. It should also be noted that resource and reserve estimates quoted by different sources vary considerably (e.g. from 15 to 22 million tonnes P_2O_5 for the Hirapur deposit in India and from 7 to 22 million tonnes for the Hazara deposit in Pakistan). It is assumed that this is because different criteria have been used to quantify the phosphate rock resources.

Phosphate rock deposits of potential economic significance occur at more than 48 locations in the selected countries of Asia. The quantity of resources varies from less than 0.01 million tonnes to greater than 100 million tonnes and the average P_2O_5 concentration ranges from <5% to >35%. Resource estimates are available for 48 phosphate rock deposits in the selected countries of Asia (Table 1). Phosphate rock occurrences with undefined resources are recorded in the country profiles. Phosphate rock deposits in the selected countries of Asia are irregularly distributed and many are too small, remotely situated, or lack adequate infrastructure, to be of economic importance at present.

With the notable exception of China, Christmas Island, DPR Korea, India, Vietnam and Nauru in the central Pacific, there is very limited phosphate rock production in Asia and the Pacific (Table 2). The total output amounted to over 32 Mt in 1999, of which 90% was derived from China. Small amounts of phosphate rock are also produced in Pakistan, Sri Lanka and Thailand. In addition, relatively minor amounts of phosphatic rock or phosphatic guano are or have been produced in Indonesia, Cambodia, Korea, Malaysia, Pakistan, the Philippines, and Thailand. It is estimated that less than 1% of the phosphate rock produced in the region is used as direct application fertilizer. India is by far the largest producer and user of phosphate rock for direct application. In Malaysia and Indonesia nearly all the reactive phosphate rock used for direct application in the plantation industry is imported.

Excluding the output from China, production in the other Asian and Pacific countries totalled only about 3.2 Mt in 1999, so that there is still a marked dependence of the region upon imports, notably from Jordan, Morocco and the USA.

Of the selected countries covered by this report, India, Pakistan, and Thailand produce significant quantities of manufactured chemical fertilizers - most of which are used domestically (Tables 5 and 6).



Location of phosphate deposits in India, Nepal, Pakistan and southeast Asia

Table 1 Approximate phosphate rock resources (Million tonnes; Mt) and grades

Country	Deposit	Type	Geological age	Resources Mt	Average (range) P_2O_5 (%)
Cambodia	Phnom Thom	Sedimentary	Carb-Permian	0.3	23
Cambodia	Tuk Meas	Sedimentary	Carb-Permian	0.3	17
India	Barabhu	Metamorphic	Precambrian	9.5	8-13
India	Birmania	Sedimentary	Precambrian	2.5	10-18
India	Cumbum-Cuddapah	Sedimentary	Precambrian	3.5-4.5	20-30
India	Fategarh	Sedimentary	Jurassic	?	5-15
India	Hirapur	Sedimentary	Precambrian	13-22	20-23
India	Jhabua	Sedimentary	Precambrian	7-26.6	20-28
India	Jhamarkotra	Sedimentary	Precambrian	80	15->30
India	Kanpur	Sedimentary	Precambrian	8	10-30
India	Kasipatnam	Metamorphic	Precambrian	0.22-2.6	25-42
India	Khasi-Jainita	Igneous	Cretaceous	1.7	10
India	Lalitpur	Sedimentary	Precambrian	6.3-9	15-25
India	Maton	Sedimentary	Precambrian	12936	12-35
India	Mussoorie	Sedimentary	Cambrian	45	16-22
India	Pithoragarh	Sedimentary	Precambrian	?	?
India	Purulia	Metamorphic	Precambrian	3.5	18-25
India	Sevathur	Igneous	Precambrian	small	?
India	Singhbhum	Metamorphic	Precambrian	2.5-10	7-25
India	Tiruchirapally	Sedimentary	Cretaceous	8	30
India	Udaipur (region)	Sedimentary	Precambrian	143	?
India	Valdavur	Sedimentary	Cretaceous	?	30
Indonesia	Kandangan	Guano	Recent	0.075	12-37
Indonesia	Kromong Mts.	Guano	Recent	?	?
Indonesia	Lamongan	Guano	Recent	0.186	31
Indonesia	Pati	Guano	Recent	0.119	10-38
Malaysia	Gomanton	Guano	Recent	0.01	10-21
Malaysia	Madai	Guano	Recent	0.01	?
Malaysia	Niah	Guano	Recent	0.03	23
Malaysia	Perlis	Guano	Recent	0.05	2-36
Nepal	Baitadi	Sedimentary	Precambrian	?	10-32
Nepal	Bajhang	Sedimentary	Precambrian	?	15-20
Nepal	Barahkshetra	Sedimentary	Precambrian	?	<5
Nepal	Khulia Khola	Sedimentary	Eocene	?	>4.5
Pacific Islands	Christmas Island	Sedimentary	Quaternary	214	28-37
Pakistan	Hazara	Sedimentary	Cambrian	7-22	9-29
Pakistan	Loe Shilman	Igneous	Tertiary	59-200	5
Philippines	Bantigue	Guano	Recent	0.8	15
Philippines	Imelda	Sedimentary	Tertiary	1	?
Sri Lanka	Eppawala	Residual	Mesozoic-Tertiary	60	33

Country	Deposit	Type	Geological age	Resources Mt	Average (range) P_2O_5 (%)
Sri Lanka	Ridigama	Residual	Mesozoic-Tertiary	?	16-39
Thailand	Fang-Chiang Dao	Sedimentary	Devonian	6	14
Thailand	Kanchanaburi	Guano	Recent	0.15	14-34
Thailand	Lamphun	Guano	Recent	0.05	36
Thailand	Phetchbun	Guano	Recent	0.03	20-35
Vietnam	Lao Cai	Sedimentary	Devonian	100	35
Vietnam	Thanh Hoa	Guano	Recent	<0.01	?
Vietnam	Vinh Thinh	Guano	Recent	0.2	15-37

Table 2 Production of phosphate rock (tonnes) (BGS, 2001)

Country	1995	1996	1997	1998	1999
Cambodia	na	na	na	na	na
China	31,200,800	31,040,200	25,093,700	27,091,000	29,117,700
Christmas Island **	421,590	542,800	567,860	587,660	699,828
India	1,319,328	1,349,983	1,623,190	1,276,269	1,643,430
Indonesia	275	na	533	752	617
Korea, Dem. P.R. of	*70,000	*70,000	*70,000	*70,000	*70,000
Pakistan	15,094	...	11,045	...	3,456
Philippines	na	na	na	33	181
Sri Lanka	32,114	34,044	29,635	37,598	30,258
Thailand	9,301	3,528	3,818	3,029	3,880
Vietnam	470,000	475,000	581,500	585,000	710,000
Nauru **	527,073	551,320	541,050	...	...
World Total	138,577,662	142,173,350	141,809,671	141,650,961	138,479,755

Note(s)
*Estimate ** Exports

Table 3 Imports of phosphate rock ('000 tonnes)

Country	1995	1996	1997	1998	1999
Bangladesh (b)	133.2	84.6	138.1	188.9	...
India (c)	2,443.8	2,038.3	2,667.8	3,099.5	...
Indonesia	591.1	955.8	680.0	787.5	...
Korea, Dem. P.R. of	0.7	5.5	9.3	...	...
Korea, Republic of	1,658.8	1,630.5	1,640.6	1,517.9	1,481.9
Malaysia					
Phosphate rock	538.9	586.9	602.9	560.2	728.9
Guano	5.3	5.1	...	...	...
Pakistan (b)	253.3	240.5	154.0	144.0	159.3
Philippines	742.4	707.3	331.3	557.6	...
Sri Lanka	2.3	1.1	1.4	6.7	...
Taiwan	373.9	313.5	265.2	235.4	224.1
Thailand	16.2	16.0	120.4	250.3	194.8

Note(s) :-
(a) Years ended 20 March following that stated
(b) Years ended 30 June of that stated
(c) Years ended 31 March following that stated
Source: BRITISH GEOLOGICAL SURVEY. 2001. *World Mineral Statistics 1995-99:* (Keyworth, Nottingham: British Geological Survey.)

Table 4 Exports of phosphate rock ('000 tonnes)

Country	1995	1996	1997	1998	1999
China	948.9	1,368.7	1,660.4	2,150.2	2,5030
Christmas Island (a) (b)	421.6	542.8	567.9	587.7	699.8
Indonesia	12.9	10.2	1.6	0.2	...
Malaysia	2.4	2.0	5.8	0.9	...
Australia	11.1	13.1	8.3	5.2	7.6
Nauru	527.1	551.3	541.1	*535.0	*750.0

Note(s):-
(a) Including phosphate dust
(b) Years ended 30 June of that stated
Source: BRITISH GEOLOGICAL SURVEY. 2001. *World Mineral Statistics 1995-99* (Keyworth, Nottingham: British Geological Survey.)

Fertilizer production statistics for the selected countries in Asia are compared with production data for the whole of the World in Table 5 and 6.

Table 5. Fertilizer production in selected countries in Asia and Oceania in 1990 ('000 tonnes P_2O_5; source: IFA)

1990/91 – 1990	Ground rock, direct application				SSP + TSP				Ammonium phosphate P				NPK P				Total Phosphate			
Country	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.
Australia	0.0	0.0	0.0	0.0	238.5	71.2	0.0	249.0	10.9	230.2	0.0	204.1	0.0	1.4	0.0	68.7	269.6	302.8	0.0	578.9
New Zealand	0.0	18.9	0.0	18.9	167.6	19.0	0.0	186.6	0.0	26.1	0.0	26.1	0.0	1.5	0.0	1.5	167.6	46.6	0.0	214.2
Others Oceania	0.0	0.0	0.0	0.0	0.0	2.7	0.0	2.7	0.0	0.0	0.0	0.0	0.0	4.1	0.0	4.1	0.0	6.8	0.0	6.8
Oceania	0.0	18.9	0.0	18.9	406.1	92.9	0.0	438.3	10.9	256.3	0.0	230.2	0.0	7.0	0.0	74.3	437.2	356.2	0.0	799.9
Afghanistan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4
Bangladesh	0.0	0.0	0.0	0.0	43.2	140.4	2.3	231.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.2	140.4	2.3	231.8
India	25.2	0.0	0.0	25.2	609.3	0.0	0.0	600.1	876.3	991.3	0.0	1929.7	318.5	24.4	0.0	320.8	2077.0	1015.7	0.0	3124.5
Nepal	0.0	0.0	0.0	0.0	0.0	2.3	0.0	5.8	0.0	4.6	0.0	0.3	0.0	1.2	0.0	1.2	0.0	22.1	0.0	19.1
Pakistan	0.0	0.0	0.0	0.0	30.8	0.0	0.0	30.8	0.0	229.3	0.0	263.9	0.0	4.6	0.0	2.8	104.6	252.9	0.0	388.5
Sri Lanka	9.1	6.8	0.0	11.2	9.1	25.8	0.0	27.3	0.0	0.0	0.0	0.0	0.0	2.4	0.0	1.9	9.1	28.2	0.0	29.2
South Asia	34.3	6.8	0.0	36.4	692.4	168.5	2.3	895.8	876.3	1225.6	0.0	2194.3	318.5	32.6	0.0	326.7	2233.9	1459.7	2.3	3793.5
Indonesia	0.0	0.0	0.0	0.0	588.8	68.2	0.0	580.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	588.8	68.2	0.0	580.9
Japan	0.0	0.0	0.0	0.0	179.0	21.0	0.0	218.0	0.0	239.0	0.0	0.0	250.0	20.0	29.0	472.0	429.0	280.0	29.0	690.0
Korea Republic	0.0	0.0	0.0	0.0	23.7	0.0	2.3	14.3	84.9	0.0	57.4	0.0	347.2	0.0	101.8	215.3	515.8	0.0	224.5	229.6
Malaysia	0.0	105.9	0.0	105.9	0.0	112.5	0.0	112.5	0.0	10.1	0.0	10.1	24.0	7.1	0.0	31.1	24.0	129.7	0.0	153.7
Myanmar	0.0	0.0	0.0	0.0	0.0	13.8	0.0	14.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	0.0	14.6
Philippines	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	65.7	10.2	26.7	17.7	66.7	4.8	33.8	40.1	199.0	19.3	93.9	104.8
Taiwan, China	0.0	0.0	0.0	0.0	51.1	0.0	0.0	50.8	0.0	0.0	0.0	0.0	30.9	0.0	0.0	32.4	82.0	0.0	0.0	83.2
Thailand	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.0	0.0	0.0	0.0	132.7	0.0	210.3	0.0	301.0	0.0	318.3
East Asia	0.0	105.9	0.0	105.9	842.6	215.5	2.3	991.3	150.6	325.3	84.1	27.8	718.8	164.6	164.6	1001.2	1838.6	812.0	347.4	2175.1
China	300.0	0.0	0.0	300.0	3932.0	61.6	13.0	3980.6	87.0	1435.0	0.0	1522.0	0.0	172.2	0.0	172.0	4114.0	1668.8	13.0	5769.6
Korea DPR	0.0	0.0	0.0	0.0	137.0	21.9	0.0	158.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	137.0	21.9	0.0	158.9
Viet Nam	0.0	0.0	0.0	0.0	66.0	0.0	0.0	66.0	0.0	31.2	0.0	31.2	0.0	6.1	0.0	6.1	66.0	37.3	0.0	103.3
Others Socialist Asia	0.0	3.7	0.0	3.7	0.0	6.5	0.0	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	0.0	6.5
Socialist Asia	300.0	3.7	0.0	303.7	4135.0	90.0	13.0	4212.0	87.0	1466.2	0.0	1553.2	0.0	178.3	0.0	178.1	4317.0	1734.5	13.0	6038.3

Table 6. Fertilizer production in selected countries in Asia and Oceania in 1998 ('000 tonnes P_2O_5; source: IFA)

1998/99 - 1998	Ground rock, direct application				SSP + TSP				Ammonium phosphate P				NPK P				Total Phosphate			
Country	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.
Australia	0.0	0.0	0.0	0.0	288.0	131.0	0.0	342.0	0.0	561.0	0.0	449.0	0.0	7.0	0.0	86.0	357.0	699.0	0.0	1039.0
New Zealand	0.0	20.0	0.0	20.0	260.0	40.0	0.0	296.0	0.0	79.2	0.0	79.0	0.0	1.0	0.0	1.0	260.0	120.2	0.0	376.0
Others Oceania	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	8.0	0.0	9.0	0.0	9.0
Oceania	0.0	20.0	0.0	20.0	548.0	172.0	0.0	639.0	0.0	640.2	0.0	528.0	0.0	16.0	0.0	95.0	617.0	828.2	0.0	1424.0
Afghanistan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bangladesh	0.0	0.0	0.0	0.0	41.1	115.0	0.0	143.5	0.0	18.0	0.0	17.9	0.0	0.0	0.0	0.0	41.1	133.0	0.0	161.4
India	11.8	0.0	0.0	25.0	591.9	0.0	11.7	615.1	1777.6	984.8	0.0	2681.0	423.6	0.0	0.0	429.0	3186.9	984.8	11.7	4112.2
Nepal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.3	0.0	32.3	0.0	0.0	0.0	0.0	0.0	32.3	0.0	32.3
Pakistan	0.0	0.0	0.0	0.0	3.9	55.9	0.0	34.4	21.2	355.9	0.0	348.8	0.0	0.0	0.0	3.4	90.7	434.7	0.0	465.0
Sri Lanka	10.2	3.6	0.0	13.1	10.2	17.3	0.0	28.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.2	17.3	0.0	28.9
South Asia	22.0	3.6	0.0	38.1	647.1	188.2	11.7	821.9	1798.8	1391.0	0.0	3080.0	423.6	0.0	0.0	432.4	3328.9	1602.1	11.7	4799.8
Indonesia	0.0	0.0	0.0	0.0	237.6	0.0	12.5	312.8	0.0	25.0	0.0	25.0	0.0	24.0	0.0	24.0	237.6	49.0	12.5	361.8
Japan	0.0	0.0	0.0	0.0	122.4	35.1	0.0	153.3	0.0	257.9	0.0	261.3	126.5	27.9	1.5	146.7	248.9	320.9	1.5	561.3
Korea Republic	0.0	0.0	0.0	0.0	10.0	4.0	5.0	16.0	130.0	0.0	130.0	0.0	281.0	0.0	93.0	172.0	421.0	4.0	228.0	188.0
Malaysia	0.0	180.0	0.0	75.0	0.0	182.0	0.0	75.0	0.0	18.0	0.0	18.0	0.0	40.0	6.0	140.0	0.0	240.0	6.0	233.0
Myanmar	0.0	0.0	0.0	0.0	0.0	32.2	0.0	32.2	0.0	0.0	0.0	0.0	0.0	2.3	0.0	2.3	0.0	34.5	0.0	34.5
Philippines	0.0	0.0	0.0	0.0	2.2	0.0	2.2	0.0	33.3	15.3	14.5	21.2	110.0	0.0	61.2	52.1	192.7	15.3	78.3	118.6
Taiwan, China	0.0	0.0	0.0	0.0	36.0	0.0	0.0	36.0	0.0	0.0	0.0	0.0	48.0	0.0	0.0	48.0	84.0	0.0	0.0	84.0
Thailand	0.0	0.0	0.0	0.0	0.0	6.0	0.0	6.0	0.0	223.0	0.0	223.0	85.0	114.0	0.0	199.0	85.0	370.0	0.0	455.0
East Asia	0.0	180.0	0.0	75.0	408.2	259.3	19.7	631.3	163.3	539.2	144.5	548.5	650.5	208.2	161.7	784.1	1269.2	1033.7	326.3	2036.2
China	0.0	0.0	0.0	0.0	5406.0	0.0	108.0	5298.0	1135.0	2537.0	33.0	3639.0	0.0	343.0	7.0	336.0	6629.0	2892.0	148.0	9373.0
Korea DPR	0.0	0.0	0.0	0.0	10.0	0.0	0.0	10.0	0.0	11.0	0.0	11.0	0.0	5.0	0.0	5.0	10.0	16.0	0.0	26.0
Viet Nam	0.0	0.0	0.0	0.0	144.0	0.0	5.0	139.0	0.0	176.0	0.0	176.0	0.0	63.0	0.0	63.0	144.0	239.0	5.0	378.0
Others Socialist Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	4.0	0.0	1.0	0.0	1.0	0.0	8.0	0.0	8.0
Socialist Asia	0.0	0.0	0.0	0.0	5560.0	0.0	113.0	5447.0	1135.0	2728.0	33.0	3830.0	0.0	412.0	7.0	405.0	6783.0	3155.0	153.0	9785.0
WORLD	214.6	241.1	20.1	187.9	11802.2	1911.2	1758.2	10724.5	16659.6	8861.2	9112.1	14073.4	4487.7	1726.3	1593.2	6476.6	33920.4	12820.0	12680.7	33349.2

AGRONOMIC ASSESSMENT

Food security in Asia has been achieved through the use of high yielding varieties of rice and wheat, irrigation and the use of N fertilizers. There has been an overall emphasis on use of N because of its importance for lowland rice and irrigated upland wheat production. This has resulted in an average N:P:K application ratio of 100:12:8 which has significant consequences for overall soil fertility. Overproduction, especially in lowland rice systems, has led to severe reduction in the P, K and micronutrient levels in soils with concomitant reductions in soil fertility and crop yields. Large land areas in Asia are P-deficient, partly due to P sorption onto organic matter, secondary Al and Fe oxides. As a consequence, substantial P inputs are required to maintain crop productivity. In southeast Asia, there are large areas with acidic soils characterised by a low cation exchange capacity and aluminium toxicity. Rainfall is generally not limiting and under these soil and climatic conditions direct application of PR is an efficient way of dealing with P-deficiency, especially for plantation crops such as tea, palm oil, rubber and cocoa (Maene, 2001).

In lowland cropping systems, P deficiencies have become widespread throughout southeast Asia. Water-soluble P fertilizers are generally used in lowland rice cropping systems at a rate of about 25 kg P/ha. However there is some evidence that rice responds to medium and reactive PRs if it is broadcast and incorporated 2 to 3 weeks prior to flooding (Bado and Hien, 1998; Bhardwaj et al., 1996; Boonampol and Cholitkul, 1995; Harliyah, 1995; Hellums, 1995; Henao and Baanante, 1999; Medhi and DeDatta, 1996a; Melgar et al., 1998; Pandian, 1999; Puthea and Sovuthy, 1995; Rajkhowa and Baroova, 1998; Raju et al., 1997; Raju and Reddy, 1999; Sahu, 1983; Van Chien, 1995; White et al., 1999; Zaharah and Sharifuddin, 1995). The neutral pH stops PR dissolution after flooding, whereas flooding does not reduce availability of P from soluble sources.

Phosphate is frequently the most limiting nutrient in agricultural production systems in the upland areas of southeast Asia. As a consequence, the crops most commonly grown, including upland rice and cassava, are more tolerant to high acidity and have a low phosphate requirement compared with other cereals. A number of studies have shown that direct application of PR may be used as an effective substitute for soluble P in upland rice production (Boonampol and Cholitkul, 1995; Harliyah, 1995). Plantation crops including oil palm, coconut, rubber and tea, offer optimum conditions for PR use due to low pH, low P and Ca, and long term growth (Harliyah, 1995; Jaggi and Chulet, 1995; Joo and Soon, 1995; Ling et al., 1990; Pushparajah et al., 1990; Yogaratnam, 1988; Zaharah and Sharifuddin, 1995). The efficiency of PR in plantation systems reflects mineralization of organic P, solubilization by root mycorrhizae and extensive root systems that provide access to broadcast PR. In general, water-soluble P sources give better yields for annual food crops such as maize and vegetables although exceptions have been recorded (Hellums, 1995). Whereas PR is certainly not an effective source of P in all situations in southeast Asia, medium and high reactivity PR is undoubtedly a useful source of P when applied in appropriate cropping systems, such as plantation crops. In the tea and rubber plantations of Sri Lanka, even low solubility PRs are effective sources of P (Dissanayake, 1995; Sivasubramaniam et al., 1981; Yogaratnam, 1988; Zoysa et al., 1998b).

Increased inputs of P fertilizer will be required, especially in the upland areas of southeast Asia, although this will need to be part of a management plan that incorporates the use of acid tolerant legumes, crop rotation, proper tillage, erosion controls and appropriate irrigations systems. Diversification away from monoculture of rice and reliance on N fertilizer input is required to assure future food security in Asia (Hellums, 1995).

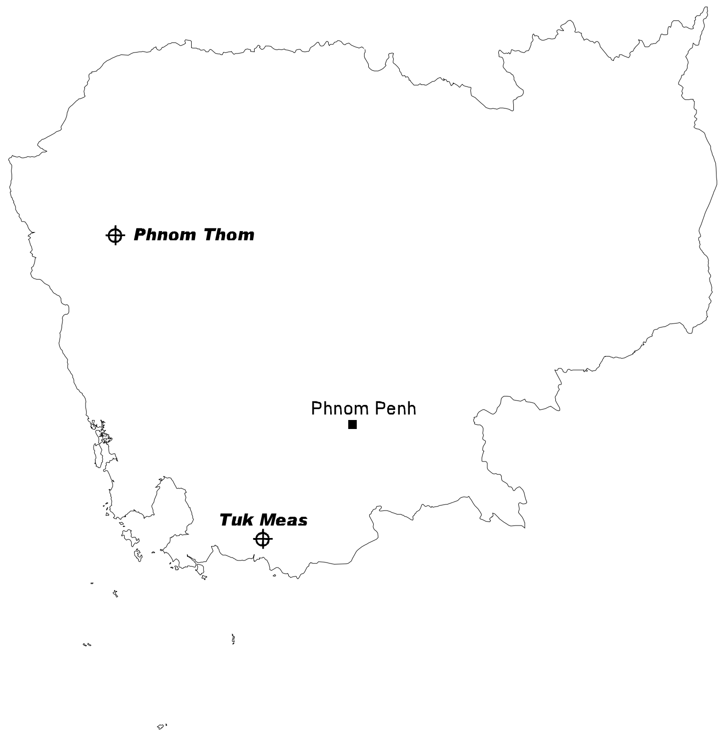
Most attempts to develop the acid soils of the tropics and subtropics in Asia have not been very successful because rapid soil degradation followed forest clearance by subsistence farmers and man-made savanna has encroached over more than 40 Mha. A rapid decrease in soil organic matter has occurred because only small amounts of crop residues have been returned to the soil. In addition, poor soil structure makes the soils susceptible to the impacts of flooding, drought and erosion. Deforestation and mismanagement after forest clearance currently creates an additional 1 to 1.5 Mha of unproductive man-made savanna land each year (Johnston and Syers, 1998; Maene, 2001). Rehabilitation and lasting improvement of man-made savanna land can be achieved using large initial applications of phosphate. One tonne of phosphate rock per ha, or alternatively 400 kg TSP plus one tonne of lime per ha, or combinations of both, have been used successfully. PR application is followed by the establishment of an initial leguminous cover or cash crop. The PR basal application must be accompanied by erosion control, maintenance phosphate applications and appropriate agricultural practices. Unfortunately, poor smallholder farmers, for whom investment in the massive initial phosphate application is economically unfeasible, cultivate most of the acid upland soils in Asia (Maene, 2001).

The World Phosphate Institute (IMPHOS) initiated several agronomic projects in Asia over the last 20 years that have been designed to increase production of irrigated crops and cropping sequences; to realize the potential yields of rain-fed crops, particularly those grown on upland acid soils; and to promote a balanced mineral fertilization in order to achieve sustainable crop production (Nassir, 2001). One project evaluating the use of reactive phosphate rock for the rehabilitation of anthropic savannah in Indonesia, demonstrated that PR application is an economical and effective means of rehabilitating abandoned lands. An agronomic and economic evaluation of various phosphate rocks for direct application to acid soils (mainly alfisols and ultisols) was executed in India, China, Indonesia, and Malaysia. Finally, the use of reactive phosphate rocks for improved crop production in acid sulphate soils was investigated in China, Indonesia, Malaysia, Thailand, and Vietnam. Acid sulphate soils cover 18-20 million hectares in Asia, mainly in Cambodia, China, Indonesia, Malaysia, Thailand, and Vietnam. The soils develop as result of wetting and drainage of parent materials that are rich in pyrite (FeS_2). Oxidation of pyrite to sulphuric acid occurs when previously waterlogged soils are drained – generally reducing the soil pH to less than 4 and the production of acid-sulphate soils. An IMPHOS project is testing production technologies that will overcome the multiple constraints of acid sulphate soils, with the objective of developing a strategy for sustainable crop production. The project, being implemented by IMPHOS in collaboration with CIRAD (France) has four main objectives: (i) improve rice yield on acid-sulphate soils through good fertilizer management; (ii) improve phosphorus nutrition of crops, especially flooded rice; (iii) track any durable changes in soil fertility and phosphorus status in particular; and (iv) study the economics of fertilizer use on acid-sulphate soils (Nassir, 2001).

For a wide-ranging discussion on phosphorus requirements for sustainable agriculture in Asia and Oceania see the symposium proceedings volume produced by the International Rice Research Institute (Belmehdi and Nyiri, 1990; Chien et al., 1990; Hedley et al., 1990; IRRI, 1990). Dahanayake et al. (1995b) contains a series of review articles on the use of direct application fertilizers and appropriate technology fertilizers in Asia. Other useful sources are the general review papers (Kumar, 1998; Mutert and Sri Adiningsih, 1998; Ruaysoongnern and Keerati-kasikorn, 1998; Sahu and Dev, 1998) in the proceedings of the International Conference on *Nutrient Management for Sustainable Crop Production in Asia* (Johnston and Syers, 1998). For information on the mineralogy and characterization of phosphate rocks in Asia, see Van Kauwenbergh (1995c).

COUNTRY PROFILES

Cambodia



Location, quantity and quality

Small deposits of low-grade replacement phosphate rock fill fissures and cavities in Carbo-Permian limestone in Kampot Province in the south and Battambang Province in the north-west of Cambodia. The Tuk Meas deposits (16-18% cent P_2O_5) located about 40 km ENE of Kampot were worked opencast at various times between 1919 until they finally closed in 1991 (Puthea and Sovuthy, 1995). Only about 3,000 tons of phosphate rock was produced in 1919 (Notholt, 1999). Extraction of phosphate rock from the Tuk Meas deposit is reported to have recommenced in 1961 to provide finely-ground phosphate rock for direct application to acid rice soils. Use of the phosphate rock in a proposed superphosphate plant at Tuk Meas with an annual production capacity of at least 20,000 tons was considered (Notholt, 1999).

The Phnom Thom deposit (average 23% P_2O_5) located about 14 km SW of Battambang opened in 1930 and closed in 1990. The two areas had estimated reserves of 300,000 tons with 15 to 25 per cent P_2O_5. The yellowish-brown concretionary phosphate deposits were transported to Battambang for fine grinding and then by barge along the Mekong River to Saigon. 980 tons of PR (20% P_2O_5) was produced in 1930 (Notholt, 1999).

Agronomic testing and use

Imported phosphate rock of good quality was widely used as a fertilizer in the 1960's. In contrast the locally produced PR was generally of poor quality. Production at the two mines ceased mainly because the quality and size of the ground PR was too inconsistent for the local farmers (Puthea and Sovuthy, 1995).

Recent experimental results indicate that local PR and products made from PR are as effective as TSP for rice. In addition, the local PR produced good residual effects. PR applications to *Sesbania rostrata* grown as a nitrogenous green manure crop provided increased yields in the subsequent rice crop compared to PR applied directly to the rice crop (Puthea and Sovuthy, 1995).

White et al. (1999) conducted field and greenhouse experiments over several seasons and soil types to compare the use of triple superphosphate (TSP) and several products developed from the local phosphate rock as fertilizers for rice production. Growth of plants receiving PR on all the soils was as good as or better than that of plants receiving TSP. The relationship between shoot growth and shoot P concentration was the same across all soil types when TSP and PR were applied but varied with the soil type when the PR product was applied. White et al. (1999) concluded that local rock phosphate rock appears to be an effective, viable, low cost alternative to imported P fertilizers for rice production in Cambodia.

Christmas Island

Location, quantity and quality

Christmas Island (10°25'S, 105°43'E) is an elevated coral atoll lying in the Indian Ocean approximately 350 km south of Java Head and is composed of an interbedded succession of volcanic rocks, limestones and dolomites, mainly of Eocene and Miocene age. It has an area of about 140 km^2.

The phosphate deposits form thick blankets mainly of oolitic and pisolitic phosphate over a deeply dissected limestone surface. An upper reddish-brown layer, called ‘C’ grade phosphate, is a lateritic residual deposit composed principally of iron and aluminium phosphates (crandallite/millisite) that averages 28% P_2O_5, and has a combined Fe_2O_3 and Al_2O_3 content of nearly 37%. Measured reserves of apatite ore (‘A’ grade) amount to 5.4 million tonnes averaging 36.8% P_2O_5. 'B' grade phosphate contains some apatite and the hydrous calcium aluminium phosphate minerals crandallite and millisite, which are the chief constituents of 'C' grade ore.

Processing of the ores involves washing, screening and calcination (Savage, 1987).

Production

Production of phosphate rock was about 2.3 million tonnes in 1986 but this has declined to 0.4 to 0.7 million tonnes during the period 1995-1999 (Table 2), all of which is exported (Table 4). The deposits on Christmas Island have been worked since the beginning of the century, and have provided the bulk of the phosphate rock consumed by the Australian and New Zealand fertilizer industries since the Second World War (Anon., 1989).

Sources: (Anon., 1989; Cook et al., 1990; Notholt, 1980; Notholt, 1994; Notholt, 1999; Notholt and Hartley, 1983; Notholt et al., 1989; Savage, 1987)

Agronomic testing and use

No agronomic trials have been carried out on Christmas Island but ground rock phosphate from this deposit has been used in laboratory and field trials in other countries in Asia, Australia and New Zealand. Details are given in other sections of this report.

Sources: (Bolland, 1993; Bolland et al., 1995; Boonampol and Cholitkul, 1995; Bramley, 1990; Cullen, 1988; Hanafi et al., 1996; Hanafi and Syers, 1994a; Hanafi and Syers, 1994b; Hanafi et al., 1992a; Hanafi et al., 1992b; Joo and Soon, 1995; Lim and Gilkes, 2001; Loganathan et al., 1994; McLaughlin et al., 1992; Palmer and Gilkes, 1983a; Palmer and Gilkes, 1983b; Zaharah and Bah, 1997; Zaharah and Sharifuddin, 1995; Zaharah et al., 1997)

India

Location, Quantity, Quality

Systematic exploration for phosphate, begun during the l950s, has led to the discovery of sizeable sedimentary phosphate deposits in the states of Uttar Pradesh and Rajasthan, together with several promising occurrences elsewhere. Carbonatite complexes have been discovered in the states of Tamil Nadu, Gujarat, Andhra Pradesh and Rajasthan, but these have not been investigated in detail as possible sources of phosphate, nor have the phosphatic nodules and sediments found off the western and eastern coasts of India. Nodules occurring at depths of 250-300 m along the Malabar Coast of south-western India are reported to contain 10% P_2O_5 (Notholt, 1994).

The following is a brief summary derived from a number of key publications to which reference should be made for greater detail (Banerjee, 1986a; Banerjee, 1986b; Jaggi, 1995; Notholt, 1994; Notholt, 1999; Notholt and Sheldon, 1986; Notholt et al., 1989; Savage, 1987).

Proterozoic-Lower Palaeozoic

The most important sedimentary deposits in India are those in the late Precambrian Aravalli Supergroup, near Udaipur in Rajasthan. The deposits are stromatolitic and occur in the basal dolomitic limestones of the Udaipur Formation, and also in association with quartzites, marbles and dolomites near the top of the underlying Maton Formation. At least 12 separate deposits have been identified near Udaipur, and those at Jhamarkotra, Maton and Kanpur are worked on a commercial scale. The siliceous, relatively unreactive, Jhabua phosphorite deposit is an extension of the Udaipur deposits, being similar to the deposits at Jhamarkotra.

Phosphate rock has also been found in Rajasthan near Birmania in the Jaisalmer District approximately 120 km NNW of the nearest town and railhead, Barmer. The deposit occurs in a sequence of limestones, sandstones, shales and chert known as the Birmania Formation, to which a Proterozoic-Cambrian age has been tentatively assigned. Resources of 4.5 Mt with an average of 10% P_2O_5, occur in a 1-4 m thick beds.

The Mussoorie phosphate deposits in the State of Uttah Pradesh, northern India, occur within the chert-shale-phosphorite sequence of the Neo-Proterozoic-Cambrian Lower Tal Formation. Phosphate sedimentation occurred during the Proterozoic-Cambrian phosphogenic episode. In the Dehra Dun and Tehri districts, notably near Mussoorie, phosphate beds ranging from a few centimetres to nearly 5 m in thickness have been mapped over a distance of 120 km in the Mussoorie Synform. Phosphate rock is extracted from two underground mines (Maldeota and Durmala) owned and operated by the Government of India organisation *Pyrites, Phosphates and Chemical Limited (PPCL)*. At Maldeota mine, the dark footwall chert has an average thickness of 12 m although it varies from 0.8 m to about 20 m. The chert is succeeded by approximately 4 to 5 m of granular, laminated and banded black-grey phosphorite in which swelling and pinching of the banding and different lithologies is common. Nodular phosphorite also occurs at Maldeota but stromatolitic phosphorite occurs only at Durmala on the northern limb of the Mussoorie Syncline. The phosphorite is generally a dull, dark grey to brownish black colour and it varies from massive to friable (highly fractured) when it disintegrates into a powdery black material. Towards the top of the phosphorite is a hard, 15-20 cm thick pyritiferous phosphorite band above which occurs approximately 0.5-0.7 m of more shaley phosphorite (Appleton, 1994). Relatively high contents of 0.02-0.04% U_30_8 have been reported from the Lower Tal Series phosphate beds.

In the Lalitur District, in the far southeast of Uttar Pradesh, phosphorites with 15-20% P_2O_5 are associated with brecciated quartzites and shales of the Sonrai Formation, Bijawar Group. In neighbouring Madhya Pradesh, similar phosphorite deposits occur in the Hirapur area (Sagar and Chattarpur districts) where the phosphorites are ferruginous and contain 15-20% P_2O_5. The phosphate rock is unsuitable for SSP fertilizer manufacture and is used only as a direct application fertilizer on acid soils.

A comparatively recent discovery in the Pithoragarh District, close to Nepal, is that of moderately phosphatic beds in the Precambrian Gangolihat Dolomites. The presence of these beds suggests a possible extension of a Precambrian phosphate province, which includes deposits of similar age in Rajasthan and in western China. A phosphatic sequence has been traced for a distance of some 15 km to the northwest of Pithoragarh.

Apatite is produced from several lenses and veins of apatite-magnetite-biotite-chlorite rock in Precambrian mica-schists that occur near Dhalbhum, in the Singhbhum District of Bihar,. At least 40 individual deposits have been delineated, some several hundred metres long and up to 15 m wide, within shear zones in the Singhbhum "Copper Belt". The depth to which the deposits persist is largely unknown, but similar lenticular bodies can be expected to depths of 100 m or more in the same mineralized zone. The Pathargara deposits appear to offer the best potential for further development, with resources to a depth of 15 m estimated at 10 Mt containing a minimum of 15% P_2O_5. Similar deposits are worked in the adjacent part of West Bengal, near Barabhu, Purulia District, where there is estimated to be 3 Mt averaging 18% P_2O_5.

Of note also as an environment worthy of more detailed study as a potential source of phosphate are the steeply dipping veins of apatite magnetite-vermiculite rock, some of which are reported to be distinctly radioactive. These occur in Andhra Pradesh near Kasipatnam, about 60 km northwest of Vishakhapatnam. The veins fill fractures in country rock, which consists essentially of a highly metamorphosed and migmatized complex of Precambrian rocks. Most of the ore bodies are tabular and lenticular in shape, being in places more than 2.5 m thick, 30-50 m long and extending to depths of 25-35 m. Resources of apatite have been estimated at 2.6 Mt with an average of 33% P_2O_5. Even though the deposit is difficult to mine and has a high chlorine content, it was worked on a very small scale in the 1950's and 1960's.

Further south, approximately 3.5 Mt of phosphorite resources have been identified in the Upper Proterozoic Cuddapah Group near Chelima, Pachcherla and Peddasettipalle (Banerjee, 1986b) in the Cumbum-Cuddapah area. The deposits are relatively small and have not been exploited.

Small apatite resources of little economic importance are associated with the Precambrian Sevathur carbonatite complex (Savage, 1987).

Cretaceous

Occurrences of Cretaceous sedimentary PR include phosphate nodules containing up to 30% P_2O_5 that were formerly worked within an area of Upper Cretaceous (Uttatur Stage) rocks situated about 30 km NNE of Tiruchirapalli (Tiruchirapa) in Tamil Nadu. Although resources to a depth of 60 m have been estimated at 8 Mt, the remaining deposits do not appear to be of sufficient size individually to justify a revival of mining in the area (Notholt, 1994). Similar phosphate nodules have been recorded from the Valdavur area (Savage, 1987).

The Fategarh phosphorite deposit, located 8 km south of Fategarh and 60 km south of Jaisalmer, on the Jaisalmer-Barmer road, represents a possible Cretaceous-Tertiary phosphogenic event (Mathur and Kumar, 2001). Phosphatic sandstone in the Lathi Formation contains 5-15% P_2O_5 and has been traced over a distance of about 12 km. Total resources of low-grade PR in the sandstone may be substantial (Notholt, 1994).

Apatite carbonatites with reserves of about 1.7 Mt (10% P_2O_5) have been located in the Kahsi-Jaintia area, Meghalaya State.

Rao et al. (Rao et al., 2000) have suggested that the Pleistocene phosphorites on the continental margin off Chennai, southeast India may be analogs of ancient phosphate stromatolites. They occur abundantly off Chennai in the depth range of 186-293 m and are associated with glauconites and large shells of molluscs and rhodoliths. The phosphorites comprise laminated phosphatized microbial mats with clay particles scattered throughout the matrix. Carbonate fluorapatite and low magnesium and high-magnesium calcites are the major mineral phases. whilst quartz, feldspar, and goethite are accessory minerals, The phosphatic stratiform stromatolites were subsequently reworked into a shelf-margin depression and resulted in the occurrence of condensed phosphorites (Rao et al., 2000).

Production

Jaggi (1995) reviewed Indian phosphate PR reserves, resources, mining, production, and their agronomic evaluation for direct application, concentrating on the Jhamarkotra, Jhabua, Hirapur, Kangpur, Lalitpur, Maton, Mussoorie and Purulia phosphate rock resources. Total PR resources in India are estimated to be about 260 million tonnes (Table 7).

The reserves at Maldeota are expected to last for another 20 years at current levels of production, which are approximately 75,000 tonnes at both Maldeota and Durmala. The overall monthly production is about 15,000 t although in July and August production is only 5-6000 t due to high rainfall. Phosphate rock is processed at the Harrawala grinding plant situated adjacent to the railway line on the outskirts of Dehradun. Here, the relatively friable higher grade (20-24% P_2O_5) Durmala ore has to be stored under cover whilst the more resistant and blocky Maldeota ore (18-20% P_2O_5) is stockpiled in the open. Blending of the two ores is controlled by chemical analysis. The PR is passed through a crusher prior to grinding to -100 BSS mesh in an airflush ball mill (12 t/h capacity) and three roller mills (each 6 t/h). 50 kg bags of ground PR are stored in warehouses prior to freighting by rail to the regional centres. 2000 t loads are sent by rail from Dehra Dun to Delhi and then to regional centres at Calcutta, Bangalore and Bihar from where the rock phosphate is distributed through Government agencies such as co-operatives, agro-industrial companies and also sold directly to the private sector. There is a marked seasonal demand as large quantities of rock phosphate have to be available at a specific centre at the correct time for fertilizer application. The grade of the

MUSSOORIE PHOS fertilizer (PPLC, 1987) varies from 18 to 24% P_2O_5 and is sold as two different grades: 18-20% and +20% P_2O_5. A beneficiation pilot plant was installed adjacent to the Harrawala grinding plant in 1986 but the process is currently uneconomic due to low recovery and the high percentage of fine, which produces a disposal problem in this environmentally sensitive area (Appleton, 1994).

The annual demand for direct application phosphate rock fertilizer in India is reported to be 0.25 million tonnes mostly from the estate sector so PPCL is investigating the possibility of marketing other PR's such as Jhamarkotra PR. However, this will not be possible until agronomic trials have been completed and the PR approved as a direct application fertilizer by the Indian Government. There are problems with increasing the production at Mussoorie as the underground mines have high mining costs. The Jhamarkotra PR would be cheaper to supply to the southern part of India as both mining and transportation costs would be less than for Mussoorie rock phosphate (Appleton, 1994).

Most phosphate rock is produced in the Udaipur (Jhamarkotra, Maton and Kanpur) and Mussoorie areas. Of the total amount produced in 1995 (1,319,328 mt) about 120,000 mt (22,000 mt P_2O_5) from Mussoorie and 50,000 mt from Jhamarkotra was used a direct application fertilizer. Mussoorie PR is used on the acid soils of Kerala, Karnataka, Tamil Nadu, Assam and the north-eastern States whilst most of the Jhamarkotra PR is used on acid soils in Kerala. Approximately 15,000 tpa of phosphate rock from the Purulia deposit is also used for direct application. The remainder is used by the phosphate fertilizer industry, which also has to import an additional 3 million tonnes per year of high-grade phosphate rock. It has been estimated that the potential total annual consumption of P_2O_5 on acid soils in India is around 200,000 tonnes. The low grade Jhamarkotra, Purulia and Maton PRs have been tested and approved for direct application. Producers have planned to increase production of direct application fertilizers to 270,000 tpa of >18% P_2O_5 PR (50,000 tpa P_2O_5) (Jaggi, 1995). Total production of phosphate rock in 1999 was 1,643,430 mt.

Total P_2O_5 consumption increased from 1,091,000 mt in 1980 to 4,112,000 mt in 1998. In the same period PR consumption increased only from 17,000 mt P_2O_5 to 25,000 P_2O_5 (Maene, 2001).

Rao et al. (1992) highlighted the importance of low-grade phosphate ore beneficiation and the problems associated with beneficiation of different types of ores. Rao et al. (1992) classified the Indian phosphate deposits and summarised the mineralogical characteristics of some typical rock phosphate samples. A two-step flotation scheme was employed to beneficiate a low-grade, cherty-calcareous rock phosphate ore from the Jhabua district, Madhya Pradesh, India (Prasad et al., 1995). The total P_2O_5 recovery for the composite concentrate would be 73%. Froth flotation was employed to beneficiate Hirapur lean-grade, siliceous, fluorapatite rock-phosphate ore. The main gangue minerals were quartz, iron oxides and aluminium oxides. The process provided a useable phosphate concentrate containing 34.18% P_2O_5 and 14.20% SiO_2 with a P_2O_5 recovery of 70.4% (the weight yield was 25.0%) (Prasad et al., 1998).

Production and transport costs of MPR and other locally produced fertilizers are subsidised by the Government of India on the basis that use of MPR utilizes a national resource and saves foreign exchange. Fertilizer prices are controlled by the Government of India. In 1990 these were: MPR Rs 3.75/kg P_2O_5 or Rs 750/t MPR; DAP Rs 5.50/kg P_2O_5 or Rs 2530/t DAP; SSP Rs 6.00/kg P_2O_5 or Rs 1080/t SSP (1990 exchange rate : £1=Rs 28; US$ 1=Rs 18). The total production costs for MPR were approximately Rs 700/t (1990 prices) comprising mining costs (Rs 300/t), local transport (Rs 60/t), crushing and grinding (Rs 130/t), bagging (Rs 150/t) and overheads (Rs 40/t) (S.D.Prasad, PPCL, pers.comm., 1990). Production costs of Rs 700/t (US$ 40/t) were similar to those in Colombia in Latin America (Martínez, 1987). A Government of India subsidy of approximately Rs 600/t was equivalent to the average cost of transporting MPR to the regional centres, such as Kerala in southern India. Additional local transport costs from the regional centre to plantation were about Rs 40/t (Appleton, 1994).

A general account of the economics of direct application of MPR is given in PPCL (1987). The comparative economics of MPR, TSP and DAP use in India are complicated by the substantial government subsidies on fertilizers and it is likely that the relative economic efficiency of MPR would not be so high under a non-subsidy system (Appleton, 1994).

Table 7. Indian phosphate rock resources/reserves (million tonnes) (Source: Jaggi (1995))

Name of deposit and location	Resources/Reserves (Mt)	Annual production (mt)	Grade % P_2O_5	Mining organisation
Jhamarkotra (High grade)	14.67	400,000[1]	>30	RSMML
Jhamarkotra (Low grade)	51.81	450,000	15.17	RSMML
Jhabua (cherty)	14.1	90,000	20	MPSMC
Jhabua (carbonate –resource)	12.5	-	12	none
Hirapur (resource)	22.0	-	7-10	none
Hirapur	18.7	25,000	23	MPSMC
Mussoorie (Maldeota & Durmala)	16.0	130,000[2]	18-22	PPCL
Mussoorie (other blocks)	25.0	-	16-18	none
Maton	6.0	100,000	22-24	HZL
Lalitpur	6.3	50,000	15-20	UPSMDC
Purulia	3.5	15,000	20-25	WBMTC
Singbhum (resource)	2.5	-	7-25	none
Kasipatanum	0.22	-	25-42	APL
Cumbum (Cuddapah)(resource)	3.5	-	20-30	none
Kanpur Group	8.0	25,000	15-25	RSMDC
Jhamarkotra (H block)	1.8	?	22-25	RSMDC
Birmania	2.5	?	10-18	RSMDC

Mining Organisations: RSMML Rajasthan State Mines & Minerals Ltd, Udaipur; MPSMC M P State Mining Corpn. Bhopal; PPCL Pyrites, Phosphates and Chemicals Ltd., New Dehli; UPSMDC U P State Mining Corpn. Ltd, Lucknow, Calcutta; APL Andhra Phosphate Ltd., RSMDC Rajasthan State Mines development Corprn. Ltd., Jaipur

[1] 50,000 mt/year ground phosphate rock for direct application; [2] all production is ground phosphate rock for direct application

Sources:(Appleton, 1990; Appleton, 1994; Banerjee, 1986a; Banerjee, 1986b; Banerjee, 1987; Banerjee et al., 1982; Burnett, 1981; Choudhuri, 1989; Choudhuri and Roy, 1986; Das, 1999; IGCP and Geological Survey of India, 1981; Jaggi, 1995; Khan et al., 1989; Maene, 2001; Mukherjee et al., 1986; Nassir, 2001; Notholt, 1982; Notholt, 1994; Notholt and Sheldon, 1986; Pant et al., 1989; Pradip, 1991; Prasad et al., 1995; Prasad et al., 1998; Prasad et al., 2000; Raha, 1990; Rao et al., 1992; Rao et al., 2000; Shanker, 1989; Sharma et al., 2001; Singh et al., 1992a; Tiwari, 1996)

Agronomic testing and use

In India, there are about 49 Mha of acid soils, most of which have a low P availability. In such soils, the P content and its availability depend on the degree and nature of the acidity, the extent of base depletion, the organic matter content, the oxidation-reduction conditions, and land use practices. The country has total reserves of approximately 213 Mt of indigenous PR, but because of its low P_2O_5 content and quality much of the PR is unsuitable for the phosphate processing industry. An alternative use is for direct application, in order to partially meet the P requirements of crops. The phosphate rock is a source not only of P and calcium (Ca), but it also contains variable amounts of other essential nutrients such as magnesium, sulphur, iron, copper and zinc. The presence of Ca gives it a liming value (Maene, 2001).

Jaggi (1982; 1986; 1995; 1986) reviewed the agronomic evaluation for direct application of Indian PRs concentrating on the Jhamarkotra, Maton, Mussoorie, and Purulia phosphate rock resources. Jaggi (1995) concluded that fertilizer production would have to increase by about 50% over a 5 year period in order to meet increased demand for food production. Cheaper sources of phosphate are needed and Jaggi (1995) suggested that ground PR was a good potential source for crops grown on the acid and semi-acid soils of India. Good agronomic responses had been demonstrated with the Mussoorie, Purulia, Jhamarkotra and Maton PRs.

Agronomic evaluation of the relatively soluble Mussoorie phosphate rock (MPR) (Jaggi, 1982; Jaggi, 1986; Jaggi, 1995; Jaggi et al., 1986; PPLC, 1987; Tandon, 1987) has demonstrated that:

- MPR is an effective substitute for SSP for a variety of crops grown on acid soils
- MPR gives a performance comparable to SSP even for short duration crops
- on neutral soils (pH 7.2), MPR is effective for paddy and wheat in some areas although a mixture of 25% SSP and 75% MPR is probably the optimal P-fertilizer for neutral soils. 50:50 mixtures are recommended for more alkaline soils
- MPR and pyrites mixed 1:2.5 is as effective as SSP for potatoes
- MPR shows a better residual effect than SSP in acid soils and if mixed with farm yard manure it also shows a better effect in neutral soil
- the relative economic efficiency (REE) of MPR is two to three times that of SSP.

For a general review of the use of phosphate rock in Indian agriculture see Biswas and Das (1995) who concluded that as most Indian soils have low to medium P contents, the direct use of PR should be encouraged if environmentally and agronomically effective. Biswas and Das (1995) also outlined the impact of 15 factors (including soil pH, graded of PR, time of application, etc.) on the effectiveness of powdered phosphate rock as a direct application fertilizer for a range of crops in India.

Agronomic tests over a 3 year period have shown that the Maton PR is significantly superior or equal to other P sources. The cost benefit to farmers ranges from Rs. 435 to Rs. 600 per ha. (1995 data). Maton PR is reported to have potential for use with agricultural and plantation crops on the acid and neutral soils of Karnataka, and also for reclaiming degraded acid soils (Jaggi and Chulet, 1995).

Agronomic research in India has demonstrated that MPR is more effective for some crops if placed in the root zone and not broadcast. In the case of groundnuts, the furrow is ploughed, fertilizer applied and then the seeds planted and the soil covered over. Using this application method, more P will be available in the root zone than if the MPR is broadcast onto soils with high P absorption capacity when most of the P will be absorbed by Fe and Al oxides and become relatively unavailable to the plants. Broadcasting is considered to be more appropriate for pasture fertilization. The application procedure varies with pH of soil - if the pH is less than 5 then MPR is either applied 14-21 days before planting and ploughed into the soil or placed in the furrow at the time of planting.

The liming effect of MPR, which contains approximately 40% calcite and dolomite, is not well documented. Some short-term yield enhancement may be related to liming rather than P derived from the MPR. However, at application rates of 60 kg P_2O_5/ha (equivalent to 300 kg MPR/ha), only 120 kg/ha of calcium/magnesium carbonate is applied to the soil. At this level, the liming effect is unlikely to be very substantial. Conventional application rates for agricultural lime are 1000 to 2000 kg/ha.

Although approximately 80% of the approximately 150,000 t/a of MPR produced by PPCL is sold for use in the plantation and commercial sector (tea, coffee, rubber, coconut, cashew nuts, cardamon, and orchard fruit crops such as apple and plum), it is also used for a variety of other crops on acid, low P soils including paddy rice, groundnut, wheat, soyabean, and gram. In the plantation sector MPR is used for coffee in Karnataka; coffee and rubber in Kerala; tea in Tamil Nadu and Assam; rubber and tea in Tripura/Agartala; and tea in NW Bengal. The remaining 20% of MPR is used in Bihar, Orissa, Tamil Nadu, NW Bengal and W.Bengal for paddy rice and potatoes. In the southern plateau latosols of Bihar, MPR is used for paddy rice and groundnuts whilst in Orissa, MPR is used for rice, groundnuts and millet (PPLC, 1987).

The efficacy of India's PRs have been confirmed in acid soils on several crops, such as rice, wheat, maize, gram, soybeans and peas. PR is recommended for direct application in several states in India but constraints to its use include (1) variable composition of the available PR, which necessitates analysis before application; (2) PR is not readily available in the open market; (3) there is a limited understanding of the soils on which PR can be efficiently and economically used, and (4) the application of PR is not adequately supported by extension services (Maene, 2001). Ghosh (2001) provides a useful review of the technologies for the utilisation of low-grade rock phosphates as fertilisers.

Results of agronomic testing for specific crops are given in the following sub-sections followed by a review of studies carried out in India on methods of improving the solubilisation of Indian rock phosphates.

Coconut

A field study conducted for six years in a laterite soil has shown that single super phosphate, nitro phosphate, ammonium phosphate and rock phosphate had similar effect on the yield of nuts per palm. However, when percentage over pre-treatment yield was computed, rock phosphate proved most effective followed by ammonium phosphate. The increase in soil available P with increase in dose of fertilizer applied was least with rock phosphate. Rock phosphate is considered to be an ideal source of P for coconut and is extensively used in fertilization programmes. The cost of fertilizer applied per palm was lowest with rock phosphate (Khan et al., 2001).

Fish culture

Jana and Das (1992) tested the fertilizer value of Mussoorie phosphate rock (MPR) in outdoor tanks by evaluating the growth performance of Indian major carps using 6 treatment combinations: MPR (low and high doses), single superphosphate (SSP), SSP mixed with MPR, composted MPR, and compost of water hyacinth and cow manure. Increase in fish yield was related to the orthophosphate level of the water rather than the input of P_2O_5. The net fish yield as well as net primary productivity tended to rise with an increase of concentration of orthophosphate in the water up to 0.33 to 0.34 mg per liter but declined with a further rise of orthophosphate to 0.52 mg per litre.

Groundnut

Giri (1993) conducted a field experiment on the direct and residual effects of N and P on groundnut (*Arachis hypogaea L.*) - wheat (*Triticum aestivum L. emend. Fiori & Paol.*) cropping sequence and demonstrated that groundnut responded to direct application of N and P in the initial season only. Neither nutrients applied to wheat nor directly applied to groundnut in subsequent seasons caused significant improvement in the pod yield of groundnut. Groundnut needed 12.5 kg N and 21.5 kg P/na in the first season only. A beneficial residual effect of P @ 21.5 kg/ha on the succeeding wheat crop was observed in the second year only.

Jute

Banik et al. (1989) suggested that rock phosphate may be a viable substitute for SSP in jute cultivation.

Lentils

Krishnareddy and Ahlawat (1996) evaluated the growth and yield response of lentil cultivars to phosphorus, zinc and biofertilizers (*Rhizobium and VAM fungi*) on a sandy loam soil. Application of 17.2 kg P ha^{-1} as single superphosphate (SSP) along with 5 kg Zn ha^{-1} as zinc sulphate resulted in marked improvement in growth and yield attributes, grain yield and harvest index when compared with the 17.2 kg P as rock phosphate (with and without Zn) and the control treatments. Combined inoculation of *Rhizobium* and VAM fungi resulted in improved growth and yield attributes, grain yield and harvest index when compared with inoculation of either of the inocula.

Maize-Wheat (Soybean-Wheat, Rice-Groundnut)

In India, there are about 26 Million ha of acid soils that have a pH less that 5.5 whereas 23 Million ha have a pH between 5.6 and 6.5. In these soils, there is an acute deficiency of phosphorus (P), which is one of the major limiting nutrient in crop production. The soils are rich in sesquioxides, low in humus and have high P fixing capacity. In these soils, crops respond to applied P only after their P fixing capacity is satisfied, justifying the need for high levels of applied P to crop. Rock phosphate (RP) can supply P at a unit cost much lower than that from other commonly used fertilisers containing water soluble P and can be used as P source for agricultural production especially in acid soils (Nassir, 2001).

An evaluation is being carried out of the residual effect of P applied through rock phosphate on the performance of different cropping sequences in acid soils representing 3 agro-climatic regions in India i.e Bihar site on red loam soil (pH = 6.0), Himachal Pradesh site on mountainous acid soil (pH = 5.7) and Orissa site on lateritic soil (pH = 5.8). The treatments consisted of 4 rock phosphates (Gafsa-Tunisia, Djebel Onk - Algeria, Youssoufia-Morocco and Mussoorie-India) to supply 250 and 500 kg P_2O_5/ha applied at the start of the crop sequence and the residual effect of these applications for 9 cropping sequences, compared to (i) the application of diammonium phosphate (DAP)/single super phosphate (SSP) at 50 kg P_2O_5/ha to every crop and (ii) a control treatment in a randomised block design with three replicates. In the soybean-wheat rotation in red loam, Gafsa and Youssoufia RPs applied once at 500 kg P_2O_5/ha in soybean showed a significant residual value in influencing the yield of the following crop (wheat). This effect was equal or superior to DAP applied at 50 kg P_2O_5/ha to every crop. In the maize-wheat cropping sequence in mountainous acid soil, 500 kg P_2O_5/ha applied through Djebel Onk RP produced the highest maize and wheat yields. Increasing the level of P from 250 to 500 kg P_2O_5/ha through all RPs except Mussoorie RP produced higher yield of crops in the sequence. In the rice-groundnut sequence in lateritic soil, the rice yield with directly applied P, and groundnut yield resulting from the residual effect of a single RP application, both increased (Nassir, 2001).

Sharma et al (2001) reported the results of long-term studies on the agronomic effectiveness of African and Indian rock phosphates in relation to the productivity of maize and wheat crops in mountain acid soils of Western Himalayas, India. Phosphorus deficiency, its poor availability to crops coupled with low phosphorus use efficiency and high phosphorus fixation are the dominant constraints to crop productivity. Many African rock phosphates, which have high contents of citrate soluble phosphates compared with the Indian PRs, are entering the Indian market under liberalization programme. The African rock phosphates could therefore prove economically superior compared to Indian PRs. Long-term field experiments were conducted to evaluate African and Indian rock phosphates in relation to productivity of maize and wheat crops in mountain acid soils of the Western Himalayas. An initial application of 500kg P_2O_5 ha-1 was applied to 10 crops (5 maize and 5 wheat) through three African rock phosphates (Tebessa, Youssofia and Gafsa (30% CSP)) and Mussoorie RP (18% CSP) in comparison superphosphate applied each season for each crop of maize and wheat @ 50kg P_2O_5 ha^{-1}; for 5 years. The single application of P for 5 years @ 500kg ha^{-1} from Tebessa; Gaffsa and Youssofia PRs had a significant effect in improving the average productivity of maize giving an average yield of 4.63, 4.78 and 4.64 t ha^{-1} over control which was 49.8, 54.7 and 50.2 % higher than control and those three sources did not differ significantly among themselves. However, the Indian Mussoorie Rock Phosphate recorded a comparatively lower yield of 4.22 t ha^{-1} though significantly higher than the control (36.6%). The performance of SSP was significantly better than all the rock phosphates. For wheat, it was found that the average grain productivity due to Tebessa, Gaffsa, Youssofia and Indian Rock rock phosphates applied at 500 kg P_2O_5 ha^{-1} was 54.1, 39.8 50.8 and 39.8% higher compared with the control. Seasonal application of SSP at 50 kg P_2O_5 ha^{-1} over 5 years produced a 61.4% increase compared with the control, which was higher than all the RPs. There was an improvement in soil quality in terms of amelioration of soil characteristics that are often associated with the availability of P from rock phosphates such as soil pH, OC, exchangeable Ca, Al, acidity, effective CEC, pH buffer capacity, extractable Al and P fixing capacity, thereby, improving the availability of P from rock phosphates and eventually the productivity and P uptake in these crops. Higher monetary benefits accrued in respect of African rock phosphates compared to SSP (Sharma et al., 2001).

Das et al. (1991) evaluated the efficacy of SSP as well as PR in combination with manure in maize crop production on P-deficient alfisols grown on terraced land in Meghalaya. The maximum response in grain yield was noticed under 5 tonnes poultry manure + 28 kg P/ha as SSP (4.95 tonnes/ha), followed by poultry manure alone (3.81 tonnes/ha). The relative effectiveness of amended inorganic P carriers followed the trend: poultry manure + inorganic P > pig manure + inorganic P > farmyard manure + inorganic P, with the first and second maize crops grown in succession.

Millet

Singaram and Kothandaraman (1992) conducted a field experiment with a Typic Ustochrept soil at Coimbatore to study the effect of phosphatic fertilizers on inorganic phosphorus fractions. Application of P sources (SSP, PR, PR+SSP, PR + phosphobacterium and DAP) at 3 levels (13, 26 and 39 kg P/ha) significantly increased the status of inorganic P fractions when compared with the control. There was no significant difference among the P sources and levels with regard to the status of iron P and reductant-soluble P. Rock phosphate and its combinations (PR + SSP and PR + phosphobacterium) accounted for higher calcium P in relation to DAP and SSP.

Singaram et al. (1995) evaluated the agronomic effectiveness of Mussoorie phosphate rock (MPR), a 2:1 mixture of MPR and single superphosphate (SSP) and SSP as phosphate fertilizers for a three crop sequence: finger millet (*Eleusine coracana*), maize (*Zea mays L.*), and blackgram (*Phaseolus mungo*) grown on a calcareous soil under irrigated conditions. The phosphate fertilizers were applied to finger millet and/or maize but not to the blackgram. When used on finger millet, the RAE of MPR, calculated at a yield which corresponded to 90% of the calculated maximum yield for SSP, was 42%. The RAE was 68% for the mixture of MPR and SSP. For maize, the yield with MPR levelled out at too low a level (about 80% of calculated maximum yield for SSP) to calculate a RAE but for the RAE was 80% for MPR/SSP. The residual effectiveness of fertilizers on the second crop, compared against freshly applied SSP, was 41% for SSP, 49% for MPR, and 73% for MPR/SSP. Economic calculations indicated that the application of MPR and MPR/SSP was of equal value to SSP for the cropping sequence, whereas MPR/SSP was of equal value to SSP for individual crops (Singaram et al., 1995).

Moong-bean

Sagwal and Kumar (1995) examined the effect of the presence of oxalate, citrate, sulphate, and chloride anions on P availability from different P sources (RP, SSP, and DAP) in a P-deficient Haryana soil using moong-bean (*Vigna radiata*) as the test crop. The relative agronomic effectiveness (RAE) of soluble fertilizer (SSP and DAP) was much higher than water insoluble P (RP). The percent utilization of added P generally increased with increasing P levels applied through RP but it decreased with increasing P levels when applied through soluble P sources (SSP and DAP).

Pasture

Prasad and Singh (1992) conducted an experiment to evaluate the response to lime and P sources on *'Mescavi' egyptian* clover or berseem (*Trifolium alexandrinum L.*), 'Anand 2' lucerne (*Medicago sativa L.*) and their residual effects on succeeding deenanath grass (*Pennisetum pedicellatum Trin.*).. SSP and MPR in equal proportion was as good as SSP for forage production in berseem and lucerne. The effect of lime was apparent in the first year, while higher levels of lime adversely affected the green- and dry-herbage yields of both legumes. Neither the lime, the P sources nor berseem and lucerne as the preceding crops, influenced the forage yield of succeeding deenanath grass significantly.

Potato

Sharma (1991), Sharma & Singh (1991) conducted a field experiment with 'Kufri Jyoti' potato (*Solanum tuberosum L.*) to study the release pattern of nitrate-nitrogen from nitrogenous fertilizers in Meghalaya acidic soil (pH 5.2). More NO_3-N was produced in the soil by application of ammonium sulphate, urea alone or in combination with magnesium carbonate or calcium carbonate than from slow-release N sources (gypsum-coated urea and RP-coated urea), up to 60 days after planting. Tuber yield increased significantly with the application of ammonium sulphate, gypsum-coated urea and RP-coated urea compared with other N sources. The tuber yield was the highest with ammonium sulphate (22.4 tonnes/ha) and lowest with urea (19.9 tonnes/ha).

Sorghum

Verma et al. (1993) measured the agronomic effectiveness of a 50% partially acidulated phosphate rock (PAPR) compared with SSP in a field experiment with sorghum (*Sorghum bicolor* cv. CSH-6) in a shallow Alfisol in Hyderabad. P response was evaluated at a single relatively high N rate (120 kg ha^{-1}) with five rates of P (0, 2.2, 4.4, 8.8, and 17.6 kg P ha^{-1}). A significant response to P was obtained at rates up to 17.6 kg P ha^{-1}. There was no significant difference due to the source of P in terms of sorghum grain yield or total P uptake.

Soybean

Marwaha et al (1981) and Marwaha (1986) investigated the direct and residual effectiveness of Mussoorie PR on soybean-wheat rotations on acid alfisols.

Rice

Bhardwaj et al. (1996) carried out a field experiment in an acidic silt-loam soil that showed significant direct effects of RP:SSP mixtures on rice grain yield and nutrient uptake. The maximum grain yield and nutrient uptake were recorded with the 50:50 RP:SSP treatment. Application of RP to the rice crop produced a significant positive residual effect on the yield and nutrient uptake in the succeeding linseed crop. Ghosal et al. (1998) evaluated the direct and residual effect of RP fertilizers on rice (Oryza sativa) grown on lateritic land in eastern India. Mutanal et al. (1998) carried out a field experiment near Karnataka to study the effect of phosphorus and liming sources on rice (*Oryza sativa*) grain yield under transplanted conditions. The combination of RP+DAP (50:50) significantly increased yield (5,205 kg/ha). This was similar to DAP alone (4,790 kg/ha) but greater than RP alone (4,690 kg/ha). Net profit (Rs 7,114/ha) was higher for RP+DAP (50:50) followed by the DAP (Rs 5 920/ha) and lowest was with SSP (Rs 4 651/ha).

Pandian (1999) conducted a field experiment to study the effect on rice (*Oryza saliva L.*) growth and yield of RP directly applied to rice and pre-season green manure (GM) (*Sesbania rostrata*) with different levels of nitrogen. Phosphorus application at 60 kg P_2O_5/ha applied half each to GM and rice resulted in higher rice grain yield. Application of 120 kg N/ha also enhanced the rice yield. Rajkhowa and Baroova (1998) carried out an experiment to study the effect of Udaipur rock phosphate (UPR), SSP and UPR:SSP (50:50) at different levels on rice (*Oryza sativa L.*) grown in acid soils of Assam. Application of UPR:SSP (50:50) was more effective than UPR alone and was similar to SSP in increasing rice yield. The agronomic and physiological efficiencies were highest with 12.9 kg P/ha and declined progressively as the level of P increased.

Raju et al. (1997) conducted a field experiment to study phosphorus levels and sources on the growth and yield of rice (*Oryza sativa L.*). A significant improvement in yield was noticed up to 60 kg P_2O_5/ha. Ammonium polyphosphate gave significantly superior yield to the other P sources except DAP. Rock phosphate by itself or amended with P-solubilizing bacterial culture gave lower yields. These studies were expanded to include the impact of FYM (Raju and Reddy, 1999). Ramachandran et al. (1998) carried out greenhouse experiments to evaluate the yield, P and Cd contents of rice (*Oryza sativa L.*) grown as a second crop on an Ultisol repeatedly fertilized with three Indian RPs, with and without addition of vegetable compost. MRP was significantly superior to the other two rock phosphates in enhancing the dry matter yield of the rice crop. Addition of vegetable compost enhanced the yields and P concentration of the rice plant. Incorporation of vegetable compost effectively reduced the Cd contents of both shoots and grain.

Singh et al. (1999a) conducted a field experiment on sandy clay loam soil to study the efficiency of different forms of urea (prilled (PU), lac coated (LCU), rock phosphate coated (RCU), karanj cake coated (KCU) and neem cake coated (NCU)) at varying N rates (40, 80, 120 kg/ha) on the productivity of rice and their residual effect on a succeeding wheat crop. LCU produced markedly higher rice grain yield compared with the other forms of urea. Verma et al. (1991) evaluated the agronomic effectivenesss of Mussoorie PR as a source of phosphate for rice (*Orysa-sativa*).

Tea

Sharma et al. (1995b) examined the effect of different phosphorus sources on yield and quality of tea (*Camellia-Sinensis*) in a hill acid soil. SSP and MRP applied at four levels (26.2, 52.4, 78.6 and 104.8 kg/ha) increased the yield of tea by 16.8, 10.2, 9.8 and 3.1% respectively. P sources showed non-significant effect. Graded doses of P through SSP and MRP significantly increased the status of available P (3.6, 5.3, 6.8 and 9.2 kg/ha) and Ca (0.34, 0.43, 0.50 and 0.62 meq/100 g) in the soil. The P application also improved the quality of tea.

Wheat

Verma and Sharma (1994) carried out a field investigation on a sandy-loam soil examine the residual effect of different phosphatic fertilizers applied to wheat (*Triticum aestivum* L. emend. Fiori & Paol.) on a succeeding crop of greengram.(*Phaseolus radiatus* L). RP alone or in combination with cattle-dung did not increase the grain yield of greengram. SSP alone and in combination with pyrite or mixing of RP with SSP showed significant residual response in terms of grain yield and phosphorus uptake. Mixtures of RP+SSP (75% + 25%) and RP + pyrite (1 : 3) were more effective than other sources at 60 kg and 90 kg doses of P_2O_5/ha respectively for grain yield and net return. The residual effect of various phosphatic fertilizers did not affect the straw yield significantly.

Sharma et al. (1995a; 1996) assessed the agronomic effectiveness of Udaipur RP as influenced by organics in wheat- maize cropping sequence. Sharma and Sharma (1997) investigated the direct and residual effects of compost in a wheat (*Triticum aestivum L. emend.* Fiori & Paol.) - rice (*Oryza sativa* L.) sequence on crop yield, nutrient uptake and soil parameters on an acid alfisol. A compost rich in P and N was prepared by composting MRP with fresh cowdung and green lantana (*Lantana camara L.*) biomass for 90 days in different treatment combinations. Composting increased the solubilized P (water soluble and citric acid soluble), total P (%) and N (%) contents and lowered the C:N ratio. Inoculation of the composting materials with *Aspergillus awamori*, a P- solubilizing fungus, further increased the solubilized P content and lowered the C:N ratio. The compost applied at 5 tonnes/ha (on dry-weight basis) was comparable with SSP (39.3 kg P/ha + 5 tonnes farmyard manure on dry- weight basis) in terms of crop yield, nutrient uptake and nutrient status of the soil. Verma and Rawat (1999) examined the use of low grade RP as a potential source of phosphorus for the soybean (Glycine max)-wheat (Triticum aestivum) cropping system.

Solubilization processes

Numerous studies have been carried out in India on methods of improving the solubilisation of Indian rock phosphates. These have been carried out largely because the Indian RPs have relatively low reactivity but also to enhance the effectiveness of RP directly applied to soils and crops that are not ideally suited to direct application of rock phosphate. Jaggi et al. (1986) produced one of the earliest reviews on methods of enhancing the agronomic efficiency of ground phosphate rock in India. Agronomic results associated with solubilization processes are discussed below under the following sub-headings: biological, composting, pyrite.

Biological

Singh and Amberger (1991) measured the solubilization and availability of phosphorus during decomposition of wheat straw and cattle urine with two types of low grade RP, MRP and Hyperphos (HRP). The rate of solubilization of insoluble phosphorus from both MRP and HRP increased significantly up to 60 days and thereafter decreased with increasing decomposition time. Molasses incorporation enhanced solubilization; it reached a maximum of 24.5 and 14.7% of the added insoluble phosphate for both MRP and HRP, respectively. About 95 to 99% of the solubilized P was converted into organic forms. MRP solubilized more readily and retained a greater amount of labile and moderately labile P_o than HRP.

Gupta et al. (1993) demonstrated that *Bacillus licheniformis* solubilized a range of inorganic phosphates and five different low grade Indian RPs to varying extent in broth culture and in soil.

Singh and Singh (1993) examined the interaction of RP, *Bradyrhizobium*, vesicular-arbuscular mycorrhizae (VAM) and phosphate-solubilizing microbes (PSM) on soybean grown in a sub-Himalayan mollisol. Grain and straw yields did not increase following RP addition or mycorrhizal inoculation but increased significantly after inoculation with *Bradyrhizobium* or PSM. In general, the application of RP, *Bradyrhizobium*, VAM and PSM in combinations of any two or three resulted in significant increases in nodulation, plant growth, grain yield and uptake of N and P.

Singal et al. (1994) found that *Aspergillus japonicus* and *A. foetidus* solubilized five types of Indian RPs at pH 8 and 9. Solubilization was higher in the presence of pyrite than in controls lacking either pyrite or fungal inoculum. Both the aspergilli were found to be good pyrite solubilizers and could grow over a wide pH range. Solubilization of RPs was the result of organic acid release and pyrite oxidation.

Dubey (1996a) investigated the combined effect of *Bradyrhizobium japonicum* and phosphate- solubilizing *Pseudomonas striata* on nodulation, yield attributes and yield of rainfed soybean under different sources of phosphorus in Vertisols. Among different sources of P, SSP at 26.4 kg P/ha gave the highest yield (1.87 tonnes/ha). It was equally effective as RP at 13.2 kg P/ha + combined inoculation of *B.japonicum* and *P. striata* for dry weight of seed yield (1.81 tonnes/ha). However, RP without *P. striata* was an ineffective source of P. RP at 13.2 kg P/ha + combined inoculation was found to be a cheaper source, giving high net profit (Rs 1,426/ha), benefit:cost (8.77) and less additional cost (Rs 183/ha) compared with SSP. Combined inoculation was also found to be more profitable (Rs 935/ha) than the RP at 13.2 kg P/ha (Rs 422/ha) and single inoculation (control).

Tomar et al. (1996) conducted a field experiment to evaluate the efficacy of the phosphate solubilizing bacteria biofertilizer (PSB) with various sources and levels of phosphorus on the production of gram. The PSB inoculant enhanced grain yield by 2.37 q/ha (10.7%) and net return by Rs 1.9 l/ha. Among the P sources, RP + pyrite proved the best followed by SSP, DAP, RP. Extra grain yield ranged from 3.3 to 5.7 q/ha (11 to 20%) and net profit from Rs 3,175 to 5,422/ha. The best combination was PSB + RP + pyrite + 60 kg P_2O_5, giving 38.9 q/ha grain yield and Rs 32,478/ha net return, although this was comparable with uninoculated + RP + pyrite + 60 kg P_2O_5/ha.

Gyaneshwar et al. (1998) assessed the effect of buffering on the phosphate-solubilizing ability of bacteria (PSB) isolated from alkaline Indian vertisols. The two PSBs solubilized both RP and di-calcium phosphate in unbuffered media but failed to solubilize RP in buffered media. The organic acids secreted by these PSBs were 20-50 times less than that required to solubilize phosphorus from alkaline soil.

Vora and Shelat (1998) studied the impact of different carbon and nitrogen sources on the solubilization of RP by phosphate-solubilizing micro-organisms (*Bacillus circulans, Bacillus brevis, Bacillus coagulans* and *Torulospora globosa*). Maximum solubilization was observed in glucose, sucrose and fructose. Ammonium sulphate was the best nitrogen source for all the bacterial strains examined, but it was poorly utilized by the yeast. None of the strains could successfully utilize sodium nitrate.

Singh and Kapoor (1999) demonstrated that inoculation with PSM and a VAM fungus, with or without MRP improves dry matter yield and nutrient uptake by wheat grown in a nutrient deficient sandy soil.

Narsian and Patel (2000) showed that *Aspergillus aculeatus*, a rhizosphere isolate of gram (*Cicer ariatenum*) invariably solubilized both foreign (China and Senegal) and Indian (Hirapur, Udaipur, Sonrai) rock phosphates. Nitrates, while supporting good growth, did not support good phosphate solubilization. Maximum phosphate solubilization (PS), growth and acidity of the medium never occurred simultaneously with all C-to-N ratios (8 to 120). Although increasing concentration of RP in the culture medium favoured mycelium growth and a decrease in pH, soluble phosphate concentrations were reduced, probably owing to consumption by the rapidly growing fungus.

Sahu and Jana (2000) examined phosphate-solubilizing bacteria (PSB) and solubilization of MPR in simulated fish ponds using four treatments: (a) addition of compost of straw, waterhyacinth and cattle manure; (b) exogenous introduction of PSB, compost and MPR: (c) compost and MPR and (d) bacteria-free compost. Exogenous introduction of PSB with the compost resulted in the highest concentrations of different species of phosphate in water or sediments among all treatments. The MPR-leached phosphate was strongly influenced by PSB, followed by alkaline phosphatase in all treatments, except for that treated only with compost.

Composting

Mishra et al. (1982) evaluated the effect of compost enriched with MPR on crop yield. Bhardwaj and Kanwar (1991) studied the use of wild sage as a green-manure for wheat by incorporating 0, 5 and 10 tonnes/ha of the plant material in acidic silty, clay-loam soil under field conditions in combination with 0, 60, 90 and 120 kg/ha of fertilizer N. It was concluded that wild sage was a highly useful raw material for compost production, particularly in combination with cattle-dung and RP.

Hajra et al. (1992) investigated the effect of enriched city compost on the dry matter of crop plants, uptake of nutrients and fertility of an alluvial soil. Compost from a mechanical plant in Calcutta was enriched with *Azotobacter chroococcum Beijerinck*, RP and P- solubilizing cultures of *Bacillus sp* and *Penicillium sp* along with inorganic N and pyrite. This enriched compost significantly increased the dry-matter yield of rice (*Oryza sativa L.*)-rice-blackgram (*Phaseolus mungo L.*) cropping sequence and the uptake of N and P, in addition to increasing biomass carbon in a gangetic alluvial soil.

Singh et al. (1992b) examined the effect of the addition of N on the enrichment of phospho-compost and its effect on the yield of wheat (*Triticum aestivum* L. emend. Fiori & Paol.). The nitrogen- and phosphorus-enriched compost was prepared by incorporating MRP, pyrite and urea-N at 10%, 10% and 1% of the dry weight of compostable material respectively during composting of plant residues. This compost contained 2% total N and 1.29% total P after 90 days of decomposition. Pyrite addition with MRP retained 88.8% of the added urea-N, of which about 30% was in organic form. The N-enriched phospho-compost, when applied to supply 28.3 kg P/ha, was found to be as effective as SSP (28.3 kg P/ha) in field trials with wheat. Its application saved 30 kg N/ha. Both wheat yield and nutrient uptake were more with N-enriched phospho-compost compared with the phospho-compost.

Singh and Amberger (1997) examined the influence of humic (HA) and fulvic acids (FA) from wheat straw compost on the solubilization of Mussooriephos (MP) and Hyperphos (HP). Solubilization of P from both RPs increased up to 4:1 RP to HA ratio, and 6:1 RP to FA ratio but thereafter decreased drastically, becoming negligible when the pH of the equilibrium reached 7.35. P solubility from HP was higher at lower ratios in comparison to MP. Fulvic acids had 80% higher P solubilizing capacity than humic acids.

Singh and Amberger (1998) examined the effect of nitrogen, molasses and low-grade RP enrichment on the production of organic acids and solubilization of phosphorus during wheat straw composting. The occurrence of glycolic, oxaloacetic, succinic, fumaric, malic, tartaric and citric acids was very high, resulting in higher solubilization of added insoluble P at the beginning of 30 days, but decreased drastically thereafter reaching negligible amounts at 120 days of composting. Nitrogen addition increased the production of all the above organic acids. Addition of nitrogen + molasses increased all except oxaloacetic acid at 30 days and glycolic acid at both 30 and 60 days of composting. However, the incorporation of both Mussooriephos and Hyperphos precipitated out oxaloacetic, tartaric and citric acids so that their concentrations decreased in the aqueous solution.

An important source of soil organic matter/crop nutrients is lost because of burning, which also creates environmental pollution. Rice-straw is one of the major crop residues burnt in the Philippines, Vietnam, Sri-Lanka, Pakistan and India. Although it is an important cattle feed in some parts of these countries, in other areas where supply exceeded demand, the straw is burnt. For example, about 12 million t of rice- and wheat-straw are burnt annually in the Punjab, India leading to the loss of N worth US$ 18 million annually. In addition, it causes environmental pollution (smoke) and annual produces 28 million t of the greenhouse gas CO_2 each year. Incorporation of rice-straw in soil and its natural decomposition is possible but the short time between the rice harvest and sowing of the next crop can result in its incomplete decomposition and can reduce the yield of the subsequent crop. Consequently, long-term experiments (7 to 11 years) on the incorporation of rice-straw in the region have not been encouraging. Furthermore, farmers need to use extra tillage for incorporation of the straw and extra water for its decomposition. Unfortunately, the machinery needed for incorporation is not available to most farmers so that burning of crop residues is an attractive alternative. The straw could be used as surface mulch, but little research has been conducted on this in the intensively cropped regions of Asia. Several farmers in a high rainfall area of the Philippines have been composting rice-straw. This method, however, had to be modified for use in the semi-arid tropics. Farmers in the intensively cropped areas of rice and wheat cultivation where the crop residues are in excess are highly unlikely to adopt the method because few farmers in these areas scientifically compost cattle dung, a much simpler process than composting rice-straw. The method was therefore targeted as a village level enterprise. The project objective was to develop rapid (35 to 45 days) rice-straw composting technology that will reduce burning of the straw and have the potential to improve crop yields. The composting method involves the use of 0.3% nitrogen (N), 6% RP, on dry mass basis of rice straw, activating fungus (*Aspergillus awamori*), and cement composting cylinders. The technology is being tested in three cropping systems (soybean-safflower, pigeon pea-mustard or barley, rice (upland)-chickpea). Alternatively, the wetted rice-straw can be mixed with 6% (dry weight basis) powdered RP and placed in heaps 5-meter long, 1.5 meter wide and 1.5 meter high (ICRISAT, 2000).

Pyrite

Chahal (1981) evaluated efficiency of RP with FYM and iron pyrite. Gopalakrishnan and Palaniappan (1992) carried out a field experiment to evaluate the effectiveness of MRP and SSP, both applied at 35.2 kg P/ha, with various solubilizing agents like pyrites, phosphobacteria and farmyard manure for soybean (*Glycine max (L.) Merr*. cultivation. Plots receiving SSP showed the highest number of pods/plant, followed by those receiving SSP - MRP (1:1). Soil-P was higher in the plots receiving SSP than in those receiving MRP. Farmyard manure (FYM) application at 12.5 tomes/ha significantly increased the yield and P uptake.

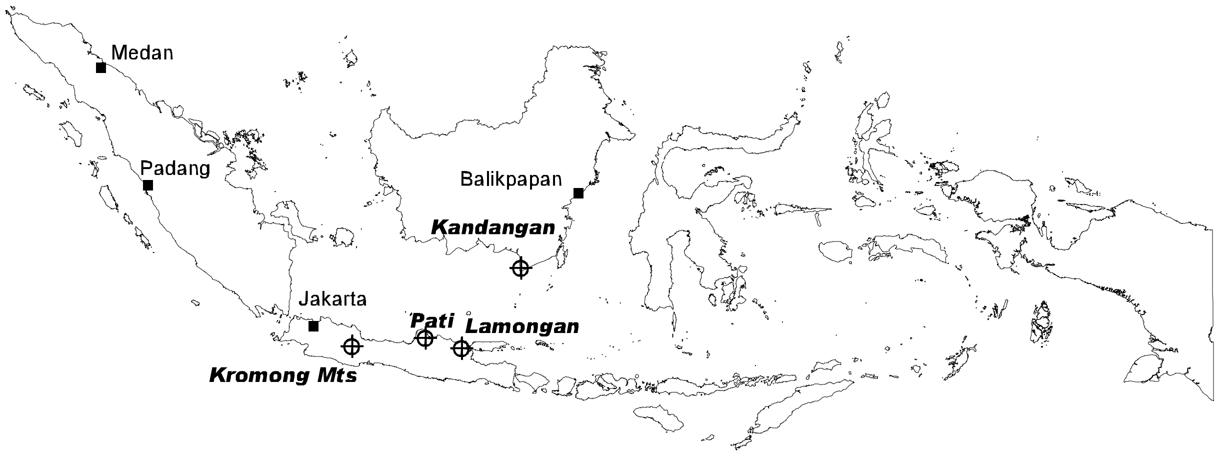
Biswas et al. (1996) used incubation experiments to study the mobilization of phosphorus from MRP using fresh cowdung and pyrite. Pyrite (10%) in addition to cowdung did not increase P solubility initially, but maintained larger amount of formic and citric acid soluble P. Cowdung and pyrite solubilized 4.72% of total P in the MRP using Olsen's reagent. The release of SO_4-S was negatively correlated with P extracted by all the three extractants.

Sharma and Prasad (1996) examined the efficiency of Mussoorie rock phosphate-pyrite mixture as a phosphate fertilizer. MRP, MRP + pyrite (25% by weight), DAP, ammonium polyphosphate (APP) and nitrophosphate (NP) were compared in a field experiment as fertilizers for wheat. At 20 kg P ha^{-1}, MRP was only 6 per cent as effective as DAP. However, when it was mixed with pyrite, the efficiency of MRP increased to 64 per cent at 20 kg P ha^{-1} compared with 97 per cent at 40 kg P ha^{-1}. The P requirement for a targeted yield for 4.5 t ha^{-1} decreased from 39.4 kg P ha^{-1} as MRP to 23.7 kg P ha^{-1} as MRP + pyrite.

Sources: (Appleton, 1990; Appleton, 1994; Banik et al., 1989; Bhardwaj and Kanwar, 1991; Bhardwaj et al., 1996; Biswas and Das, 1995; Biswas et al., 1996; Chahal et al., 1981; Chakravorty, 1993; Das et al., 1991; Debnath and Basak, 1986; Dev, 1998; Dubey, 1996a; Dubey, 1996b; Dubey and Agarwal, 1999; Ghosal et al., 1998; Ghosh, 2001; Giri, 1993; Gopalakrishnan and Palaniappan, 1992; Gough and Herring, 1993; Gupta et al., 1993; Gyaneshwar et al., 1998; Hajra et al., 1992; ICRISAT, 2000; Jaggi, 1982; Jaggi, 1986; Jaggi, 1995; Jaggi et al., 1986; Jaggi and Chulet, 1995; Jana and Das, 1992; Khan et al., 2001; Krishnareddy and Ahlawat, 1996; Maene, 2001; Marwaha, 1986; Marwaha et al., 1981; Mathur and Sarkar, 1998; Mishra et al., 1982; Mutanal et al., 1998; Narsian and Patel, 2000; Pandian, 1999; Perumal and Mahimairaja, 1998; Prasad and Singh, 1992; Rajendran, 1994; Rajkhowa and Baroova, 1998; Raju et al., 1997; Raju and Reddy, 1999; Ramachandran et al., 1998; Sagwal and Kumar, 1995; Sahu, 1983; Sahu and Jana, 2000; Sarkar et al., 1995; Sekhar and Chauhan, 1998; Sharma et al., 1995a; Sharma et al., 1996; Sharma and Sharma, 1998; Sharma et al., 1995b; Sharma and Sharma, 1997;

Sharma and others, 1998; Sharma et al., 1992; Sharma et al., 1982; Sharma and Prasad, 1996; Sharma et al., 1983; Sharma, 1991; Sharma and Singh, 1991; Singal et al., 1994; Singaram and Kothandaraman, 1992; Singaram et al., 1995; Singh and Myhr, 1998; Singh and Amberger, 1990; Singh and Amberger, 1991; Singh and Amberger, 1997; Singh and Amberger, 1998; Singh et al., 1983; Singh et al., 1987; Singh and Singh, 1993; Singh and De, 1990a; Singh and De, 1990b; Singh et al., 1999a; Singh et al., 1999b; Singh and Yadav, 1986a; Singh and Yadav, 1986b; Singh and Yadav, 1988; Singh and Kapoor, 1999; Singh et al., 1992b; Tandon, 1987; Tandon, 1989; Tandon and Sekhon, 1988; Tiwari and Nema, 1999; Tiwari et al., 1989; Tomar et al., 1983; Tomar et al., 1996; Tomlinson et al., 1998; Tripathi and Minhas, 1991; Venkitaswamy et al., 1991; Verma et al., 1993; Verma and Rawat, 1999; Verma and Sharma, 1994; Verma et al., 1991; Verma et al., 1990; Vora and Shelat, 1998)

Indonesia



Location, Quantity, Quality

Palaeogene-Recent

Residual deposits occur as irregular lenses, pockets and veins, and in depressions and caves throughout the Indonesian archipelago, principally on the island of Java. The deposits, which are believed to be of Pleistocene age and derived from guano, are associated with the development of karst topography on bioclastic limestones of Middle or late Miocene age. The infill may be as much as 15 m thick although most of the deposits, such as those in the Ciamis area, ESE of Jakarta, are of low tonnage (100-1,000 t.). Larger deposits, containing perhaps 1 Mt or more, have been found in extensive depressions beneath reddish-brown residual soil. The richest phosphate is a white, soft powdery material with variable grades of up to 36% P_2O_5 present as apatite. Reddish-brown to ochreous, clayey, earthy phosphate deposits are common in depressions that lack adequate drainage. Crandallite is the main phosphate mineral in these deposits which average around 27% P_2O_5. It is likely that many such buried residual deposits remain to be discovered (Notholt, 1994).

These numerous cave deposits of phosphatic guano with up to 40% P_2O_5 comprise the main phosphate resources in Indonesia (Harjanto, 1986). Phosphate reserves defined by the Indonesia Directorate of Mineral Resources are summarised in Table 8.

Phosphatic sinter deposits, containing the hydrous iron sulphate mineral jarosite, occur near Tjiater on the north eastern slopes of Tangkuban Parahu volcano, some 16 km north of Bandung, West Java. The soft, porous, and pale to brownish-yellow secondary material has been developed on hard jarosite and its ferruginous crust. A thickness of nearly 7 m was recorded at one locality but erosion has reduced the thickness to about 3 m in other areas. Resources are small and have not attracted commercial interest (Notholt, 1994).

Table 8 Phosphate deposits in Indonesia with greater than 25,000 tons.*

Location	Reserve (tons)	P_2O_5 content (%)
Ciamis region, W Java	99,459	1-38
Sukolilo, Brati, Pati C Java	119,000	10-38
Karangrayung, Grobogan C Java	54,500	26
Tuban, E Java	25,831	28
Lamongan, E Java	186,680	31
Gresik, E Java	25,500	29
Madura Island, E Java	74,518	28
Kandangan, Kalimantan	75,240	12-37
Kakabiya Island, SE Sulawesi	45,000	0.4-21

*Data from Industrial Minerals Inventory and Exploration Project, 1968-1985 (Harjanto, 1986).

Production

The phosphatic guano and replacement deposits were exploited on a small scale since 1919 for direct application to acid soils (Harjanto, 1986) but current production is very small (500-750 tonnes/pa, Table 2). Production in the 1930's was mainly from the Kromong Mountains area, southwest of Tjirebon.

Ten producers of PR registered with the Ministry of Industry in 1995 had a combined production capacity of 246,350 tonnes, which exceeded demand by more than 40%. At that time, the major consumers were state and private plantations and the Government in newly opened areas under the Ministry of Transmigration (Harliyah, 1995).

Maene (2001) reports that the total consumption of P_2O_5 in Indonesia increased from 274,000 tonnes in 1980 to 360,000 tonnes in 1998 whilst PR consumption (presumably for direct application on plantation crops) increased from 13,000 tonnes to 69,000 tonnes in the same period. These figures contrast starkly with figures issued by IFA (IFADATA statistics from 1973 to 1998, 2000), which indicate that no phosphate rock was used for direct application in Indonesia. The use of local phosphates as a raw material in the fertilizer industry is now very limited and the direct use of local phosphates is low. Most of the directly applied PR is imported (Van Os, 1996).

The fertilizer industry aims to increase the use of local phosphates by defining a lower quality requirement with a minimum grade at 26 per cent P_2O_5, while imported material will be accepted only if the grade exceeds 29 per cent P_2O_5. Despite this concession, the supply of Indonesian phosphate rock with a sufficient P_2O_5 content is limited. Low reactivity limits the potential for direct application of phosphate rock on the land, although some experiments show positive long-term agronomic effects on acidic soils (Van Os, 1996).

Sources:(Harjanto, 1986; Maene, 2001; Notholt, 1994; Savage, 1987; Van Os, 1996).

Agronomic testing and use

Santoso et al. (1996) demonstrated that the use of rock phosphate in combination with erosion control ('fertility traps') and legume cover crops can be effective in restoring soil fertility. Case studies for a number of sites in Sumatra confirmed the practical possibility of reclaiming grasslands for food and tree crops.

The use of a single large application (1 ton per hectare) of reactive RP for the rehabilitation of abandoned land has been investigated in Indonesia and concluded to be both economic and effective. Soil rehabilitation involved burning and spraying the regrowth of *Imperata Cylindrica* with glyphosate herbicide. Phosphate and calcium (Ca) deficiency was then corrected by a single large application (1 t ha^{-1}) of reactive RP (North Carolina PR, Morocco PR) or the equivalent (1998 monetary value) in the form of 400 kg triple superphosphate (TSP) and 1000 kg lime. A fast growing leguminous creeper (*Mucuna cochinchinensis*) was then planted as a rehabilitation fallow. The agronomic effectiveness of RP was comparable to TSP and persisted over 7 cropping seasons after the initial P application. (Nassir, 2001)

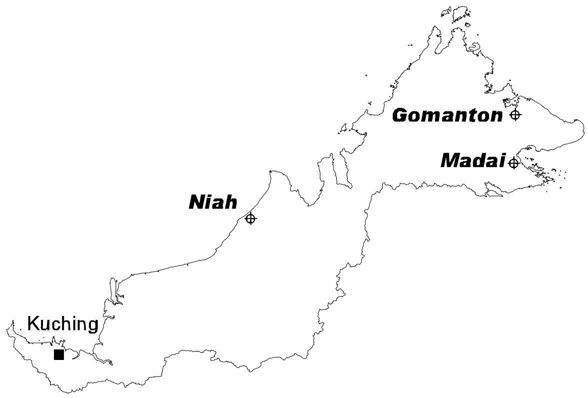
Based on previous experiments on the use of reactive PR for the rehabilitation of alang-alang (*Imperata Cylindrica*) land in Indonesia for 5 years, reactive PR is considered more suitable form of phosphate fertilizer. Farm trials in an upland area concluded that medium and high reactivity PR application maintained its residual effectiveness over 3 years on more than 5 cropping seasons. Reactive PR when directly applied at initial rates of between 80-360 kg P_20_5/ha, not only increased yields of corn, upland rice, soybean and groundnut on ultisols and oxisols, but resulted in similar or even larger yields than TSP. A comparison of the effectiveness of different P sources was carried out on upland farmer's fields at Pelaihari, South Kalimantan. Some reactive PR performed as effectively as SP-36 in several trials; the various PR sources that were evaluated in the field experiment on Typic Hapludults Pelaihari in South Kalimantan were equally effective in crop yield. Unground PR from Morocco (OCP-PR), Tunisia (Gafsa-PR), Algeria (Djebel Onk – PR), and Senegal (ICS-PR) was as effective as ground PR. The large initial application of PR (300 kg P_20_5/ha) was found to maintain residual effectiveness over 5 cropping seasons on upland acid soils (Typic Hapludults) in Pelaihari, South Kalimantan. The large initial application of P reduced Al saturation to the level of about 30% which is suitable either for growing maize or upland rice, but not for legume crops. If legume crops like cowpea and soybean are planted on upland acid soils in Pelaihari, the large initial application of PR should be combined with lime to reduce Al saturation to less than 15%. The large initial application of P fertilizer increased available P, total P, and the concentration of exchangeable Ca and Mg in the soil; soil treated with OCP ground PR and Djebel Onk ground PR had the highest amount of available P compared to the other PR sources tested. The large initial application of P increased soil pH slightly but soil pH tended to return to its initial level after the fourth cropping season (Nassir, 2001).

There are large areas in Sumatra, Kalimantan, Sulawesi and Irian Jaya islands having potential for agricultural expansion that will help to satisfy the increased demands for food production. Sri Adiningsih (2001) estimates about 38.4 mill ha of upland with slopes less than 8% have potential for food production. About 42% of this are covered by low fertility ultisols and oxisols for which phosphorous is the most limiting factor for plant growth.

Since the removal of fertilizer subsidy in Indonesia, the price of water soluble P (TSP or SP-36) are quite high whilst PRs are now the cheapest source of P. Research on food crop production on lowland and upland acid soils and tidal swamp land indicate that reactive phosphate rocks (RPR) were equally as effective as TSP/SP-36. Furthermore, RPR had a greater residual impact than water-soluble P sources. A large initial application rate of RPR or P-recapitalization increases and sustains productivity of upland acid soils for more than two years. Although research indicates the benefit of direct application of RPR, many adoption constraints exist at the farmer level including quality control, the distribution system, marketing and the doubts of some farmers and policy makers regarding the benefits of RPR (Sri Adiningsih et al., 2001)

Sources:(Baon and Wibawa, 1998; ICRISAT, 2000; Maene, 2001; Nassir, 2001; Penot et al., 1998; Santoso, 1998; Santoso et al., 1996; Sofyan et al., 1998; Spears, 1980; Sri Adiningsih and Fairhurst, 1998; Sri Adiningsih et al., 2001; Tambunan et al., 1993; Van Os, 1996)

Malaysia



Location, Quantity, Quality

The only phosphate resources identified in Malaysia are the deposits of phosphatic guano and phosphatized bedrock that have been encountered in many limestone caves in Peninsular Malaysia, Sarawak and Sabah. Numerous deposits have been worked since at least the early part of the 20th century.

Deposits of phosphatic bat guano occur on the Malaysian peninsula, chiefly in the States of Perlis, Kedah, Perak, Selangor and Pahang. They are all located in caves developed in Carboniferous to Permian limestones, which form steep-sided hills and exhibit a very irregular surface reminiscent of 'karst' topography. The most important deposits are situated in Perlis State. Aluminium phosphate is frequently present, probably as the mineral wavellite, and is thought to have been produced by percolating solutions acting on the deposits (Notholt, 1999). Substantial cave deposits are reported to exist also in Pahang and Kuantan, but no quantitative estimates for these deposits or of those in Perak and Selangor are available. It is considered highly probable that all the available estimates relate to guano rather than to the hard secondary phosphate (Notholt, 1999).

Three basic varieties of phosphatic material of variable thickness and distribution have been identified in caves examined by the Geological Survey of Malaysia (Notholt, 1999). A top layer of guano consists of a dark-brown, unconsolidated, earthy, clay-like, mass with a variable phosphate content that averages less than 10% P_2O_5. This is underlain by "fossil" guano averaging 9.6% P_2O_5. The cave phosphate currently attracting the most commercial interest is the third variety, a hard phosphate rock occurring as laminated crusts which is believed to have formed by the downward percolation of phosphate-rich solutions derived from the overlying guano, followed by re-precipitation on limestone surfaces, cracks and fissures. This material is a high-grade, secondary phosphate rock, with an average of 32.5% P_2O_5 (Notholt, 1999).

Total reserves are estimated to be more than 100,000 tonnes (Table 9).

Table 9 Reserves and grade of phosphate cave deposits (Notholt, 1999)

Region	Deposit	Reserves	Average % P_2O_5
Malaya	Perlis	50,000*	2-36
Sabah	Gomanton	12,000	10-21
Sabah	Madai	8,400	nd
Sarawak	Niah	28,200	23
Sarawak	Gunong Staat & Gunong Selabor	9,120	2-17

* estimated minimum aggregate tonnage of 100 caves.

Phosphate deposits consisting of bird and bat guano, occasionally underlain by phosphatised rock, occur in a number of caves in Sabah particularly in the Gomanton cave deposits, located at the north-eastern end of a limestone escarpment, about 32 km south of Sandakan. At Madai there are about 25, mostly small, caves in limestone hills, located about 43 km south-west of Lahad Datu. The main Madai Cave and the Pidtong Caves about half a kilometre further to the north-west are the only ones thought to contain much phosphate (Notholt, 1999).

The Niah caves, situated about 10 km south-west of the village of Niah in Sarawak, contain guano deposits more than 15 cm thick covering about 14,000 m^3, while the average depth of phosphate in the main caves was about 3 m (Notholt, 1999).

Total phosphate resources in Malaysia have been estimated to amount to approximately 108,000 t, assuming the minimum of 50,000 t in respect of cave deposits in Perlis State in northern Peninsular Malaysia. The guano caves in Sabah and Sarawak were estimated in 1951 by the (then) Geological Survey Department to contain nearly 58,000 t, located mainly in the Niah Caves, with averages of 10% P_2O_5 at the surface to over 20% P_2O_5 at depth (Notholt, 1999).

Production

Local farmers have used guano from the small guano deposits in Malaysia for many years although the total production was reported to be small. In the mid-1980's it was estimated that six processing plants produced about 12,000 tons per year. However, approximately 50% of the phosphate rock processed was probably imported from Thailand (Ismail, 1986).

Production in Sarawak over the period from 1920 to the late 1980's was obtained principally from caves near the village of Niah, where the most important deposits are situated. The guano deposits of the Perlis area used to represent a small but valuable source of phosphate for direct application in a predominantly agricultural region where the soils are deficient in plant nutrients. The guano has been used mainly in rice nurseries to promote the growth of rice seedlings (Notholt, 1999).

Sources: (Ismail, 1986; Notholt, 1999; Savage, 1987)

Agronomic testing and use

Hanafi et al. (1992a) assessed the effect of pH and calcium (Ca) on the dissolution of Gafsa (GPR) and Christmas Island A (CIPR) phosphate rocks (PR) in closed-incubation and open-leaching systems in six acid, Malaysian soils. Dissolution of PR decreased with increasing levels of $CaCO_3$ or $CaCl_2$, but the decrease was more pronounced in CaCO3-treated than in CaCl2-treated soils. The effect of $CaCO_3$ and $CaCl_2$ on PR dissolution varied between soils and was related to pH-buffering and the Ca-sink size. In an open-leaching system, large amounts of Ca (8-40%) added as $CaCO_3$ were removed in the leachate and hence the decrease in GPR dissolution with $CaCO_3$ addition was less in the open-leaching than in the closed-incubation system.

Hanafi and Syers (1994a; 1994b) investigated the agronomic and economic effectiveness of Christmas Island phosphate rock (CIPR) and Gafsa phosphate rock (GPR), compared to TSP, in acid Malaysian soils. The response of *Setaria* to the P treatments was clearly indicated by the DM yield and for each soil TSP was superior to either CIPR or GPR. The RAE of GPR (90%) was higher than that of CIPR (72%). However, for the long-term supply of P, both CIPR and GPR were much more cost-effective than TSP, with REE values of 131 and 143% for CIPR and GPR, respectively.

Total P_2O_5 consumption in Malaysia increased from 119,000 tonnes in 1980 to 361,000 tonnes in 1998. During the same period, PR consumption increased from 74,000 to 187,000 tonnes (Maene, 2001), most of which was imported from Christmas Island, Australia, Tunisia, Algeria, China and Jordan (Yusdar and Hanafi, 2001). The bulk of the phosphate rock is imported mainly as unground chips from Jordan and Tunisia whilst the China rock is in a finely ground form (Zakaria et al., 2001). Adequate facilities exist for milling phosphate rock to the required specification. The price of phosphate rock is very much higher in Sabah and Sarawak due to cost of shipping so direct shipment of ground China PR is favoured. The use of ungrounded Gafsa and North Carolina reactive phosphate rock may be more attractive economically, particularly when compared to the more expensive soluble-P (TSP/DAP).

Of the 521,000 tonnes imported in 1994, 415,000 mt was used for oil palm and rubber whilst rice, cocoa and fruits consumed 16.3%. Phosphate rock was applied directly or blended. Use of reactive PR for food crops was foreseen but apparently not practised (Zaharah and Sharifuddin, 1995).

In Malaysia the area under plantation crops exceeds that under food crops by a ratio of 10:3, direct use of phosphate rocks accounts for a much greater proportion of the total P consumption than elsewhere in southeast Asia. Phosphate rock (generally, Christmas Island (CIRP) Grade A dust) has been used for many years as the almost exclusive P source for plantation crops including oil palm. This source was shown in early pot and field trial to be as effective as soluble P fertilizer. However, studies conducted on oil palm seedlings have shown that soluble P sources are more effective at the seedling stage. Studies have also shown that oil palm yield responses to application of various P sources varies depending upon the characteristics of the P source, soil types, and the age of the palm. Recent data have shown that for mature oil palm production, most PRs are equally as effective as soluble P sources (including the reactive PR). With the availability of several sources of PRs from different origin, a precise knowledge on their residual effectiveness is important in order to improve fertilizer efficiency (Zakaria et al., 2001).

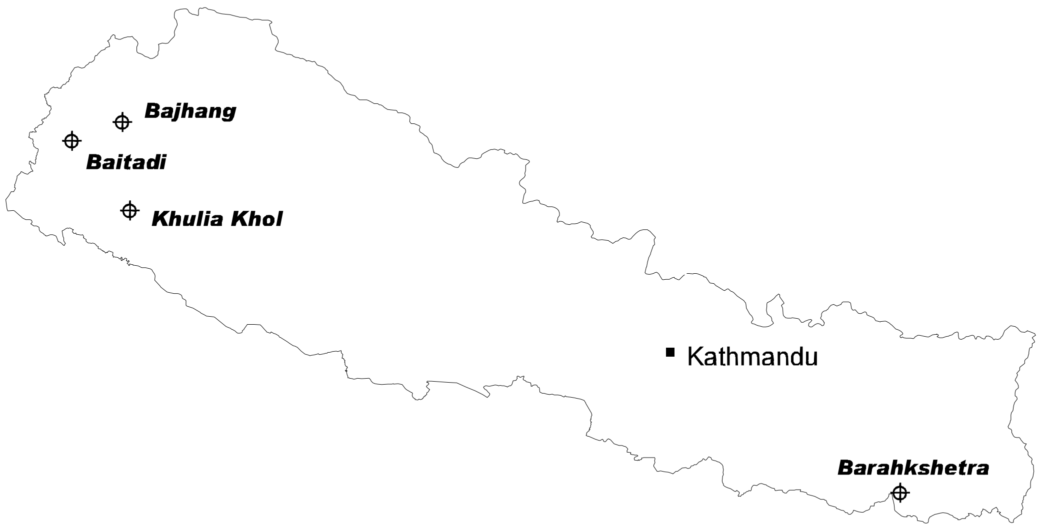
PR used for oil palm, rubber and cocoa is applied in the nursery, prior to planting a legume crop during land preparation, in the planting hole, every two or three years to immature trees and every year to mature trees. In 1995, an analysis of the relative economic efficiency of different P sources for rubber found that PR was less costly than SSP by 30% to 68% per unit of P.

The role of PR in increasing fertilizer use efficiency in Malaysia for perennial crops (cocoa, forest tree, pepper, rubber, oil palm, and fruit) and annual crops (rice, maize/corn, mucuna, soybean, groundnut, and grass) were recently reviewed by Yusdar and Hanafi (2001). Malaysian soils are highly weathered and are generally acidic and inherently low in P and high in P fixing capacities. They are characteristically high in iron and aluminium in their clay fractions, which results in substantial P-fixation. The high P-fixing capacities are normally overcome by additional P fertilization (Zakaria et al., 2001).

The performance of specific P sources depends on the characteristics of PR and soil, types of crop, and environmental conditions. Thus, evaluation of P sources in a real field situation is very important to determine the best source of PR for each soil-crop-environmental combination. Judicious selection of P sources should be based on the relative economic efficiency (REE) in that particular situation. The use of reactive North Carolina PR (NCPR) could increase production of cocoa, maize (corn), and *Mucuna sp*. Gafsa (GPR), Rhenian (RPR) and Jordanian (JPR) are additional alternative P sources for *Mucuna* and other legume crops. Inoculations with VAM fungi have been shown to increase the growth of *Acacia* *mangium* in the glasshouse and in the field. In the field, VAM inoculation along with 50 g GPR $plant^{-1}$ may be considered to be optimum for *A. mangium* on tin mine tailings (Yusdar and Hanafi, 2001).

Sources: (Arulandoo and Bidin, 1998; Hanafi and Syers, 1994a; Hanafi and Syers, 1994b; Hanafi et al., 1992a; Hanafi et al., 1992b; Maene, 2001; Warren, 1994; Yusdar and Hanafi, 2001; Zaharah and Sharifuddin, 1995)

Nepal



Location, Quantity, Quality

Beds of sedimentary PR have been found in eastern Nepal, along the southern boundary of the tectonically complex Pre-Cambrian - middle Palaeozoic Midland Group. The occurrences lie between Takure and Tangsar, a total distance of over 160 km. Four individual beds have been found at Barakhshetra, some 30 km from Takure, on the Sun Kosi River but the beds are thin and erratic and only occasionally exceed 5% P_2O_5 (Notholt, 1994). Shales of Eocene age contain traces of phosphate as well as nodules with up to 15% P_2O_5 at Dang in the Rapti Anchal district (Notholt, 1999). Phosphatic beds with more than 4.5% have been recorded from the Khulia Khola area, northwest of Chispani in western Nepal in a series of Eocene shales and limestones (Tater, 1980).

Prospecting in Far Western Nepal revealed a 50 km phosphorite belt stretching from Dhikgad in Baitadi District to Tarugad in Bajhang District. The phosphorite horizons are 70 cm to 4.7 m thick, contain 5% to 32% P_2O_5 and have low solubility. Laboratory tests are being carried out to upgrade the phosphate content and to produce fused magnesium phosphate (Foreign Investment Promotion Division, Ministry of Industry, Nepal[1]). The phosphorites occur in Precambrian cherty dolomites that extend over 25 km in Baitadi district and 19 km in the Bajang area. In Baitadi, the horizon is up to 4.7 m thick and contains 10 to 32% P_2O_5 whereas the phosphorite is lower grade (20% P_2O_5) and only 0.65 m thick in the Bajang area (Pradhananga, 1986).

Production

Phosphate rock is not produced in Nepal and there is little consumption of phosphatic fertilizers in the country.

Sources: (Notholt, 1994; Notholt, 1999; Pradhananga, 1986; Tater, 1980)

[1] http://www.catmando.com/gov/industry/fipd/fipd6.htm accessed 14 August 2002

Agronomic testing and use

Phosphorus is the second most important soil nutrient limiting crop production in Nepal. Most cultivated soils exhibit moderately low to low levels of available phosphorus, but under existing management, deficiency signs are not obvious. Fertilizer consumption in Nepal is quite low. Peak nutrient consumption of 35 kg/ha/yr in 1994/95 constituted 24.8 kg N, 8.1 kg P_2O_5, and 0.6 kg K_2O. In general, the average amount of fertilizer applied per hectare is far below the recommended rate for most crops.

No information is readily available on the agronomic evaluation of rock phosphate in Nepal although Brown et al (1999) developed a soil nutrient budget model to assess inputs, redistribution and losses relative to soil fertility. Nutrient balances were most critical under rainfed maize production where 94% of the farms were in deficit. Current shortages of organic matter make elimination of nutrient deficits problematic but improvement of composting, biological N-fixation and fertilizer efficiency and reducing erosion were found to be potential options. Schreier et al. (1999) evaluated the phosphorus dynamics and soil P-fertility constraints in Nepal.

Sources: (Brown et al., 1999; Schreier et al., 1999)

Pakistan

Location, Quantity, Quality

Palaeozoic

Phosphate rock occurs in various parts of Pakistan in sediments of Palaeozoic, Jurassic, Cretaceous and Palaeocene age. Palaeozoic deposits in the Hazara District, north of Abbottabad have been investigated in detail since 1971. In this structurally complex area, phosphorite beds, lenticles and stringers in a thick sequence of cherty dolomites comprise the upper part of the Abbottabad Formation. In the Kakul area, about 10 km north east of Abbottabad, individual beds up to 3 m thick are known; further north in the Mirpur area there are several thin high-grade phosphorites. In the less accessible area of Lagarban, 15 km NNE of Abbottabad, sections have been proved of up to 4 m thickness averaging more than 20% P_2O_5 and a section about 15 m thick has been reported near Dalola, close to the Kunhar River, about 30 km north-east of Abbottabad.

Phosphate rock has also been found in Palaeozoic rocks which are apparently stratigraphically equivalent to the Abbottabad Formation, in the Peshawar District. The extension of the Palaeozoic rocks north eastward into Chitral and Gilgit merits further investigation but outside the Hazara District, only a limited amount of exploration work has been undertaken on the Abbottabad Formation (Hasan, 1989; Notholt, 1994). Reserves for the five principal ore bodies are given in Table 10. The grade is very consistent at 29% P_2O_5 whilst R_2O_3 ranges from 1.66 to 5.84% and MgO from 0.22 to 4.89% (Khalil, 1995).

Table 10. Reserves of the Hazara phosphorites (Khalil, 1995)

Ore body	Quantity ('000 tonnes; measured + indicated)
Lagarban South	2,088
Eastern	2,453
Batkanala	1,009
Southern	658
Kakul	700
Total	6,908

Palaeogene-Recent

Apatite is a relatively abundant constituent of the Loe-Shilman carbonatite, which straddles the Pakistan-Afghanistan border, approximately 80 km north-west of Peshawar. The carbonatite, which intrudes slates, phyllites and marbles of the Palaeozoic Landikotal Formation, is about 1.8 km long (in Pakistan) and from l00 to 200 m thick. In some specimens, apatite makes up about 50% of the rock. The exposed body is estimated to contain 59 Mt averaging 4.4% P_2O_5. The carbonatite is unusual by virtue of its tabular shape (which is reminiscent of Kaluwe, in Zambia) and its occurrence in a mountain fold belt (Hasan and Asrarullah, 1989; Notholt, 1994).

Production

Development work began at Kakul in 1984 aimed at the production of 200 tonnes per day. A crushing and grinding plant was installed in 1985 to produce pulverised product with a minimum of 28.5% P_2O_5 for SSP manufacture (Hasan, 1989). 270,000 tonnes rock phosphate was supplied to the National Fertilizer Corporation of Pakistan (Pvt) Ltd. for SSP manufacture during the period 1985-1996. Mine production terminated in 1995 (Sarhad Development Authority, 2002). In July 2002, the Sarhad Development Authority web site[2] stated that the Kakul Phosphate Mining Project was awaiting rehabilitation through joint venture with the National Fertilizer Corporation of Pakistan (Pvt) Ltd. together with the development of the major Lagarban and Tarnawai rock phosphate deposits which are reported to have resources of 7.5 Mt and 4.4 Mt, respectively, of recoverable reserves (Sarhad Development Authority, 2002).

Zafar (1993) studied the possible beneficiation of the Hazara low-grade carbonate-rich phosphate rocks using dilute acetic-acid solution. The tricalcium phosphate (TCP) percent can be raised by up to 23% following treatment of the ground ore with acetic acid, corresponding to a reduction of up to 62% in the calcium carbonate content of the samples. Zafar et al (1995) evaluated thermal beneficiation as a method for improving the quality of the Haraza phosphate rock. They demonstrated that concentrates obtained from the ore assaying 16% P_2O_5 content after desliming can be enriched to a product containing 31-34% P_2O_5 without using the expensive chemicals and energy required in conventional flotation and calcination methods.

Sources:(Banerjee, 1986a; Banerjee, 1986b; Hasan, 1986; Hasan, 1989; Hasan and Asrarullah, 1989; Khalil, 1995; Khan et al., 1998; McClellan and Saavedra, 1986a; McClellan and Saavedra, 1986b; Notholt, 1994; Notholt and Sheldon, 1986; Sarhad Development Authority, 2002; Savage, 1987; Shergold and Brasier, 1986; Zafar, 1993; Zafar et al., 1995)

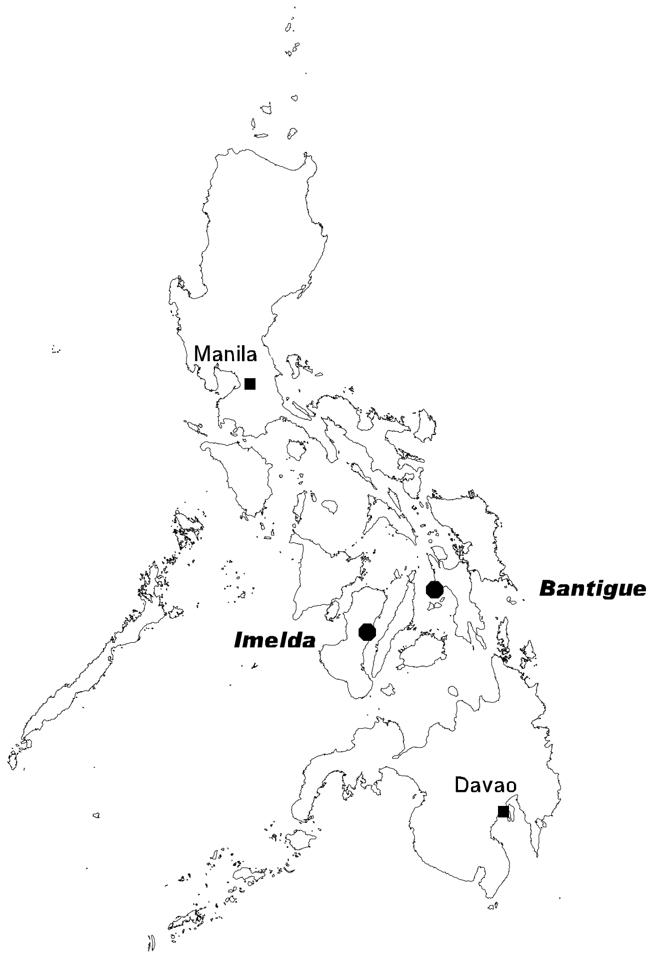
[2] http://www.sda.org.pk/message.html; accessed July 2002

Agronomic testing and use

No information is readily available on the agronomic testing of the Hazara phosphate rock in Pakistan apart from a review by Khalil (1995) who reported that efforts were being made to use biotechnology to treat phosphate rock for direct application. Laboratory trials have shown that approximately 30-40% phosphate rock solubilization after 15 days incubation can be achieved using phosphorus-solubilizing microorganisms (PSM). P availability in soil increased from 0.67 ppm to 17.78 ppm with PSM innoculation in a 20 day period. Khalil (1995) concluded that there is potential for the direct application of phosphate rock in Pakistan and that partial acidulation may extend the use of phosphate rock in calcareous soils

Sources: (ICRISAT, 2000; Khalil, 1995; Weerasuriya et al., 1992b)

Philippines



Location, Quantity, Quality

Palaeogene-Recent

The most widespread resources identified in the Philippines are deposits of guano and phosphatized bedrock which have been found in many limestone caves throughout the archipelago. As on Indonesia, numerous deposits have been worked since the early part of the present century and they continue to represent a small but nevertheless valuable source of phosphate for direct application in a predominantly agricultural region. The guano has been used mainly on rice farms and sugar plantations. Total resources have been estimated to amount to about 3 Mt, mostly in the provinces of Northern Leyte, Cebu, Davao del Norte, Palawan, Negros and Masbate. Numerous other caves in the Philippines remain unexplored for phosphate. Samples of phosphatic material (i.e. guano and phosphatized limestone) show a range of 0.25-39.6% P_2O_5 (Notholt, 1994). In 1984, the Bureau of Mines in Manila estimated that the total reserves of guano and guano-overlain phosphatised rock were 812,207 mt and 2,090,694 mt, respectively (Vargas and Escalada, 1986).

An exploration and development programme initiated in 1982 led to significant discoveries of phosphatic calcarenites and secondary deposits developed in the Late Tertiary-Pleistocene coral limestones of the Visayan basin. The secondary deposits have developed through the action of guano derived phosphatic solutions and contain 1-12% P_2O_5, with up to 12% Fe_2O_3 and 3% Al_2O_3. The most substantial resources of this type are located at Bantigue, Isabel, in Leyte, about 3 km from the Philphos fertilizer plant. In the Bantigue area, the Hubay Limestone, which is of Pliocene-Pleistocene age, consists predominantly of porous poorly bedded to massive coral limestone, gently dipping and weathering to give a dark brown and reddish brown, clayey, soil. Karstic features (sinkholes and caves) are common and the limestone has been extensively replaced, cavities and voids being filled with generally dark brown, laminated, often botryoidal, phosphate. Individual laminae may be up to several centimetres thick. The replacement phosphate appears generally as massive, lense-shaped or oval bodies in limestone and as fracture fillings in dolomite. The Bantigue deposit is estimated to have combined alluvial and replacement phosphate reserves of 800,000 mt with more than 15% P_2O_5 (Vargas and Escalada, 1986) of which 'replacement phosphates' comprise 137,700 t averaging 10.03% P_2O_5 (Notholt, 1994). Less well-documented deposits of a similar type are located at Pinamungahan and Balamban in Cebu (Vargas and Escalada, 1986). These deposits have been classified as collapsed-cave phosphate deposits in which the PR is essentially the same as the guano-overlain PR except that the cave roof and guano deposits are absent (Vargas and Escalada, 1986).

Marine phosphorite occurring between U Miocene and Pliocene limestones on the islands of Cebu, Negros and Siquijor was discovered in the late 1950's (Savage, 1987). The most important example of this type of deposit is the phosphatic calcarenite of the Imelda deposit located near Guihulngan on Negros Island. This has potential ore resources of 1 million tons with low Fe_2O_3 and Al_2O_3 (4-8% R_2O_3) and 29-35% P_2O_5 (Vargas and Escalada, 1986).

Production

Production at the Batingue deposit was scheduled to start in 1986 but production figures (Table 2) indicate that only 181 mt of phosphate rock was produced in 1999 (434 mt in 2000, unpublished data). In the early 1980's, 500-2400 tons of guano and 4000 to 18,000 tons of replacement phosphate rock were produced annually (Notholt, 1999). This had declined to 25 t of guano in 1998 and none in 1999 (unpublished data from the Mines and Geoscience Bureau, Manila).

Sources (Notholt, 1994; Notholt, 1999; Savage, 1987; Vargas and Escalada, 1986)

Agronomic testing and use

Medhi and DeDatta (1996a) carried out field experiments to evaluate alternative fertilizer phosphorus (P) sources in lowland rice under irrigated conditions in Quezon Province, Philippines. In another field experiment fertilizer P recycling through a green manure crop applied to the succeeding rice crop, was investigated. Addition of fertilizer P increased grain yield by 1.5-2.0 t/ha (46%) in the wet season (WS) and by 1.6-2.1 t/ha (56%) in the dry season (DS). However, fertilizer P source and application level did not affect grain yield significantly. Results indicated that the less water-soluble and less expensive partially acidulated phosphate rock (PAPR), phosphate rock (PR) and less reactive PR were as effective as the more soluble but more expensive TSP. The relative effectiveness (RE) of local guano was significantly lower than that of other sources of fertilizer P. Fertilizer P applied to a pre-rice *Sesbania rostrata* green manure increased rice grain yield by 1.5-1.9 t/ha during DS. *S. rostrata* fertilized with Morocco phosphate rock (MPR) gave significantly higher rice grain yield than did rice fertilized with MPR applied alone. Phosphorus uptake did not differ significantly among P sources and levels. Results suggest that P uptake was improved with green manuring and that there was a close correlation between (i) P uptake and dry matter yield and (ii) P uptake and grain yield.

Medhi and DeDatta (1996b) also evaluated the residual effect of fertilizer phosphorus in lowland rice in field experiments in Quezon Province, Philippines. Average grain yield increase was 0.50-0.9 t/ha due to the residual effects of inorganic fertilizer P, regardless of source. Residual effects of fertilizer P with *Sesbania rostrata* or alone increased grain yield by 0.3-1.0 t/ha over the control. Significantly higher yields were obtained with *S. rostrata* fertilized with Morocco phosphate Rock (MPR) and *S. rostrata* + MPR applied on rice than the control. Results revealed that there is a promising effect of residual P from the applied P sources in increasing rice grain yield. Total P uptake increased due to residual P from fertilizer P applied and also in parallel with increases in dry matter and grain yield.

Details on the ICRISAT project that is investigating rapid composting of rice-straw are given in the section on India above (ICRISAT, 2000).

Sources: (ICRISAT, 2000; Ling et al., 1990; Medhi and DeDatta, 1996a; Medhi and DeDatta, 1996b)

Sri Lanka

Location, Quantity, Quality

The Eppawala phosphate deposit located in the Anuradhapura district of Sri Lanka, about 200 km NNE of Colombo, is reported to have proven reserves of 30 million tonnes (38% P_2O_5) (Jayawardena, 1988; Jayawardena, 1989). Total reserves are estimated as 60 million tonnes with an average grade of 33% P_2O_5 (Dinalankara, 1995). The deposit comprises a steeply dipping, lenticular body, up to 800 m wide, extending for a distance of about 5 km in a north-south direction parallel to the regional foliation of the surrounding Precambrian country rocks. Eppawala phosphate rock (EPR) has a breccia-conglomerate texture and comprises crystals and fragments of primary green apatite, ranging in size from a few millimetres to over 1 m, in a fine grained, sometimes partly silicified, matrix composed of secondary phosphate minerals and goethite. The residual phosphate deposit is thought to have developed from a Precambrian carbonate-apatite rock as a result of dissolution of the carbonate minerals under tropical weathering conditions. The primary apatite-carbonate rock has been leached to depths of 60 m or more. Although it has been assumed for many years that the Eppawala phosphate deposit developed from an apatite carbonatite, petrographic and chemical data do not fully support an igneous origin (Dahanayake, 1995; Jayawardena, 1976; Jayawardena, 1980). Silva (1983) and Tazaki et al. (1986; 1987) suggest that the apatite-carbonate rock that underlies the deposit is a marble for which a sedimentary origin is favoured. Recent isotope studies indicate a metasedimentary origin (Dahanayake, pers. comm., 1989). However, it should be noted that REE data for primary apatite from the carbonate rock indicate an igneous origin (Tazaki et al., 1986).

Dahanayake and Subasinghe (1988; 1989a; 1989b) suggest that uplift, weathering and erosion of Precambrian apatite marble took place under tropical equatorial conditions, possibly since the Late Cretaceous. Accumulation of primary apatite crystals in dissolution cavities was followed by the precipitation of secondary phosphate, possibly facilitated by microbial activity. Repetitive precipitation led to the formation of a laminated stromatolitic groundmass and the development of phosphatic allochems. Dahanayake and Subasinghe (1988; 1989a) identified "laminar phoscretes" in the Eppawala deposit by comparison with similar rocks in Australia (Southgate, 1986a). The residual phosphate rock at Eppawala can be described as a "phoscrete" in the sense that ferricrete, silcrete and calcrete were originally used by Lamplugh (1902) to describe conglomerates cemented by iron oxides, silica or calcium carbonate derived and redeposited from percolating solutions and through the agency of infiltrating waters. In the case of the Eppawala phosphate rock, the solutions were rich in P_2O_5 and deposition of secondary phosphate minerals provided the cementing matrix to the rock. At the working face of the opencast mine, the proportion of laminated phosphate rock is relatively small and the mass of the deposit is formed of the conglomeratic phoscrete. A thin 10-20 cm lateritic soil overlies the leached apatite "phoscrete" zone at the mine face.

A similar deposit is developed on apatite gneiss at Ridigama (Dahanayake et al., 1995a)

Production

PR from the Eppawala deposit has long been used in Sri Lanka as a direct application fertilizer, in particular in the rubber and tea estates. Mining, milling, and commercialisation of ground rock phosphate are summarised by Dinalankara (Dinalankara, 1995) and Appleton (1989; 1991). Run of the mine rock contains 37% P_2O_5 and 5.3% R_2O_3 (2.8% NAC soluble P_2O_5) (Dinalankara, 1995; Jayawardena, 1986). The finely ground phosphate rock is sometimes used for bulk blending with nitrogen and potash. In 1998, PR consumption amounted to 13 Kt P_2O_5, out of a total P_2O_5 consumption of 30 Kt (Maene, 2001).

Although the Eppawala phosphate deposit is large with proven reserves of 30 million tonnes (>30% P_2O_5), the PR unfortunately has relatively low solubility (6% P_2O_5 in 2% citric acid) and is difficult to convert into conventional water-soluble fertilizers such as TSP due to the high chloride content (1%) and high R_2O_3 (Al and Fe) impurities (>5%). Consequently a range of alternative methods for the manufacture of soluble phosphate fertilizer from Eppawala rock phosphate have been proposed (Mining Magazine, 1985; Ranatunga and Tennakone, 1988), including:

- Production of Rhenania phosphate from EPR using soda ash and silica.
- Fusion with alkali hydroxide and quartz at 950°C in a process that is similar to the Rhenania process (Gunawardane and Annersten, 1987). Potassium could be incorporated by partially replacing the sodium hydroxide by potassium hydroxide. The economics of the process or feasibility of industrial scale manufacture is uncertain.
- Enhancement of apatite dissolution in the presence of pyritiferous peat (high-sulphur peat) from a large peat deposit at the coast of Sri Lanka (Dahanayake et al., 1991; Gunawardane, 1987a), and in coir dust (a waste product from the coconut fibre industry) (Van Straaten and Perera, 1995). EPR and peat are mixed in a 1:1 ratio and cured for 2-3 months. Reaction between the EPR and peat is reported to be rapid up to 8 weeks but slow after that. The fertilizer product has 12% available P_2O_5, and 2% sulphur. Pot trials were reported to be in progress to test the agronomic efficiency of the peat-EPR mixture (Gunawardane, 1987a).
- Acidulation using locally produced hydrochloric acid instead of imported sulphuric acid. A disadvantage of this process is the highly hygroscopic nature of the bi-product calcium chloride, which causes problems during drying and storage (IGC Mining, 1999; Tennakone, 1988a). A process has been proposed whereby the calcium chloride is rendered insoluble by double decomposition with ammonium sulphate, which generates diammonium phosphate, ammonium chloride and calcium sulphate (Tennakone, 1988b; Tennakone et al., 1988).
- Acidulation of the high quality fraction of Eppawala ore with nitric acid (70%) at approximately the stoichiometric level needed to generate dicalcium phosphate. The reaction products are mixed

with ground ammonium sulphate to yield a dry, non-hydroscopic solid containing almost all phosphorus in the "available" form (i.e. approximately 80% water soluble and approximately 90%, 2% citric acid soluble). Reversion is negligible, as demonstrated by a decrease in water soluble P_2O_5 of less than 1% after 6 months' storage (Tennakone and Weragama, 1992).

- Partial acidulation with sulphuric acid or by mixing with finely ground elemental sulphur inoculated with sulphur oxidising bacteria (Ranatunga, 1988; Silva, 1988). Imported 95% H_2SO_4 costs US$90/mt (1989 price) in Sri Lanka, so production of PAPR may cost more than imported TSP and may not be of economic benefit (Appleton, 1994).
- Dehalogenation of EPR by heating to 900-1300^oC in the presence of steam. The removal of Cl is reported to be greater than F. IFDC (unpublished report) found that calcination at 900-1000^oC in the presence of steam reduced the Cl content but not to the 500 ppm level required for wet process acid production. Total removal of Cl occurs when the EPR is heated with soda ash at 1100^oC (Gunawardane and Annersten, 1987).
- Dissolution by organic acids (Sagoe et al., 1998a; Sagoe et al., 1998b). The ability of tartaric and oxalic acids to dissolve effectively the PRs was attributed to the formation of an insoluble calcium compound which was precipitated from the solution. Oxalic or tartaric acid could be used to improve the P availability of PRs to plants with favourable residual effects in terms of available P and soil pH, without exerting any adverse effects on plant growth or nutrient acquisition.

None of these procedures appear to have been developed beyond the experimental stage.

Recent plans by IMC-Agrico and Tomen Corporation of Japan to develop a major mine at Eppawala have led to major protests by local people concerned about the possible environmental impacts of the mine which is planned to cover 56 km^2. The project envisages the development of a 1 million tpa phosphate rock mine with an estimated capital cost of $425 million. Ownership of the Lanka Phosphates venture is shared between IMC Agrico (65%), Tomen Corp. (25%) and the Sri Lankan Government (10%) (Anon., 2000). A processing plant, sulphuric and phosphoric acid plants, and a granulation plant are planned for a 450 acre site at Trincomalee (www.twnside.org.sg/title/deal-cn.htm). A Supreme Court judgement in June 2000 is reported to have ordered the Government to desist from going ahead with the phosphate-mining project.

Sources:(Anon., 1985 ; Appleton, 1989; Appleton, 1994; Dahanayake and Subasinghe, 1988; Dahanayake and Subasinghe, 1989a; Dahanayake and Subasinghe, 1991; Gunawardane, 1982; Gunawardane, 1987b; Gunawardane and Annersten, 1987 ; Herath, 1975; IFDC, 1980; Jayawardena, 1988; Jayawardena, 1989; Jayawardena, 1976; Jayawardena, 1980; Jayawardena, 1986; Maene, 2001; Notholt, 1994; Sagoe et al., 1998a; Sagoe et al., 1998b; Santhy and Kothandaraman, 1988; Silva, 1988; Silva, 1983; Southgate, 1986a; Southgate, 1986b; Tazaki et al., 1986; Tennakone, 1988a; Tennakone, 1988b; Tennakone et al., 1988; Tennakone and Weragama, 1992; Weerasuriya et al., 1992a)

Agronomic testing and use

Eppawala phosphate rock is used extensively in compound fertilizers for the plantation sector in Sri Lanka along with imported phosphate rock (IPR) from Egypt, Christmas Island and Israel. PR is used on the acid soils of the tea and rubber plantations because the soils have a high P-fixation capacity for water soluble phosphorus. A slow release source of P is therefore preferred.

The response to P in plantation crops is not as significant as N, K, Mg and Zn but the level of P fertility in the soil can be economically maintained using EPR. The Tea Research Institute of Sri Lanka (TRI) recommend the use of EPR except in nursery tea. Although very little or no response to P applied as rock phosphate has been recorded in the Sri Lankan tea plantations, P application is recommended in order to replace P removed in the harvested crop (3.0 to 4.5 kg $ha^{-1}yr^{-1}$) and to reduce the potential for antagonistic effects on the uptake of other nutrients such as N and K (TRI, 1986). The recommendation by the TRI that EPR should be substituted for IPR was based on chemical reactivity tests and a greenhouse experiment with young tea (Sivasubramaniam et al., 1981). Phosphate rock is particularly suitable for tea because of the enhanced rate of release of P in the very acid soils which is further augmented by malic acid exudates of the tea plant roots (Aiyadurai and Sivasubramanian, 1977; Golden et al., 1981a; Golden et al., 1981b; Jayman and Sivasubramanian, 1975; Jayman and Sivasubramanian, 1980; Sivasubramaniam et al., 1981).

The Rubber Research Institute of Sri Lanka recommend the use of Eppawala rock phosphate as the only source of phosphate for rubber in production in Sri Lanka. In fact only 36% substitution of EPR for IPR has been achieved in the rubber sector whereas 73% substitution has been achieved for tea. In 1987, 13,600 t of EPR and 5,500 t of IPR were used for tea and 3,400 t EPR and 6,800 t IPR for rubber (Ranatunga, 1988). The more reactive imported rock phosphate (IPR) is recommended for immature rubber and nursery tea plants (Liyanage and Pereis, 1984; Peries and Fernando, 1983; Silva, 1988; Yogaratnam, 1988). Response to P applied to mature rubber trees is not very great and P-fertilizer is applied partly as an insurance policy and partly on the basis of nutrient cycle information.

In the higher pH soils of the coconut growing areas, where phosphate fixation is less of a problem, a more soluble form of P fertilizer is preferred (Yogaratnam, 1988 1988). In 1987, 9,800 mt of imported (Middle East) PR, 1,500 mt of EPR and 7,100 mt of TSP were used for coconut. Imported PR is also preferred for coffee.

Although annual crops, such as paddy, require a fertilizer with high water solubility in order to produce maximum yields, Santhy and Kothandaraman (1988) have demonstrated that EPR mixed 1:1 with superphosphate (TSP) proved to be a more effective and cheaper source of phosphorus than TSP alone. EPR-TSP is recommended for rice-rice-pulse cropping systems (Appleton, 1994). Dahanayake (1995a) examined the potential of Eppawala apatite as a directly applied low-cost fertilizer for rice production in Sri Lanka. In the second rice crop, residues of selectively mined primary apatite crystals (SERF) produced larger rice yields and bicarbonate-extractable P than TSP for the first crop. Imported TSP is four times more expensive than SERF which may, therefore, be a more profitable alternative fertilizer to TSP for rice on Sri Lankan acid soils. The enhanced response to SERF occurred because it has relatively high citric soluble P_2O_5 as well as higher total P_2O_5 (35 to 42%) and lower R_2O_3 contents (around 1%) than the matrix of the secondary phosphate ore (Dahanayake, 1995; Dinalankara, 1995).

Zoysa et al. (1998a) examined the effect of forms of nitrogen supply on mobilisation of phosphorus from a phosphate rock and acidification in the rhizosphere of tea. The ammonium sulphate treatment had the highest dissolution rate of Eppawala phosphate rock in the rhizosphere, whereas calcium nitrate treatment had the lowest, reflecting the degree of acidification in the rhizosphere. The study revealed that the use of the NH^{4+} form of fertiliser can increase acidification in the tea rhizosphere compared with bulk soil and this can enhance the effectiveness of PR fertiliser utilisation by tea plants.

Zoysa et al. (1998b) evaluated phosphate rock dissolution and transformation in the rhizosphere of tea (*Camellia sinensis L.*) compared with calliandra (Calliandra calothyrsus L.), Guinea grass (Panicum maximum L.) and bean (Phaseolus vulgaris L.) by studying the changes in the concentration of P fractions at known distances from the root surface in an acidic (pH in water 4.5) ultisol from Sri Lanka treated with a phosphate rock. All plant species acidified the rhizosphere and caused more rock to dissolve in the rhizosphere (10-18%) than in the bulk soil (8- 11%). Guinea grass was most effective but tea produced the largest rate of acidification per unit root surface area. The external P efficiencies (mg total P uptake) of Guinea grass, bean, tea and calliandra in soil fertilized with phosphate rock were 4.82, 4.02, 1.06 and 0.62, respectively, and the corresponding internal P efficiencies (mg shoot dry matter production per mg plant P) were 960, 1623, 826 and 861. This study showed that the various crops cultivated in tea lands differ in their rates of acidification, phosphate rock dissolution and P transformation in the rhizosphere. Zoysa et al. (1998b) recommended further testing under field conditions.

Zoysa et al. (1999) also investigated the phosphorus utilisation efficiency and depletion of phosphate fractions in the rhizosphere of three tea (Camellia sinensis L.) clones.Some clones had higher external P efficiency due to greater root surface area whereas others had higher internal P efficiency (shoot dry matter production per unit plant P). In future tea breeding programmes, Zoysa et al. (1999) recommended that attempts should be made to combine these two traits to maximise P utilisation efficiency from tea clones.

Sources:(Aiyadurai and Sivasubramanian, 1977; Appleton, 1989; Appleton, 1994; Dahanayake, 1995; Dahanayake et al., 1995a; Dahanayake et al., 1991; Dahanayake et al., 1995b; Dinalankara, 1995; Golden et al., 1981a; Golden et al., 1981b; Gremmillion et al., 1975; Gunawardane, 1987a; ICRISAT, 2000; Jayman and Sivasubramanian, 1975; Jayman and Sivasubramanian, 1980; Liyanage and Pereis, 1984; Niwas et al., 1987 ; Perera and Van Straaten, 1994; Peries and Fernando, 1983; Ranatunga, 1988; Sagoe et al., 1998a; Sagoe et al., 1998b; Sivapalan, 1988; Sivasubramaniam et al., 1981; TRI, 1986; Van Straaten and Perera, 1995; Weerakoon et al., 1992; Yogaratnam, 1988; Zoysa et al., 1998a; Zoysa et al., 1998b; Zoysa et al., 1999)

Thailand

Location, Quantity, Quality

<u>Devonian</u>

Marine phosphorite of Devonian age in the Fang-Chiang Dao area of northern Thailand, 90 km north of Chiang Mai, is of considerable geological interest as it is the first marine sedimentary phosphate deposit to have been found in the country (Bunopas et al., 1986). Beds of laminated phosphorite 0.2-4 cm thick and averaging 14% P_2O_5, are associated with chert and black shale, which contains phosphatic nodule beds up to 1 m thick (29% P_2O_5). Preliminary resource estimates indicate about 4 Mt and 2 Mt of laminated and nodular rock, respectively.

<u>Recent</u>

Eight small deposits thought to have been derived from guano occur in Palaeozoic limestone caves, though the occurrences are generally too small and scattered to be of much commercial interest. The phosphate deposits were probably formed by the replacement of limestone by phosphatic solutions derived from sea-bird guano, probably during Pleistocene times. The guano deposits range from 3,000 to 150,000 tonnes with 14 to 36% P_2O_5 (Boonampol and Cholitkul, 1995). Kanchanaburi is the largest

(150,000 tonnes with 14 to 34% P_2O_5) followed by the Mae Tha (Lamphun) deposit (50,000 tonnes with 36% P_2O_5) and the Chon Daen and Wichianburi deposits in the Phetchbun area (27,000 tonnes with 20 to 35% P_2O_5) (Boonampol and Cholitkul, 1995; Savage, 1987).

Production

Phosphate rock production was approximately 5,000 tpa between 1983 and 1987, equally divided between the Lamphun and Kanchanaburi areas (Boonampol and Cholitkul, 1995). More than 9,000 tonnes was produced in 1995 but production in the period 1996-1999 has been fairly stable in the range 3,000 to 3,800 tonnes (Table 2). In 1981, 43,000 tonnes of local and imported phosphate rock was used by small-scale fertilizer producers (50%), farmers (25%), rubber plantations (15%) and other agencies (20%) (Boonampol and Cholitkul, 1995). More recent consumption figures are not readily available.

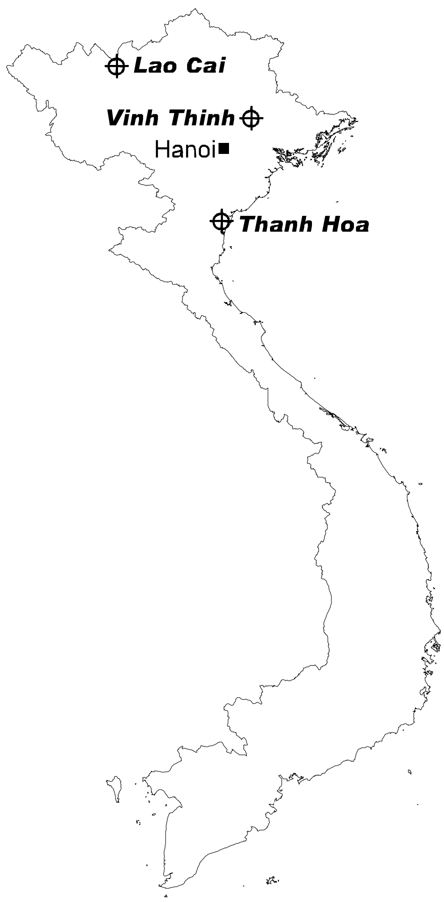
Sources:(ESCAP, 1986; Notholt, 1994)

Agronomic testing and use

Imported Christmas Island PR has been used for 30 years on the rubber plantations of Thailand. Boonampol and Cholitkul (1995) summarise the results of agronomic trials carried out with imported and local PR on a range of crops including rice, soybean, maize, sorghum, groundnuts, cassava and cotton. Use of reactive (imported) PRs on acid, low P, upland soils demonstrated significant economic yield increases. Direct application of PR to paddy rice grown on acid sulphate soils was also reasonably effective if properly managed (Boonampol and Cholitkul, 1995).

Sources: (Attanandana et al., 1998; Bhuthorndharaj and others, 1998) (Boonampol and Cholitkul, 1995)

Vietnam



Location, Quantity, Quality

Phosphate deposits have been known for many years in various parts of North Vietnam, but their economic development was hindered mainly by their relatively inaccessible location, irregular mode of occurrence and low grade. Large reserves of high-grade rock occur near Lao Cai, close to the Chinese province of Yunnan, and deposits in this area have been worked since 1940 (Notholt, 1999). The Lao Cai deposits, which lie about 260 km north-west of Hanoi, are estimated to contain at least 1,000 million tons of apatite rock containing between 30 and 40% P_2O_5. Proven reserves are estimated to be 505 Mt of which 26 Mt is high grade (36-41% P_2O_5) (USGS Mineral Yearbook, 2000). R_2O_3 is about 4%. Substantial quantities of lower grade rock undoubtedly occur. The deposits occur as thick lenses and extensive layers interstratified with micaceous or graphitic schist, quartzite, calc-schist and crystalline limestone in the upper half of the Late Precambrian Camduong Formation (Dinh, 1986).

Secondary phosphorite deposits are widespread in Devonian and Carboniferous karstic limestone trenches and caves (Dinh, 1986). The principal deposits are located near Vinh Thinh, 74 km north-east of Hanoi, and also at Thanh Hoa, Nghetinh, Caobang, Vinhphu and Hoanglienson, situated between 130 and 250 km south of Hanoi. The deposits are considered to be supergene accumulations and replacement deposits. Vinh Thinh contained estimated reserves of 150,000 tons of earthy phosphate (up to 16% P_2O_5) and 50,000 tons of blocks of phosphatized limestone containing 14 to 37% P_2O_5 with 5-15% Al_2O_3 and 2-6% Fe_2O_3.The phosphate was transported by rail to Haiphong for crushing, drying and grinding to obtain a product containing 16 to 20% P_2O_5. Most of the rock appears to be ground for use as direct application fertilizer at nearby treatment plants

Guano deposits are found only on the islands of the Hoangsa and Truongsa archipelagos (Dinh, 1986). Reserves of concretionary phosphorite in the Hoangsa archipelgo amount to 4.7 Mt with more than 20% P_2O_5, whereas estimated reserves in the Truongsa archipelgo are 0.74 Mt with 17.5% P_2O_5 (Dinh, 1986).

Production

Large-scale production at Lao Cai started in 1957 when about 55,000 tons was produced. Production between 1961 and 1966 has risen from 565,000 tons to over 900,000 tons. In the last few years (1995-1999), production has ranged between 500,000 and 700,000 tonnes (Table 2).

In the 1960's single superphosphate was manufactured at Viet Tri, on the Hanoi-Kunming railway, 130 miles south-east of Laokay, where there was a plant with an estimated annual capacity of 100,000 tons of 20 to 21% P_2O_5 superphosphate (Notholt, 1999). Most of the high grade rock is now shipped to the Lam Thao superphosphate fertilizer plant in Phu Tho Province whilst the low grade rock is used in other fertilizer plants. Annual phosphate fertilizer production is estimated to be 795,000t (Industrial Minerals, 1996).

Sources: (Notholt and Sheldon, 1986; Savage, 1987; Van Chien, 1995)

Agronomic testing and use

No record has been found of agronomic testing of the phosphate resources of Vietnam.

Sources: P requirements and recommendations (Phan thi Cong and others, 1998; Truong and Montange, 1998; Vo Dinh Quang and others, 1998).

SUMMARY

A summary of the quantity, quality (%P_2O_5), past/current production, agronomic testing, use and development potential of the phosphate resources of India, Nepal, Pakistan and southeast Asia, together with their type and geological age, is provided in the following Table.

Country	Deposit	Type	Geological age	Quantity of resources Mt)	Average (range) P_2O_5	Current (Past) production ('000mt)	Agronomic testing	Current (past) use	Development potential
Cambodia	Phnom Thom	Sed	Carb-Permian	0.3	23	(<1)	rice		low - production stopped 1990
Cambodia	Tuk Meas	Sed	Carb-Permian	0.3	17	(3)	rice	(rice)	low - production stopped 1991
Christmas Island	Christmas Island	Sed	Quaternary	214	28-37	1842			major phosphate mine in production
India	Barabhu	Meta	Precambrian	9.5	8-13				low
India	Birmania	Sed	Precambrian	2.5	10-18				low
India	Cumbum-Cuddapah	Sed	Precambrian	3.5-4.5	20-30				low
India	Fategarh	Sed	Jurassic	?	5-15				low
India	Hirapur	Sed	Precambrian	13-22	20-23	13-25			phosphate mine in production
India	Jhabua	Sed	Precambrian	7-26.6	20-28	58-90			phosphate mine in production
India	Jhamarkotra	Sed	Precambrian	80	15->30	285-850	rice	Direct application	major phosphate mine in production
India	Kanpur	Sed	Precambrian	8	10-30	25			phosphate mine in production
India	Kasipatnam	Meta	Precambrian	0.22-2.6	25-42	(v small)			small scale production
India	Khasi-Jainita	Ign	Cretaceous	1.7	10				low
India	Lalitpur	Sed	Precambrian	6.3-9	15-25	50			phosphate mine in production
India	Maton	Sed	Precambrian	6-35	12-35	95-100	rice	Direct application	major phosphate mine in production
India	Mussoorie	Sed	Cambrian	45	16-22	130	tea, coffee, rubber, coconut, cashew nuts, cardamon, orchard fruit, rice, groundnut, wheat, soyabean, gram, jute, lentils, millet, moong-bean,	Direct application for tea, coffee, rubber, coconut, cashew nuts, cardamon, orchard fruit, paddy rice, groundnut, wheat, soyabean, potato, millet and gram	major phosphate mine in production

Country	Deposit	Type	Geological age	Quantity of resources Mt)	Average (range) P_2O_5	Current (Past) production ('000mt)	Agronomic testing	Current (past) use	Development potential
							pasture, potato, sorghum		
India	Pithoragarh	Sed	Precambrian	?	?				resources not yet defined
India	Purulia	Meta	Precambrian	3.5	18-25	15	?	Direct application	phosphate mine in production
India	Sevathur	Ign	Precambrian	small					low
India	Singhbhum	Meta	Precambrian	2.5-10	7-25				low
India	Tiruchirapally	Sed	Cretaceous	8	30				low
India	Udaipur (region)	Sed	Precambrian	143					major phosphate rock producing region
India	Valdavur	Sed	Cretaceous	?	30				low
Indonesia	Kandangan	Guano	Recent	0.075	12-37	<1	?	Plantation crops	small scale production
Indonesia	Kromong Mts.	Guano	Recent	?	?	(small)		(Plantation crops)	small scale production
Indonesia	Lamongan	Guano	Recent	0.186	31	<1	?	Plantation crops	small scale production
Indonesia	Pati	Guano	Recent	0.119	10-38	<1	?	Plantation crops	small scale production
Malaysia	Gomanton	Guano	Recent	0.01	10-21	(small)		?	small scale production
Malaysia	Madai	Guano	Recent	0.01	?	(small)		?	small scale production
Malaysia	Niah	Guano	Recent	0.03	23	(small)		?	small scale production
Malaysia	Perlis	Guano	Recent	0.05	2-36	(small)		(rice)	small scale production
Nepal	Baitadi	Sed	Precambrian		10-32				resources not yet defined
Nepal	Bajhang	Sed	Precambrian		15-20				resources not yet defined
Nepal	Barahkshetra	Sed	Precambrian		<5				resources not yet defined
Nepal	Khulia Khola	Sed	Eocene		>4.5				resources not yet defined
Pakistan	Hazara	Sed	Cambrian	7-22	9-29	(73*)			Closed phosphate mine awaiting joint venture capital

Country	Deposit	Type	Geological age	Quantity of resources Mt)	Average (range) P_2O_5	Current (Past) production ('000mt)	Agronomic testing	Current (past) use	Development potential
Pakistan	Loe Shilman	Ign	Tertiary	59-200	5				not suitable for direct application
Philippines	Bantigue	Guano	Recent	0.8	15		rice		low
Philippines	Imelda	Sed	Tertiary	1					low
Sri Lanka	Eppawala	Resi	Mesozoic-Tertiary	60	33	20	tea, rubber, coconut, coffee, rice, pulses	tea, rubber	Proposals for 1 million tpa mine under consideration
Sri Lanka	Ridigama	Resi	Mesozoic-Tertiary	?	16-39				Unlikely to be developed until Eppawala resources exhausted
Thailand	Fang-Chiang Dao	Sed	Devonian	6	14				low
Thailand	Kanchanaburi	Guano	Recent	0.15	14-34	1-2	rice, soybean, maize, sorghum, groundnuts, cassava and cotton	rubber	small scale production
Thailand	Lamphun	Guano	Recent	0.05	36	1-2	-ditto-	rubber	small scale production
Thailand	Phetchbun	Guano	Recent	0.03	20-35				low
Vietnam	Lao Cai	Sed	Devonian	100	35	700			Used for manufacture of superphosphate fertilizer
Vietnam	Thanh Hoa	Guano	Recent	<0.01					low
Vietnam	Vinh Thinh	Guano	Recent	0.2	15-37				low

Deposit type: Sed = sedimentary; Ign = igneous; Meta = metamorphic; Resi = residual
* = production in 1984

BIBLIOGRAPHY

Aiyadurai, S. and Sivasubramanian, S., 1977. The influence of types of phosphatic fertilizers on the growth and nutrient uptake of tea nursery plants Tea Quarterly, 47 (1&2): 23-27.

Anon., 1985 Phosphate fertilizer from Sri Lankan apatite Mining Magazine, 125: 9-11.

Anon., 1989. Asia; introduction. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 437-442.

Anon., 2000. Sri Lankan phosphate controversy. Fertilizer International, 376(May/June): 24.

Appleton, J.D., 1989. African Carbonatites and Agrogeology Projects: Visit to Sri Lanka, March 1989. Technical Report WC/89/09/R, British Geological Survey, Nottingham.

Appleton, J.D., 1990. Agrogeology Project: Report on visits to Pyrites, Phosphates & Chemicals Ltd. (New Delhi and Dehradun) and the University of Orissa, India. March 1990. Technical Report WC/90/09/R, British Geological Survey, Nottingham.

Appleton, J.D., 1994. Direct-application fertilizers and soil amendments; appropriate technology for developing countries? In: S.J. Mathers and A.J.G. Notholt (Editors), Industrial minerals in developing countries. Geosciences in International Development Report. Association of Geoscientists for International Development, c/o Asian Institute of Technology, [location varies], International, pp. 223-256.

Appleton, J.D. et al., 1991. Potential use of phosphate resources from African carbonatites as low cost direct application fertilizers. In: D.A.V. Stow and D.J.C. Laming (Editors), Geosciences in International Development. AGID Report Series Balkema, Rotterdam, pp. 181-190

Arulandoo, X. and Bidin, A., 1998. P12. Long-term Evaluation of Three Phosphate Sources for Rice in Malaysia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Attanandana, T., Sritanyarat, W. and Na Ranong, R., 1998. P14. Rock Phosphate Availability in Rice-Growing Acid Sulphate Soils of Thailand. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Bado, V.B. and Hien, V., 1998. Agronomic efficiency of rock phosphate inputs on upland rice in Oxisols. Cahiers d'études et de recherches francophones / Agricultures, 7(3): 235.

Banerjee, D.M., 1986a. Proterozoic and Cambrian phosphorites - regional review: Indian subcontinent. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge University Press, Cambridge, pp. 70-90.

Banerjee, D.M., 1986b. Regional review; Indian subcontinent. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 70-90.

Banerjee, D.M., 1987. Environmental impact of phosphate mining in India. Journal of the Geological Society of India, 30(5): 439-450.

Banerjee, D.M., Khan, M.W.Y., Srivastava, N. and Saigal, G.C., 1982. Precambrian Phosphorites in the Bijawar Rocks of Hirapur-Bassia Areas, Sagar District, Madhya-Pradesh, India. Mineralium Deposita, 17(3): 349-362.

Banik, S., Bhattacharyya, S.K. and Pandey, S.N., 1989. Rock phosphate as a substitute for single superphosphate in tossa jute (Corchorus-olitorius) cultivation. Indian Journal of Agricultural Sciences, 59(10): 676-679.

Baon, J.B. and Wibawa, A., 1998. P18. Enhancing Phosphate Rock Use in Coffee and Cocoa Plantations by VA Mycorrhiza in Indonesia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Belmehdi, A. and Nyiri, K.F., 1990. Phosphorus fertilizer use in Asia and Oceania, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 85-96.

BGS, 2001. World Mineral Statistics 1995-99, British Geological Survey, Keyworth, Nottingham.

Bhardwaj, K.K.R. and Kanwar, K., 1991. Utilization of Wild Sage (Lantana-Camara Var Aculeata) as Green-Manure and Raw-Material for Composting. Indian Journal of Agricultural Sciences, 61(12): 898-903.

Bhardwaj, S.K., Sharma, C.M. and Kanwar, K., 1996. Effect of rock phosphate on yield and nutrient uptake in rice (Oryza sativa) and its residual effect on linseed (Linum usitatissimum). Indian Journal of Agronomy, 41(1): 35-37.

Bhuthorndharaj, S. and others, 1998. P24. Effect of Lime and Gypsum on Nutrient Dynamics in a Sandy Soil in Thailand. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Biswas, B.C. and Das, S.K., 1995. Fertilizer use in Indian agriculture with emphasis on phosphate rock. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 199-207.

Biswas, D.R., Rao, A.S. and Ganeshamurthy, A.N., 1996. Mobilization of rock phosphate phosphorus using fresh cowdung and pyrite. Indian Journal of Agricultural Sciences, 66(2): 86-90.

Bolland, M.D.A., 1993. Summary of Research on Soil Testing for Rock Phosphate Fertilizers in Western-Australia. Fertilizer Research, 35(1-2): 83-91.

Bolland, M.D.A., Clarke, M.F. and Yeates, J.S., 1995. Effectiveness of Rock Phosphate, Coastal Superphosphate and Single Superphosphate for Pasture on Deep Sandy Soils. Fertilizer Research, 41(2): 129-143.

Boonampol, P. and Cholitkul, W., 1995. Phosphate rock as a fertilizer in Thailand. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 245-251.

Bramley, R.G.V., 1990. Cadmium in New-Zealand Agriculture. New Zealand Journal of Agricultural Research, 33(4): 505-519.

Brown, S., Schreier, H., Shah, P.B. and Lavkulich, L.M., 1999. Modelling of soil nutrient budgets: an assessment of agricultural sustainability in Nepal. Soil Use and Management, 15(2): 101 (10 pages).

Bunopas, S., Maranate, S. and Lamchuan, A., 1986. The discovery of Devonian marine phosphate rocks in Thailand, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 275-279.

Burnett, W.C., 1981. Growth rates of ocean floor phosphorites. In: S. Nath and Benerjea (Editors), Fourth international field workshop and seminar on phosphorite. International Field Workshop and Seminar on Phosphorite: Abstracts. [International Geological Correlation Programme, Project 156], International, pp. 35.

Chahal, R.S., Gupta, A.P. and Singh, S., 1981. Relative efficiency of super-phosphate and rock phosphate with and without FYM and iron pyrite. Indian Journal of Agronomy, 26(4): 403-407.

Chakravorty, S.L., 1993. Rock phosphate as a direct application fertilizer: a success story from India, Bulletin International Agency for Small-Scale Mining, pp. 11-13.

Chien, S.H., Sale, P.W.G. and Hammond, L.L., 1990. Comparison of the effectiveness of phosphorus fertilizer products, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 143-156.

Choudhuri, R., 1989. Proterozoic phosphorites around Udaipur, Rajasthan, India. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 461-466.

Choudhuri, R. and Roy, A.B., 1986. Deposits; Jhamarkotra, Rajasthan, India. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 202-219.

Cook, P.J., Banerjee, D.M. and Southgate, P.N., 1990. The phosphorus resources of Asia and Oceania, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 97-114.

Cullen, D.J., 1988. The submarine phosphate resource on central Chatham Rise. DMFS Reports, 2: 1-22.

Dahanayake, K., 1995. Geological and geochemical aspects of Eppawala and Ridigama phosphate deposits of Sri Lanka. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 143-151.

Dahanayake, K., Ratnayake, M.P.K. and Sunil, P.A., 1995a. Potential of Eppawala Apatite as a Directly Applied Low-Cost Fertilizer for Rice Production in Sri-Lanka. Fertilizer Research, 41(2): 145-150.

Dahanayake, K., Senaratne, A., Subasinghe, S.M.N.D. and Liyanaarachchi, A., 1991. Potential Use of Naturally-Occurring Sulfuric-Acid to Beneficiate Poorly Soluble Phosphate from Eppawala, Sri-Lanka. Fertilizer Research, 29(2): 197-201.

Dahanayake, K. and Subasinghe, S.M.N.D., 1988. Development of recent stromatolitic structures and phosphatic enrichment in Precambrian marbles of Sri Lanka. Economic Geology, 83: 1468-1471.

Dahanayake, K. and Subasinghe, S.M.N.D., 1989a. A modern terrestrial phosphorite - an example from Sri Lanka. Sedimentary Geology, 61: 311-316.

Dahanayake, K. and Subasinghe, S.M.N.D., 1989b. Secondary phosphate mineralization in a karstic environment in central Sri Lanka. Mineralium Deposita, 24(3): 169-175.

Dahanayake, K. and Subasinghe, S.M.N.D., 1991. Mineralogical, chemical and solubility variations in the Eppawala phosphate deposit of Sri Lanka - a case for selective mining for fertilizers. Fertilizer Research, 28(2): 233-238.

Dahanayake, K., Van Kauwenberg, S.J. and Hellums, D.T., 1995b. Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. IFDC Special Report SP-24, Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka (IFC), Muscle Shoals, Alabama, USA (IFDC).

Das, B.K., 1999. Environmental pollution of Udaisagar lake and impact of phosphate mine, Udaipur, Rajasthan, India. Environmental Geology, 38(3): 244-248.

Das, M., Singh, B.P., Ram, M. and Prasad, R.N., 1991. Response of maize (Zea-mays) to phosphorus-enriched manures grown in P-deficient alfisols on terraced land in Meghalaya. Indian Journal of Agricultural Sciences, 61(6): 383-388.

Debnath, N.C. and Basak, R.K., 1986. Evaluation of the Fertilizer Value of Some Indigenous Rock Phosphates and Basic Slag of India. Fertilizer Research, 8(3): 241-248.

Dev, G., 1998. 12. Use of Phosphate Rock in Food Grain Production under Irrigated and Rainfed Conditions in India. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

DFID, 1995. Sustainable Agriculture Strategy. http://193.32.28.27/public/what/advisory/group6/rld/sassum.html

Dinalankara, D.M.S.K., 1995. Eppawala phosphate deposit of Sri Lanka - present status. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 153-163.

Dinh, H.N., 1986. Mineral deposits for fertilizers in Vietnam, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 280-284.

Dissanayake, D.M.A.P., 1995. Direct application of phosphate rock in Sri Lankan agriculture with special reference to rubber. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 3-8.

Dubey, S.K., 1996a. Combined effect of Bradyrhizobium japonicum and phosphate- solubilizing Pseudomonas striata on nodulation, yield attributes and yield of rainfed soybean (Glycine max) under different sources of phosphorus in Vertisols. Indian Journal of Agricultural Sciences, 66(1): 28-32.

Dubey, S.K., 1996b. Influence of phosphorus-solubilizing micro-organisms on P availability to soybean (Glycine max) through superphosphate and rock phosphate in Vertisols. Indian Journal of Agricultural Sciences, 66(4): 246-249.

Dubey, S.K. and Agarwal, S., 1999. Effect of phosphate-solubilizing micro-organisms as single and composite inoculant on rainfed soybean (Glycine max) in Vertisol. Indian Journal of Agricultural Sciences, 69(8): 611-613.

ESCAP, 1986. Fertilizer Minerals in Asia and the Pacific. Mineral concentrations and hydrocarbon accumulations in the ESCAP region, 1. United Nations: Economic and Social Commission for Asia and the Pacific (ESCAP), Bangkok, Thailand, 284 pp.

Ghosal, P.K., Bhattacharya, B. and Bagchi, D.K., 1998. Direct and residual effect of rock phosphatic fertilizers on rice (Oryza sativa) grown on lateritic land in eastern India. Indian Journal of Agricultural Sciences, 68(4): 235-237.

Ghosh, S., 2001. Technologies for Utilisation of Low Grade Rock Phosphates as Fertilisers. http://www.tifac.org.in/offer/tlbo/rep/TMS161.htm

Giri, G., 1993. Direct and Residual Effect of Nitrogen and Phosphorus Fertilization on Groundnut (Arachis-Hypogaea)-Wheat (Triticum- Aestivum) Cropping System. Indian Journal of Agronomy, 38(1): 6-12.

Golden, D.C., Sivasubramaniam, S. and Fonseka, J.P., 1981a. Effect of nitrogen fertilization on soil solution composition, acidity and nutrient leaching in acid red-yellow podzolic soils. Tea Quarterly, 50(3): 105-116.

Golden, D.C., Weed, S.B., Sivasubramaniam, S. and Nalliah, P., 1981b. Studies on the performance of two phosphatic fertilizers on tea soils with respect to the P-adsorption, mineralogy and plant species using 32P labelled fertilizer. Tea Quarterly, 50(2): 50-60.

Gopalakrishnan, B. and Palaniappan, S.P., 1992. Effectiveness of Mussoorie Rock-Phosphate with Solubilizing Agents in Soybean (Glycine-Max). Indian Journal of Agricultural Sciences, 62(6): 387-390.

Gough, L.P. and Herring, J.R., 1993. Geologic Research in Support of Sustainable Agriculture. Agriculture Ecosystems & Environment, 46(1-4): 55-68.

Gremmillion, L.R., McClellan, G.H. and Lehr, J.R., 1975. Characterisation of phosphate rock from Sri Lanka. Unpublished report, IFDC.

Gunawardane, R.P., 1982. Some studies on the reaction of apatite with soda ash and quartz. Journal National Science Council of Sri Lanka, 10(2): 181-194

Gunawardane, R.P., 1987a. Eppawala apatite - Mthururajawela peat mixture as a P-fertilizer. . Proceedings Sri Lanka A.A.S., 43

Gunawardane, R.P., 1987b. Studies on chlorine and fluorine in Eppawala apatite. Journal National Science Council of Sri Lanka, 15(1): 87-99

Gunawardane, R.P. and Annersten, H., 1987 Fertilizer from Eppawala apatite: conversion using alkali hydroxide and quartz. Journal National Science Council of Sri Lanka, 15(2).

Gupta, R., Aparna, Shanker, B., Saxena, R.K. and Kuhad, R.C., 1993. Solubilization of Low-Grade Indian Rock Phosphates and Inorganic Phosphates by Bacillus-Licheniformis. Folia Microbiologica, 38(4): 274-276.

Gyaneshwar, P., Kumar, G.N. and Parekh, L.J., 1998. Effect of buffering on the phosphate-solubilizing ability of microorganisms. World Journal of Microbiology & Biotechnology, 14(5): 669-673.

Hajra, J.N., Manna, M.C. and Kole, S.C., 1992. Preparation and Evaluation of Enriched City Compost in an Alluvial Soil. Indian Journal of Agricultural Sciences, 62(8): 540-544.

Hanafi, M.M., Saifulbahari, A.R. and Peli, M., 1996. A new approach to the determination of phosphate rock dissolution in organic soils using graphite furnace atomic absorption spectrophotometry. Communications in Soil Science and Plant Analysis, 27(5-8): 1479-1499.

Hanafi, M.M. and Syers, J.K., 1994a. Agronomic and Economic Effectiveness of 2 Phosphate Rock Materials in Acid Malaysian Soils. Tropical Agriculture, 71(4): 254-259.

Hanafi, M.M. and Syers, J.K., 1994b. Plant Availability of 2 Phosphate Rock Materials in Acid Malaysian Soils. Communications in Soil Science and Plant Analysis, 25(19-20): 3171-3189.

Hanafi, M.M., Syers, J.K. and Bolan, N.S., 1992a. Effect of Lime on the Dissolution of 2 Phosphate Rocks in Acid Soils. Journal of the Science of Food and Agriculture, 60(2): 155-164.

Hanafi, M.M., Syers, J.K. and Bolan, N.S., 1992b. Leaching Effect on the Dissolution of 2 Phosphate Rocks in Acid Soils. Soil Science Society of America Journal, 56(4): 1325-1330.

Harjanto, S., 1986. Phosphate deposits in Indonesia, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 191-197.

Harliyah, I., 1995. Study of phosphorus fertilizers for rice and soybean on upland acid soils in Indonesia. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 209-214.

Hasan, M.T., 1986. Deposits; Hazara, Pakistan. In: J. Cook and J. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 190-201.

Hasan, M.T., 1989. Cambrian phosphorite deposits of the Hazara Division, North West Frontier Province, Pakistan. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 449-454.

Hasan, M.T. and Asrarullah, 1989. Phosphate (apatite) resources in the Loe Shilman Carbonatite, Khyber Agency, North West Frontier Province, Pakistan. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 455-457.

Hedley, M.J., Hussin, A. and Bolan, N.S., 1990. New approaches to phosphorus fertilization, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 125-142.

Hellums, D.T., 1995. Phosphorus and its role in crop production in Asia. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 9-13.

Henao, J. and Baanante, C.A., 1999. An Evaluation of the Strategies to Use Indigenous and Imported Sources of Phosphorus to Improve Soil Fertility and Land Productivity in Mali. IFDC Technical Bulletin T-48, IFDC, Muscle Shoals, Alabama.

Herath, J.W., 1975. Mineral resources of Sri Lanka. Sri Lanka Geological Survey

ICRISAT, 2000. Rapid composting of rice-straw (ICRISAT Project no. R1.01.05). http://www.icrisat.org/text/research/nrmp/r1.01.05.html; http://www.icrisat.org/text/research/nrmp/researchbriefs/resbrief%5Frupela.asp

IFDC, 1980. Technology of production and preliminary agronomic evaluation of speciality phosphates using Eppawela phosphate rock from Sri Lanka. International Developemnt Centre, Muscle Shoals, Alabama, USA

IGC Mining, 1999. Mining news of world impact. http://www.igc.org/mining/world.html#hot0825

IGCP and Geological Survey of India, 1981. Excursion Guidebook on Dehradun-Mussoorie area. Indian National Committee for IGCP Project 156 and the Geological Survey of India, Dehli, India, 53 pp.

IRRI, 1990. Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 478.
Ismail, Y.B., 1986. Production and imports of fertilizers in Malaysia, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 209-211.
Jaggi, T.N., 1982. Phosphate rock for direct application - Indian industry experience. AGS II-3 (iii): 1-33.
Jaggi, T.N., 1986. Use of Mussoorie phosphate rock as straight phosphatic fertilizer - Indian experience. In: J.K. Wachira and A.J.H. Notholt (Editors), Proceedings of the Seminar: Agrogeology in Africa. CSC Technical Publication Series No.226 [CSC(87)WMR-9]. London: Commonwealth Science Council, Zomba, Malawi, pp. 219-230.
Jaggi, T.N., 1995. Phosphate rocks and soil in India. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 91-98.
Jaggi, T.N., Awasthi, P.K. and Saha, S.K., 1986. Enhancing the agronomic efficiency of ground phosphate rock in India. In: J.K. Wachira and A.J.H. Notholt (Editors), Proceedings of the Seminar: Agrogeology in Africa. CSC Technical Publication Series No. 226 [CSC(87)WMR-9]. London: Commonwealth Science Council, Zomba, Malawi, pp. 209-218.
Jaggi, T.N. and Chulet, M.R., 1995. Maton phosphate rock from India: its potential for direct application. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 191-198.
Jana, B.B. and Das, S.K., 1992. Fertilizer Value of Mussoorie Phosphate Rock in Carp Culture. Israeli Journal of Aquaculture-Bamidgeh, 44(1): 13-23.
Jayawardena, D., 1988. The Eppawela rock phosphate project. , Economic Review People's Bank Research Department, Colombo, Sri Lanka, pp. 10-12.
Jayawardena, D.E., 1989. The phosphate resources of the Eppawala carbonatite complex, northern Sri Lanka. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 458-460.
Jayawardena, D.E.d.S., 1976. The Eppawala Carbonatite Complex in North-West Sri Lanka (Ceylon). Geological Survey Department of Sri Lanka, Colombo.
Jayawardena, D.E.d.S., 1980. The occurrence of rock phosphate deposits in Sri Lanka in relation to the Precambrian Basement. In: A.I.N. Lee (Editor), Fertilizer Mineral Occurrences in the Asia-Pacific Region. East-West Resource Systems Institute, Honolulu, pp. 78-86.
Jayawardena, D.E.d.S., 1986. The assessment of igneous apatite deposits in Sri Lanka for manufacture of high analaysis, water soluble phosphate fertilizer, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 234-242.
Jayman, T.C.Z. and Sivasubramanian, S., 1975. Release of bound iron and aluminium from soils by the root exudates of tea (Camellia sinensis) plants. Journal Science of Food and Agriculture, 26: 1895-1898.
Jayman, T.C.Z. and Sivasubramanian, S., 1980. The use of fertilizers for tea in Sri Lanka. 3-Foliar and soil analysis with particular reference to P, Ca and Mn. Tea Quarterly, 49(3-4): 137-141.
Johnston, A.E. and Syers, J.K. (Editors), 1998. Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Joo, G.H. and Soon, C.P., 1995. Direct application of phosphate rocks to plantation tree crops in Malaysia. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 59-76.
Khalil, S., 1995. Direct application of phosphate rock and appropriate technology fertilizers in Pakistan. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 231-236.
Khan, H.H., Ghosh, D.B., Soni, M.K., Sonakia, A. and Zafar, M., 1989. Phosphorite deposits of the Jhabua District, Madhya Pradesh, India. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 467-472.
Khan, H.H., Upadhyay, A.K. and Palanisamy, C., 2001. Usefulness of rock phosphate as an ideal carrier of phosphate to coconut and in the coconut based cropping system. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Khan, K., Khan, H.M., Tufail, M., Khatibeh, A.J.A.H. and Ahmad, N., 1998. Radiometric analysis of Hazara phosphate rock and fertilizers in Pakistan. Journal of Environmental Radioactivity, 38(1): 77-84.

Krishnareddy, S.V. and Ahlawat, I.P.S., 1996. Growth and yield response of lentil cultivars to phosphorus, zinc and biofertilizers. Journal of Agronomy and Crop Science-Zeitschrift Fur Acker Und Pflanzenbau, 177(1): 49-59.

Kumar, V., 1998. 7. Balanced Use of Plant Nutrients with Particular Reference to Integrated Plant Nutrient Systems in the Asian Region. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Lamplugh, G.W., 1902. Calcrete. Geological Magazine, 9(462): 575.

Lim, H.H. and Gilkes, R.J., 2001. Beneficiation of apatite rock phosphates by calcination: effects on chemical properties and fertiliser effectiveness. Australian Journal of Soil Research, 39(2): 397-402.

Ling, A.H., Harding, P.E. and Ranganathan, V., 1990. Phosphorus requirements and management of tea, coffee and cacao, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. IRRI, Philippines, pp. 383-398.

Liyanage, A.d.S. and Pereis, O.S., 1984. A practical guide to rubber planting and processing, Rubber Research Institute of Sri Lanka, Agalawatta, Sri Lanka.

Loganathan, P., Hedley, M.J. and Bretherton, M.R., 1994. The Agronomic Value of Co-Granulated Christmas Island Grade-C Phosphate Rock and Elemental Sulfur. Fertilizer Research, 39(3): 229-237.

Maene, L.M., 2001. Direct Application of Phosphate Rock: a Global Perspective of the Past, Present and Future. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Martínez, A., 1987. Alternativas de suministro de fertilizantes fosfatados. El caso de Colombia. In: L.A. León and O. Arregocés (Editors), Memorias del Seminario "Alternativas sobre el uso como fertilizantes de fosfatos nativos en América Tropical y Subtropical", 4 a 6 de Noviembre 1987. CIID, IFDC and CIAT, Cali, Colombia, pp. 222-242.

Marwaha, B.C., 1986. Direct and residual effect of Mussoorie rock phosphate on soybean grown in sequence with wheat in acid alfisol. Indian Journal of Agricultural Sciences, 56(2): 101-106.

Marwaha, B.C., Kanwar, B.S. and Tripathi, B.R., 1981. Direct and residual effectiveness of Mussoorie rock phosphate in wheat-maize rotation. Indian Journal of Agricultural Sciences, 51(12): 870-874.

Mathur, B.S. and Sarkar, A.K., 1998. P8. The Use of Phosphate Rock Material on Red and Lateritic Soils of Eastern India. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

McClellan, G.H. and Saavedra, F.N., 1986a. Proterozoic and Cambrian phosphorites - specialist studies: chemical and mineral characteristics of some Cambrian and Precambrian phosphorites. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 108-115.

McClellan, G.H. and Saavedra, F.N., 1986b. Specialist studies; Chemical and mineral characteristics of some Cambrian and Precambrian phosphorites. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 244-267.

McLaughlin, M.J., Dann, P.R., James, T.R. and Garden, D.L., 1992. Glasshouse Comparison of North-Carolina Phosphate Rock, Alkali- Treated Christmas Island Phosphate Rock and Single Superphosphate as P-Fertilizers on an Acidic Soil. Australian Journal of Agricultural Research, 43(7): 1667-1681.

Medhi, D.N. and DeDatta, S.K., 1996a. Phosphorus availability to irrigated lowland rice as affected by sources, application level and green manure. Nutrient Cycling in Agroecosystems, 46(3): 195-203.

Medhi, D.N. and DeDatta, S.K., 1996b. Residual effect of fertilizer phosphorus in lowland rice. Nutrient Cycling in Agroecosystems, 46(3): 189-193.

Melgar, R., Casco, J., Mendez, M., Sanabria, C. and Figueroa, M., 1998. Effectivity of phosphate fertilizers for flooded rice. Pesquisa Agropecuaria Brasileira, 33(10): 1573-1579.

Mishra, M.M., Kapoor, K.K. and Yadav, K.S., 1982. Effect of compost enriched with Mussoorie rock phosphate on crop yield. Indian Journal of Agricultural Sciences, 52(10): 674-678.

Mukherjee, S.K., Choudhuri, R. and Roy, A.H., 1986. Effects on impurities on processing Indian phosphate rock. Abstracts of Papers of the American Chemical Society, 192: 19-FERT.

Mutanal, S.M., Kumar, P., Joshi, V.R., Prabhakar, A.S. and Mannikeri, I.M., 1998. Effect of phosphorus and liming sources on rice (Oryza sativa) grain yield under transplanted conditions. Indian Journal of Agricultural Sciences, 68(9): 587-589.

Mutert, E.W. and Sri Adiningsih, J., 1998. 8. Tropical Upland Improvement: Comparative Performance of Different Phosphorus Sources. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Narsian, V. and Patel, H.H., 2000. Aspergillus aculeatus as a rock phosphate solubilizer. Soil Biology & Biochemistry, 32(4): 559-565.
Nassir, A., 2001. IMPHOS experience on direct application of phosphate rock in Asia. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.
Niwas, J.M., Dissanayake, C.B. and Keerthisinghe, G., 1987 Rocks as fertilizers: preliminary studies on potassium availability of some common rocks in Sri Lanka. Applied Geochemistry, 2: 243-246.
Notholt, A.J.G., 1980. World phosphate rock production, trade and developments. In: Anonymous (Editor), Proceedings of the Sixth session of the Committee on Natural Resources; incorporating the triennial review of mineral development activities in the ESCAP region, 1976-1978. Mineral Resources Development Series. Unesco, New York, NY, International, pp. 73-81.
Notholt, A.J.G., 1982. 4th International Field Workshop and Seminar : Rajasthan and Uttar Pradesh, India, 1981. . Institute of Geological Sciences Mineral Intelligence.
Notholt, A.J.G., 1994. Phosphate rock in developing countries; a review of geology, resources and development. In: S.J. Mathers and A.J.G. Notholt (Editors), Industrial minerals in developing countries. Geosciences in International Development Report. Association of Geoscientists for International Development, pp. 193-222.
Notholt, A.J.G., 1999. Phosphate: a world monograph (A compilation of unfinished papers). British Geological Survey.
Notholt, A.J.G. and Hartley, K., 1983. Phosphate rock: a bibliography of world resources. Mining Journal Books Ltd., London, 147 pp.
Notholt, A.J.G. and Sheldon, R.P., 1986. Regional review; world resources. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 9-19.
Notholt, A.J.G., Sheldon, R.P. and Davidson, D.F., 1989. Phosphate rock resources, Phosphate deposits of the world. Cambridge University Press, Cambridge.
Palmer, B. and Gilkes, R.J., 1983a. The Fertilizer Effectiveness of Calcined Christmas Island C- Grade Aluminium-Iron Phosphate Rock and Super-Phosphate During the Early Stages of Plant-Growth. Fertilizer Research, 4(1): 31-43.
Palmer, B. and Gilkes, R.J., 1983b. The Influence of Application Rate on the Relative Effectiveness of Calcined Christmas Island C-Grade Rock Phosphate and Super- Phosphate When Applied as Mixtures. Fertilizer Research, 4(1): 45-50.
Pandian, B.J., 1999. Studies on levels and methods of phosphorus application in green manure-rice (Oryza sativa) system under varying nitrogen levels. Indian Journal of Agronomy, 44(2): 228-231.
Pant, A., Khan, H.H. and Sonakia, A., 1989. Phosphorite resources in the Bijawar Group of central India. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 473-477.
Penot, E., Syofyan, S. and Fairhurst, T., 1998. P11. The Use of Phosphate Rock in the Establishment of Rubber-based Agroforestry Systems in Indonesia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Perera, D. and Van Straaten, P., 1994. Phosphate development in Sri Lanka (LRS 1994 Annual Report - 4; Land Management). http://www.uoguelph.ca/lrs/report/r94_3.htm
Peries, O.S. and Fernando, D.M., 1983. A handbook of rubber culture and processing. Rubber Research Institute of Sri Lanka, Agalawatta, Sri Lanka, 363 pp.
Perumal, R. and Mahimairaja, S., 1998. P21. Integrated Phosphate Rock Fertilization with Bio-softwares in Enhancing Food Grain Production: Experiences in Indian Agriculture. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Phan thi Cong and others, 1998. P15. Phosphorus is Required for Efficient Nitrogen Use in Maize Production in Lam Dong Province, Vietnam. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Pound, B., 1997. An overview of soil fertility reviews. In: P.J. Gregory, C.J. Pilbean and S.H. Walker (Editors), Integrated nutrient management on farmers' fields: approaches that work. Occasional Publication Number 1. Department of Soil Science, The University of Reading, Reading, UK, pp. 27-38.
PPLC, 1987. MUSSOORIE-PHOS : A natural phosphatic fertilizer for direct application. Pyrites, Phosphates & Chemicals Ltd., New Delhi
Pradhananga, U.B., 1986. Present status of phosphorites in Nepal, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 203-208.

Pradip, 1991. New Reagents for Mineral Processing Applications in India. Transactions of the Indian Institute of Metals, 44(6): 419-431.
Prasad, M., Majmudar, A.K., Rao, G.M. and Rao, T.C., 1995. Flotation Studies on a Low-Grade, Cherty-Calcareous Rock Phosphate Ore from Jhabua, India. Minerals and Metallurgical Processing, 12(2): 92-96.
Prasad, M., Majumder, A.K., Rao, G.M. and Rao, T.C., 1998. Beneficiation of a lean-grade siliceous rock-phosphate ore from Hirapur, India. Minerals & Metallurgical Processing, 15(3): 54-56.
Prasad, M., Majumder, A.K. and Rao, T.C., 2000. Reverse flotation of sedimentary calcareous/dolomitic rock phosphate ore - An overview. Minerals & Metallurgical Processing, 17(1): 49-55.
Prasad, N.K. and Singh, A.P., 1992. Influence of phosphoris carriers and levels of lime on forage production of Egyptian clover (Trifolium-alexandrium) and Lucerne (Medicago-sativa) and their residual effect on Deenanath grass (Pennisetum-pedicellatum). Indian Journal of Agronomy, 37(2): 258-260.
Pushparajah, E., Chan, F. and Magat, S.S., 1990. Phosphorus requirements and management of oil palm, coconut and rubber, Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Philippines, pp. 399-408.
Puthea, S. and Sovuthy, P., 1995. Direct application of phosphate rock and appropriate technology fertilizers in Cambodia. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 181-186.
Raha, P.K., 1990. Some Observations on the Phosphatic Rocks of the Lower Gondwana Sequences of the Ib-River-Coal-Field, Sundergarh District, Orissa, India. Journal of the Geological Society of India, 36(1): 46-53.
Rajendran, S., 1994. Effective exploitation of some mineral deposits along the continental margin of Kerala, India. Marine Georesources & Geotechnology, 12(1): 61-69.
Rajkhowa, D.J. and Baroova, S.R., 1998. Performance of Udaipur rock phosphate and superphosphate on rice in acid soils of Assam. Indian Journal of Agronomy, 43(4): 639-643.
Raju, R.A., Reddy, K.M.N. and Reddy, K.A., 1997. Performance of phosphorus-carriers in wetland rice (Oryza sativa) on riverine alluvials. Indian Journal of Agronomy, 42(2): 272-274.
Raju, R.A. and Reddy, M.N., 1999. Effect of rock phosphate amended with phosphate solubilizing bacteria and farmyard manure in wetland rice (Oryza sativa). Indian Journal of Agricultural Sciences, 69(6): 451-453.
Ramachandran, V., Bhujbal, B.M. and D'Souza, T.J., 1998. Influence of rock phosphates with and without vegetable compost on the yield, phosphorus and cadmium contents of rice (Oryza sativa L) grown on an ultisol. Fresenius Environmental Bulletin, 7(9-10): 551-556.
Ranatunga, D.B.J., 1988. Local production and application of phosphate fertilizer. Economic Review (People's Bank Research Department, Colombo, Sri Lanka), 14(6): 6-7.
Rao, T.C., Rao, L.S. and Rao, G.M., 1992. Beneficiation of Indian Low-Grade Phosphate Deposits - Problems and Prospects. Transactions of the Indian Institute of Metals, 45(3): 195-205.
Rao, V.P., Rao, K.M. and Raju, D.S.N., 2000. Quaternary phosphorites from the continental margin off Chennai, southeast India: Analogs of ancient phosphate stromatolites. Journal of Sedimentary Research, 70(5): 1197-1209.
Ruaysoongnern, S. and Keerati-kasikorn, P., 1998. 5. Role of Phosphorus Fertilization in Improving the Soil Fertility of Acid Tropical and Subtropical Soils in Asia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Sagoe, C.I., Ando, T., Kouno, K. and Nagaoka, T., 1998a. Relative importance of protons and solution calcium concentration in phosphate rock dissolution by organic acids. Soil Science and Plant Nutrition, 44(4): 617-625.
Sagoe, C.I., Ando, T., Kouno, K. and Nagaoka, T., 1998b. Residual effects of organic acid-treated phosphate rocks on some soil properties and phosphate availability. Soil Science and Plant Nutrition, 44(4): 627-634.
Sagwal, O.P. and Kumar, V., 1995. Effect of organic and inorganic anions on availability of phosphorus applied through different phosphorus fertilizers to moong-bean grown in soil. Communications in Soil Science and Plant Analysis, 26(19-20): 3181-3192.
Sahu, S.K. and Dev, G., 1998. P6. Efficient Use of Phosphate Rocks for Sustainable Crop Production on Lateritic Soils. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Sahu, S.K.A.P., S S, 1983. Efficient utilization of rock phosphate in acidic red soil (inceptisol) under rice-wheat farming system. Indian Journal of Agricultural Chemistry, 15(3): 87-94.
Sahu, S.N. and Jana, B.B., 2000. Enhancement of the fertilizer value of rock phosphate engineered through phosphate-solubilizing bacteria. Ecological Engineering, 15(1-2): 27-39.
Santhy, P. and Kothandaraman, G.V., 1988. Economic Review (People's Bank Research Department, Colombo, Sri Lanka), pp. 3.

Santoso, D., 1998. 6. Development of Phosphorus Fertilizer Use on Acid Soils in Indonesia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Santoso, D., Adiningsih, S., Mutert, E., Fairhurst, T. and VanNoordwijk, M., 1996. Soil fertility management for reclamation of Imperata grasslands by smallholder agroforestry. Agroforestry Systems, 36(1-3): 181-202.

Sarhad Development Authority, 2002. Kakul Phosphate (Pvt) Ltd. http://www.sda.org.pk/kakul.html

Sarkar, B.C., Nayak, V.K. and Rao, P.S., 1995. Statistical Modeling of Exploration Data for Grade Potential of the Phosphorite Deposit, Khatamba Blocks, Jhabua District, Madhya-Pradesh. Journal of the Geological Society of India, 46(2): 139-147.

Savage, C., 1987. World Survey of Phosphate Deposits. British Sulphur Corporation, London, 274 pp.

Schreier, H., Brown, S., Lavkulich, L.M. and Shah, P.B., 1999. Phosphorus dynamics and soil P-fertility constraints in Nepal. Soil Science, 164(5): 341-350.

Sekhar, D.M.R. and Chauhan, Y.K., 1998. Soap flotation plant practice in India. Transactions of the Indian Institute of Metals, 51(4): 227-239.

Shanker, R., 1989. The Mussoorie Phosphate Basin, India. In: A.J.G. Notholt, R.P. Sheldon and D.F. Davidson (Editors), Phosphate deposits of the world; Volume 2, Phosphate rock resources. Phosphate Deposits of the World. Cambridge University Press, Cambridge, pp. 443-448.

Sharma, C.M., Kaul, S. and Bhardwaj, S.K., 1995a. Agronomic effectiveness of Udaipur rock phosphate as influenced by organics in wheat (Triticum-aestivum)-maize (Zea-mays) cropping sequence. Indian Journal of Agronomy, 40(1): 93-95.

Sharma, C.M., Kaul, S. and Bhardwaj, S.K., 1996. Effect of Udaipur rock phosphate alone and in combination with organics on maize (Zea mays) wheat (Triticum aestivum) production under acid soil. Indian Journal of Agronomy, 41(3): 505-506.

Sharma, D.K. and Sharma, K.L., 1998. Effect of nitrogen and potash application on yield and quality of china hybrid tea (Camellia sinensis) grown in Kangra valley of Himachal Pradesh. Indian Journal of Agricultural Sciences, 68(6): 307-309.

Sharma, D.K., Sharma, K.L., Sharma, C.M. and Bhardwaj, S.K., 1995b. Effect of Different Phosphorus Sources on Yield and Quality of Tea (Camellia-Sinensis) in a Hill Acid Soil. Indian Journal of Agricultural Sciences, 65(8): 574-577.

Sharma, J. and Sharma, C.R., 1997. Direct and residual effects of compost enriched with mussoorie rock phosphate in wheat (Triticum aestivum) - rice (Oryza sativa) sequence. Indian Journal of Agricultural Sciences, 67(7): 299-302.

Sharma, K.K. and others, 1998. P7. Comparative Evaluation of African and Indian Phosphate Rocks as Sources of Phosphorus for the Maize-Wheat Cropping Sequence in Mountain Acid Soils in Northwest India. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Sharma, K.K., Rao, D.R., Azmi, R.J., Gopalan, K. and Pantulu, G.V.C., 1992. Precambrian-Cambrian Boundary in the Tal Formation of Garhwal Lesser Himalaya - Rb-Sr Age Evidence from Black Shales Underlying Phosphorites. Current Science, 62(7): 528-530.

Sharma, P.K., Bhardwaj, S.K. and Sharma, H.L., 2001. Long term studies on agronomic effectiveness of African and Indian Rock Phosphates in relation to productivity of maize and wheat crops in mountain acid soils of Western Himalayas- India. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Sharma, P.K., Bhumbla, D.R. and Dev, S.P., 1982. Organic and Total Phosphorus in Relation to Soil Properties in Some Soils of Northwest India. Acta Agronomica Academiae Scientiarum Hungaricae, 31(3-4): 355-364.

Sharma, S.N. and Prasad, R., 1996. Mussoorrie rock phosphate-pyrite mixture as phosphate fertilizer. Fertilizer Research, 45(3): 187-191.

Sharma, S.N., Ray, S.B., Pandey, S.L. and Prasad, R., 1983. Effcet of irrigation, pyrites and phosphobacteria on the efficiency of rock phosphate applied to lentils. Journal of Agricultural Science, 101(OCT): 467-472.

Sharma, U.C., 1991. Release Pattern of Nitrate-Nitrogen from Nitrogenous Fertilizers under Field Condition in Meghalaya and Its Effect on Yield of Potato (Solanum-Tuberosum). Indian Journal of Agricultural Sciences, 61(8): 561-566.

Sharma, U.C. and Singh, K., 1991. Effect of Sources of Phosphatic and Nitrogenous Fertilizer on Potato (Solanum-Tuberosum) Crop under Acidic Soil of North-East India. Indian Journal of Agronomy, 36(4): 559-562.

Shergold, J.H. and Brasier, M.D., 1986. Specialist studies; Biochronology of Proterozoic and Cambrian phosphorites. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 295-326.

Silva, C., 1988. The significance of Eppawela rock phosphate deposit for Sri Lanka's agriculture. Economic Review (People's Bank Research Department, Colombo, Sri Lanka), 14(6): 8-9.

Silva, K.K.M.W., 1983. Some geological aspects of the Eppawala apatite deposit. In: C. Dissanayake (Editor), Symposium on the Geology of Sri Lanka, Peradeniya, Sri Lanka.
Singal, R., Gupta, R. and Saxena, R.K., 1994. Rock phosphate solubilization under alkaline conditions by Aspergillus-japonicus and A-foetidus. Folia Microbiologica, 39(1): 33-36.
Singaram, P. and Kothandaraman, G.V., 1992. Residual, Direct and Cumulative Effect of Phosphatic Fertilizers on Inorganic Phosphorus Fractions in Soils after Finger Millet (Eleucine-Coracana) Maize (Zea-Mays) Cropping Sequence. Indian Journal of Agricultural Sciences, 62(2): 118-123.
Singaram, P., Rajan, S.S.S. and Kothandaraman, G.V., 1995. Phosphate Rock and a Phosphate Rock Superphosphate Mixture as Fertilizers for Crops Grown on a Calcareous Soil. Communications in Soil Science and Plant Analysis, 26(9-10): 1571-1593.
Singh, B.R. and Myhr, K., 1998. Cadmium uptake by barley as affected by Cd sources and pH levels. Geoderma, 84(1-3): 185-194.
Singh, C.P. and Amberger, A., 1990. Humic substances in straw compost with rock phosphate. Biological Wastes, 31(3): 165-174.
Singh, C.P. and Amberger, A., 1991. Solubilization and availability of phosphorus during decomposition of rock phosphate enriched straw and urine. Biological Agriculture & Horticulture, 7(3): 261-269.
Singh, C.P. and Amberger, A., 1997. Solubilization of rock phosphate by humic and fulvic acids extracted from straw compost. Agrochimica, 41(5): 221-228.
Singh, C.P. and Amberger, A., 1998. Organic acids and phosphorus solubilization in straw composted with rock phosphate. Bioresource Technology, 63(1): 13-16.
Singh, C.P., Ruhal, D.S. and Singh, M., 1983. Solubuilization of low-grade rock phosphate by composting with a farm waste, pearl millet boobla. Agricultural Wastes, 8(1): 17-25.
Singh, C.P., Ruhal, D.S. and Singh, M., 1987. The solubilization of low-grade rock phosphate with anaerobic digestor slurry. International Biodeterioration, 23(4): 249-256.
Singh, H.P. and Singh, T.A., 1993. The Interaction of Rockphosphate, Bradyrhizobium, Vesicular- Arbuscular Mycorrhizae and Phosphate-Solubilizing Microbes on Soybean Grown in a Sub-Himalayan Mollisol. Mycorrhiza, 4(1): 37-43.
Singh, L. and De, S.K., 1990a. Effect of Mussoorie Rock Phosphate, Neem Cake and Moisture Regimes on Soil Composition. Agrochimica, 34(5-6): 570-574.
Singh, L. and De, S.K., 1990b. Influence of applied Mussoorie rock phosphate on amino-acid composition of beta-humic acid. Agrochimica, 34(3): 262-266.
Singh, M.K., Verma, U.N., Pal, S.K. and Thakur, R., 1999a. Efficacy of slow release N-fertilizers for rice and their residual effect on wheat. Indian Journal of Agronomy, 44(2): 216-218.
Singh, M.K., Verma, U.N., Pal, S.K. and Thakur, R., 1999b. Efficacy of slow release nitrogen-fertilizers to rice (Oryza sativa) and their residual effect on wheat (Triticum aestivum). Indian Journal of Agronomy, 44(1): 102-104.
Singh, R., Pradip and Sankar, T.A.P., 1992a. Selective Flotation of Maton (India) Phosphate Ore Slimes with Particular Reference to the Effects of Particle-Size. International Journal of Mineral Processing, 36(3-4): 283-293.
Singh, R.D. and Yadav, D.V., 1986a. Evaluation of low-grade rock phosphate composted with some agricultural wastes for use in crop rotation. Agricultural Wastes, 18(1): 73-79.
Singh, R.D. and Yadav, D.V., 1986b. Transformation of N, P and organic matter during paddy straw decomposition with and without rock phosphate. Agricultural Wastes, 18(3): 247-251.
Singh, R.D. and Yadav, D.V., 1988. Effects of Mussoorie Rock Phosphate Composted with Agricultural Wastes on Wheat, Paddy and Soil Properties. Agrochimica, 32(4): 295-300.
Singh, S. and Kapoor, K.K., 1999. Inoculation with phosphate-solubilizing microorganisms and a vesicular arbuscular mycorrhizal fungus improves dry matter yield and nutrient uptake by wheat grown in a sandy soil. Biology and Fertility of Soils, 28(2): 139-144.
Singh, S., Mishra, M.M., Goyal, S. and Kapoor, K.K., 1992b. Preparation of nitrogen-enriched and phosphorus-enriched compost and its effect on wheat (Triticum-aestivum). Indian Journal of Agricultural Sciences, 62(12): 810-814.
Sivapalan, P., 1988. Liming of tea fields - a critical need. Tea Bulletin, 8(1): 3-22.
Sivasubramaniam, S., Wickremasinghe, K.N. and Ayadurai, S., 1981. The use of Eppawala apatite for tea in Sri Lanka. Tea Quarterly, 50(1): 4-10.
Sofyan, A., Nursyamsi, D. and Sri Adiningsih, J., 1998. P9. The Use of Phosphate Rock for Food Crops on Acid Upland Soils in Indonesia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Southgate, P.N., 1986a. Cambrian phoscrete profiles, coated grains, and microbial processes in phosphogenesis: Georgina Basin, Australia. Journal of Sedimentary Petrology, 56: 429-441.

Southgate, P.N., 1986b. Specialist studies; Middle Cambrian phosphatic hardgrounds, phoscrete profiles and stromatolites and their implications for phosphogenesis. In: P.J. Cook and J.H. Shergold (Editors), Phosphate deposits of the world. Cambridge Univ. Press, Cambridge, United Kingdom, pp. 327-351.

Spears, J.S., 1980. Can farming and forestry coexist in the tropics? Unasylva No. 128, 32.

Sri Adiningsih, J. and Fairhurst, T.H., 1998. 13. The Use of Reactive Phosphate Rock for the Rehabilitation of Anthropic Savannah in Indonesia. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Sri Adiningsih, J., Nursyamsi, D. and Partohardjono, S., 2001. Direct application of phosphate rock: Indonesia's experience and constraints of adoption at farmer level. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Tambunan, D., Hedley, M.J., Bolan, N.S. and Turner, M.A., 1993. A Comparison of Sequential Extraction Procedures for Measuring Phosphate Rock Residues in Soils. Fertilizer Research, 35(3): 183-191.

Tandon, H.L.S., 1987. Phosphorus Research and Agricultural Production in India. Fertiliser Development and Consultation Organisation (FDCO), New Dehli, 160 pp.

Tandon, H.L.S., 1989. Sulphur Fertilisers for Indian Agriculture. Fertiliser Development and Consultation Organisation (FDCO), New Dehli, 95 pp.

Tandon, H.L.S. and Sekhon, G.S., 1988. Potassium Research and Agricultural Production in India. Fertiliser Development and Consultation Organisation (FDCO), New Dehli, India.

Tater, J.M., 1980. Ocurrences of phosphatic rocks in Nepal. In: A.I.N. Lee (Editor), Fertilizer Mineral Occurrences in the Asia-Pacific Region. East-West Resource Systems Institute, Honolulu, pp. 53-65.

Tazaki, K., Fyfe, W.S. and Dissanayake, C.B., 1986. Weathering of phosphate marble to exploitable apatite deposit, Sri Lanka. Applied Geochemistry, 1: 287-300.

Tazaki, K., Fyfe, W.S. and Dissanayake, C.B., 1987. Weathering of apatite under extreme conditions of leaching. Chemical Geology, 60: 151-162.

Tennakone, K., 1988a. Beneficiation of Eppawala apatite with hydrochloric acid. Economic Review (People's Bank Research Department, Colombo, Sri Lanka), 14(6): 20-21.

Tennakone, K., 1988b. Production of ammonium phosphate containing fertilizers from apatite unsuitable for wet process. Fertilizer Research, 17: 97-100

Tennakone, K., Weerasooriya, S.V.R., Jayatissa, D.L., Damayanthi, M.L.W.D. and Silval, H.K., 1988. Non hygroscopic superphosphate fertilizer from apatite and hydrochloric acid. Fertilizer Research, 16: 87-96

Tennakone, K. and Weragama, U.T., 1992. Nitric acid treated phosphate fertilizer from Eppawala apatite in Sri Lanka. Fertilizer Research, 32(1): 115-119.

Tiwari, M., 1996. Precambrian-Cambrian boundary microbiota from the Chert Phosphorite Member of Tal Formation in the Korgai Syncline, Lesser Himalaya, India. Current Science, 71(9): 718-720.

Tiwari, R.J. and Nema, G.K., 1999. Response of sugarcane (Saccharum officinarum) to sources and doses of phosphorus. Indian Journal of Agricultural Sciences, 69(3): 242-244.

Tiwari, V.N., Pathak, A.N. and Lehri, L.K., 1989. Effcet of cattle dung and rock phosphate on composting of wool waste. Biological Wastes, 27(3): 237-241.

Tomar, N.K., Khanna, S.S. and Gupta, A.P., 1983. Evaluation of Mussoorie phosphate for wheat. Indian Journal of Agricultural Sciences, 53(5): 330-336.

Tomar, R.K.S., Namdeo, K.N. and Raghu, J.S., 1996. Efficacy of phosphate solubilizing bacteria biofertilizer with phosphorus on growth and yield of gram (Cicer arietinum). Indian Journal of Agronomy, 41(3): 412-415.

Tomlinson, H., Traore, A. and Teklehaimanot, Z., 1998. An investigation of the root distribution of Parkia biglobosa in Burkina Faso, West Africa, using a logarithmic spiral trench. Forest Ecology and Management, 107(1-3): 173-182.

TRI, 1986. Handbook on Tea. Tea Research Institute of Sri Lanka, Talawakele, Sri Lanka, 220 pp.

Tripathi, D. and Minhas, R.S., 1991. Effect of Fertilizer Phosphorus and Farmyard Manure on P-Fixing Capacity of an Acid Alfisol. National Academy Science Letters-India, 14(8): 319-322.

Truong, B. and Montange, D., 1998. 11. The African Experience with Phosphate Rock, Including Djebel Onk, and Case Studies in Brazil and Vietnam. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.

Van Chien, N., 1995. Role of inorganic fertilizers in the agricultural production of Vietnam. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 253-261.

Van Kauwenbergh, S.J., 1995a. Case studies of indigenous resource development. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology

fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 129-141.
Van Kauwenbergh, S.J., 1995b. Indigenous resource development for the fertilizer sector: performing technoeconomic studies. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 115-127.
Van Kauwenbergh, S.J., 1995c. Mineralogy and characterization of phosphate rock. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 29-47.
Van Kauwenbergh, S.J., 1995d. Overview of the global phosphate rock production situation. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 15-28.
Van Kauwenbergh, S.J., 2001. Overview of World Phosphate Rock Production. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.
Van Os, H., 1996. Mission to Indonesia. *http://www.fadinap.org/newsprj/newsprj96_3_3.htm*
Van Straaten, P. and Perera, D., 1995. New modification techniques of Sri Lankan phosphates (LRS 1995 Annual Report - 4; Land Management). *http://www.uoguelph.ca/lrs/report/r95_4.htm*
Vargas, B.S. and Escalada, P.P., 1986. Exploration and assessment of fertilizer mineral deposits in the Philippines, Mineral concentrations and hydrocarbon accumulations in the ESCAP region. Volume 1: Fertilizer Minerals in Asia and the Pacific. Economic and Social Commission for Asia and the Pacific, Bangkok, pp. 212-233.
Venkitaswamy, R., Subramanian, S. and Veerabadran, V., 1991. Influence of Modified Forms of Urea and Nitrogen Levels on Weed Growth and Grain-Yield of Lowland Rice. Fertilizer Research, 28(3): 315-321.
Verma, D.P., Chien, S.H., Christianson, C.B. and Pardhasardhi, G., 1993. Comparison of Efficiency of Mussoorie Partially Acidulated Phosphate Rock and Single Superphosphate in a Shallow Alfisol of the Indian Semiarid Tropics. Fertilizer Research, 36(1): 29-33.
Verma, L.N. and Rawat, A.K., 1999. Low grade rockphosphate: A complimentary phosphorus source in soybean (Glycine max)-wheat (Triticum aestivum) cropping system. Indian Journal of Agricultural Sciences, 69(4): 297-299.
Verma, L.P. and Sharma, N.L., 1994. Residual Effect of Phosphatic Fertilizers Applied to Wheat (Triticum-Aestivum) on Succeeding Crop of Greengram (Phaseolus- Radiatus). Indian Journal of Agronomy, 39(2): 237-240.
Verma, L.P., Warsi, A.S. and Yadav, D.S., 1991. Agronomic effectiveness of Mussoorie rock phosphate as a source of phosphate for rice (Oryza-sativa). Indian Journal of Agronomy, 36(SS): 239-240.
Verma, M.M., Singh, C.P. and Prasad, F.M., 1990. Effect of chelated calcium and rock phosphate on yield, quality and availability of nutrients by groundnut crop. National Academy Science Letters-India, 13(5): 157-159.
Vo Dinh Quang and others, 1998. P16. The Use of Soil Analysis for Phosphorus Recommendations on Acid Soils of the Mekong Delta, Vietnam. In: A.E. Johnston and J.K. Syers (Editors), Nutrient Management for Sustainable Crop Production in Asia, International Conference, Bali, December 1996. IMPHOS and CABI Publishing, Wallingford, UK.
Vora, M.S. and Shelat, H.N., 1998. Impact of addition of different carbon and nitrogen sources on solubilization of rock phosphate by phosphate-solubilizing micro-organisms. Indian Journal of Agricultural Sciences, 68(6): 292-294.
Warren, G.P., 1994. Influence of soil properties on the response to phosphorus in some tropical soils. 2: Initial response to fertilizer. European Journal of Soil Science, 45(3): 337-344.
Weerakoon, W.L., Seneviratne, G., Desilva, M.A.P. and Seneviratne, A.M., 1992. Evaluation of Sesbania-Speciosa as a Green Manure for Lowland Rice in the Dry Zone, Sri-Lanka. Plant and Soil, 145(1): 131-139.
Weerasuriya, T.J., Pushpakumara, S. and DeTurck, P., 1992a. Acidulated pegmatitic mica: a promising new multi-nutrient fertilizer, Annual Reviews, Institute of Fundamental Studies, Kandy, Sri Lanka, pp. 62-63.
Weerasuriya, T.J.T., Pushpakumara, S. and DeTurck, P., 1992b. Can rock powders be used in the tropics to improve tropical soils ?, First South Asia Geological Congress, Abstracts Volume, Islamabad, Pakistan, pp. 45.
White, P.F., Nesbitt, H.J., Ros, C., Seng, V. and Lor, B., 1999. Local rock phosphate deposits are a good source of phosphorus fertilizer for rice production in Cambodia. Soil Science and Plant Nutrition, 45(1): 51-63.
Yogaratnam, N., 1988. The use of Eppawela rock phosphate in the plantation sector. Economic Review (Colombo, Sri Lanka: People's Bank Research Department), 14(6): 15-16

Yusdar, H. and Hanafi, M.H., 2001. Use of phosphate rock for perennial and annual crops cultivation in Malaysia: a review. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Zafar, Z.I., 1993. Beneficiation of Low-Grade Carbonate-Rich Phosphate Rocks Using Dilute Acetic-Acid Solution. Fertilizer Research, 34(2): 173-180.

Zafar, Z.I., Anwar, M.M. and Pritchard, S.W., 1995. Optimization of Thermal Beneficiation of a Low-Grade Dolomitic Phosphate Rock. International Journal of Mineral Processing, 43(1-2): 123-131.

Zaharah, A.R. and Bah, A.R., 1997. Effect of green manures on P solubilization and uptake from phosphate rocks. Nutrient Cycling in Agroecosystems, 48(3): 247-255.

Zaharah, A.R. and Sharifuddin, H.A.H., 1995. Use of phosphate rock in Malaysian agriculture. In: K. Dahanayake, S.J. Van Kauwenberg and D.T. Hellums (Editors), Direct application of phosphate rock and appropriate technology fertilizers in Asia: what hinders acceptance and growth. Institute of Fundamental Studies (IFS) and International Fertilizer Development Centre (IFDC), Kandy, Sri Lanka, pp. 225-230.

Zaharah, A.R., Zulkifli, H. and Sharifuddin, H.A.H., 1997. Evaluating the efficacy of various phosphate fertiliser sources for oil palm seedlings. Nutrient Cycling in Agroecosystems, 47(2): 93-98.

Zakaria, Z.Z., Khalid, H., Tarmizi, M. and Hamdan, A.B., 2001. Use of phosphate rock fertilizers for oil palm in Malaysia. In: IFDC (Editor), Direct Application of Phosphate Rock and Related Technology: Latest Developments and Practical Experiences. IFDC,MSSS,PPI/PPIC, Kuala Lumpur, Malaysia.

Zoysa, A.K.N., Loganathan, P. and Hedley, M.J., 1998a. Effect of forms of nitrogen supply on mobilisation of phosphorus from a phosphate rock and acidification in the rhizosphere of tea. Australian Journal of Soil Research, 36(3): 373-387.

Zoysa, A.K.N., Loganathan, P. and Hedley, M.J., 1998b. Phosphate rock dissolution and transformation in the rhizosphere of tea (Camellia sinensis L.) compared with other plant species. European Journal of Soil Science, 49(3): 477-486.

Zoysa, A.K.N., Loganathan, P. and Hedley, M.J., 1999. Phosphorus utilisation efficiency and depletion of phosphate fractions in the rhizosphere of three tea (Camellia sinensis L.) clones. Nutrient Cycling in Agroecosystems, 53(2): 189-201.