Phosphorus supply may dictate food security prospects in India

A. Subba Rao[1,]*, Sanjay Srivastava[1] and A. N. Ganeshamurty[2]

[1]Indian Institute of Soil Science, Bhopal 462 038, India
[2]Indian Institute of Horticultural Research, Bengaluru 560 089, India

Importance of phosphorus (P) in agriculture and how its availability or otherwise could influence the food security of India and the world is studied. Rock phosphate (RP) is the only economic source of P but its availability is finite and skewed. India has very limited known resource of RP which is mostly low to medium grade in quality, thus making it almost entirely dependent on imports. The low soil P fertility in large parts of the country has accentuated the problem and reinforced the importance of most scientific and judicious use of P. A large number of practical measures such as using low grade indigenous RPs, mobilization of P from RPs, some best agronomic practices to effectively and economically utilize RPs and P recovery from solid and liquid wastes are suggested in the article along with some researchable issues. These if implemented could reduce the reliance on P import as well as provide food and nutritional security.

Keywords: Availability, fertility, phosphorus, rock phosphate, yield.

PHOSPHORUS (P) is an indispensable plant nutrient and no plant on this planet can complete its life cycle without adequate supply of P. P is one of the building blocks of all forms of life and every living cell requires it. It is involved in energy transfer reactions in plants and is also a part of high energy molecules such as adenosine triphosphate (ATP) which supply energy for vital processes in plants. Phosphorus is also present in molecules that make up genes and chromosomes and so transfers the genetic traits from one generation to another. Phosphorus present in the soil enters the plant mainly through root hairs. There are two main sources of P in soil, one as a native source from inherent P present in the soil and another through external application in the form of fertilizers.

Whether the depletion of P reserves would threaten food security in the world or not has been the topic of debate in recent years[1–3]. The debate is mainly concentrated on estimates of RP deposits and the rate of their depletion leading to deficiency or sufficiency of usable rock phosphates (RPs) in the world. In one scenario, the P supply would be insufficient with large fluctuations leading to higher food prices and food insecurity. In the other scenario, the P supply would be adequate, and prices being low leading to its indiscriminate use and increasing the possibility of higher P losses and damage to the environment. Moreover, there are several parts of the world that do not have sufficient access to P fertilizers resulting in food insecurity.

With the equation given in Figure 1, the fertilizer (P_2O_5) requirement would be 8.7 million tonnes (mt) for a food grain production of 250 mt. It is projected to be 26.7 mt for 450 mt of expected food grain production by 2050. This, however, would happen if the current trend continues. A look at the P balance studies[4], showed that 2.92 mt of P_2O_5 were removed through crop uptake (in 2000–2001), where additions due to fertilizers, manures and deposition (additions through rain) were 5.24 mt, thus the overall P balance was positive. Northeastern states and Madhya Pradesh showed negative balance of P. These P balance studies point out the need to research the P fractions in soil and their contribution to P nutrition in the areas where there has been consistent positive P balance. In addition to ensuring adequate P additions, techniques need to be developed to harness the otherwise fixed or unavailable P in soil, so as to reduce the P additions.

Do our soils have enough P to meet plant P requirement?

No, our soils do not have enough P to meet the demands for P of today's high-yielding crop varieties, the yields of which have increased by more than threefolds since independence. The P status of neutral and alkaline soils is

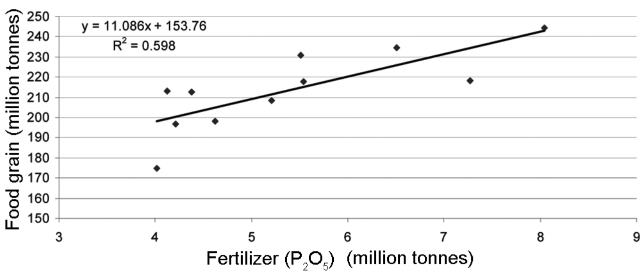

Figure 1. Relation between fertilizer (P_2O_5) additions and food grain yield in the first decade of the 21st century.

*For correspondence. (e-mail: asrao_iiss@yahoo.co.in)

Table 1. Phosphorus fertility index of different states over the years

Year	No. of samples (million)	Districts in P fertility classes (%)			Reference
		Low	Medium	High	
1969	1.3	47	49	4	7
1979	9.2	46	52	2	8
1996	9.6	49	49	2	9
2002	3.7	42	38	20	10

expressed in terms of Olsen-P which refers to the available soil P (ref. 5). However, fertility level of an area is generally expressed by nutrient index values[6], which are calculated based on the relative number of samples falling in low, medium or high categories within a specified area. Index values above 2.33 are considered high and such soils would require only maintenance dose of P, while values less than 1.67 are considered low and these soils require relatively higher rates of P additions, ideally to be determined through soil testing[7]. Based on the nutrient index values, the districts belonging to low, medium, or high categories are classified. Some studies are summarized in Table 1 on a timescale of 1969 to 2002 (refs 7–10). The data clearly show that most of the Indian soils were either low or medium in soil P fertility till 1996. Motsara[10] reported almost 20% districts in high P status. Muralidharudu *et al.*[11] while analysing the data of 430 districts found 52% districts in low, 40% in medium, and only 8% districts in high soil P fertility. While some deviation in the different estimates could be explained due to different times of sampling, differences in sample sizes as well as variability in the sample loci, the data consistently show that almost 80% of the soils are either in low or medium P fertility categories, which reinforces the need for adequate external supply of P through fertilizers.

Phosphorus requirement of Indian agriculture

A study of food grain production and P fertilizer additions, in the last decade, reveals that almost 60% variation in food grain yield is explained by P fertilizer additions (Figure 1). Indian agriculture consumed 8.1 mt of P_2O_5 in 2010–2011 to produce 235 mt of food (Table 2). Out of this consumption, 4.3 mt of P_2O_5 (54%) was met through direct fertilizer import of either diammonium phosphate (DAP) or NP/NPK grade complexes. However, rest 46% consumption to a large extent was met through imported sulphur, or high analysis RPs. DAP manufacture requires treatment of high analysis RPs (>28% P_2O_5) with phosphoric acid. Phosphoric acid is made by wet process, which requires treatment of RPs (rich in tricalcium phosphates) with sulphuric acid. Both the raw materials – sulphuric acid (manufactured by imported sulphur) and high analysis RPs are imported. Much of the phosphoric acid, however, is directly imported. Therefore, the entire DAP manufactured in India (1.7 mt P_2O_5) was, in fact, indirectly imported. Similarly, around 1.5 mt of P_2O_5 belonging to NP/NPK grades is largely imported. This shows an alarming situation, where almost 90% of the P consumption needs of the country are met through imports either directly in the forms of fertilizers or the raw materials/intermediaries, something that puts Indian agriculture in a precarious situation. The first shock of this kind was felt in 2008, when the price of RP escalated by 800% resulting in the central fertilizer subsidy of Rs 65,550 crore rupees on P and K fertilizers[12].

Phosphorus sources available in India and their quality

RP is the only source of P for production of phosphate fertilizers. The total resources including current reserves of RP as per the United Nations Framework Classification (UNFC) system as on 1 April 2010 in India are 296.3 mt with Jharkhand, Rajasthan and Madhya Pradesh consisting of 107.3, 88 and 49.4 mt respectively (Table 3)[13]. However, all the RP resources in Jharkhand belong to the inferred (inferred from geological evidence with low level of confidence) category only, as per UNFC of mineral reserves/resources. Currently, exploitable reserves in India are present only in Rajashtan and Madhya Pradesh. Grade-wise, RP that can be used in making P fertilizers is only 6%. Twenty-nine percentage are beneficiable, 12% can be used as soil amendment, 9% are blendable and rest are either low grade (39%) or unclassified (5%). Hence, conversion of low grade RPs into plant utilizable forms, would lead India towards self-reliance, in P fertilizer consumption. At present, very small amount of RP is used for direct application. For example, out of the total production of 1.26 mt of RP from Jhamarkotra (Rajasthan) only, 74,000 tonnes was distributed for direct application to soil. A portion of this is used in preparing fertilizer mixtures for plantation crops such as rubber.

A total of 24.23 mt of apatite minerals are also present in India. West Bengal is one of the leading states having apatite reserves. Apatite is a group of phosphate minerals, usually referring to hydroxylapatite, fluorapatite and chlorapatite, which respectively, contain high concentrations of hydroxyl (OH^-), fluoride (F^-) and chloride (Cl^-) ions, in the crystal.

Table 2. Import, production and consumption (000 tonnes) of various commodities in 2010–2011 in India

Ingredient	Import	Production	Consumption
Single superphosphate (SSP)	–	4,324	3,825
DAP	6,905	3,541	10,869
NP/NPKs	3,675	7,802	9,862
Rock phosphate	6,327	1,920.9	–
Rock phosphate (direct consumption)		74.0	47.4
Sulphur	1,808	–	–
Sulphuric acid		5,652.5	–
Phosphoric acid	2,139.8	1,544.6	–
N	4,570	12,179	16,558
P_2O_5	3,739	4,371	8,050
K_2O	3,840	–	3,514

Table 3. Rock phosphates and apatite resources in different states and grade-wise deposits in India

	Rock phosphate (million tonnes)			Apatite (million tonnes)	
State	Reserve	Remaining resources	State	Reserve	Remaining resources
Jharkhand	–	107.3	West Bengal	2.0	11.7
Rajasthan	16.7	71.3	Jharkhand	–	7.3
Madhya Pradesh	18.1	31.3	Meghalaya	–	1.3
Uttar Pradesh	–	25.8	Rajasthan	–	1.1
Uttarakhand	–	24.2	Andhra Pradesh	0.04	0.2
Meghalaya	–	1.3	Gujarat	–	0.35
Gujarat	–	0.3	Tamil Nadu	–	0.24

Table 4. World phosphate production and reserves (thousand tonnes)

Rank (production)	Countries	Production (2011)	Reserves
	World total (rounded)	191,000	71,000,000
1	China	72,000	3,700,000
2	United States	28,400	1,400,000
3	Morocco and Western Sahara	27,000	50,000,000
4	Russia	11,000	1,300,000
5	Jordan	6,200	1,500,000
6	Brazil	6,200	310,000
17	India	1,250	6,100

Production and import of RPs in India

The production of RPs in India started in 1970–1971 with a production of 232.9 thousand tonnes[10]. Its production took a leap in 2010–2011 with a total production of 1921 thousand tonnes. During 2010–2011, a total of 1.4 mt of RP was mined in India in four states. Close to 90% (1.26 mt) of this was from Jhamarkotra mines in Rajasthan. A small amount was mined from Jhabua (105 thousand tonnes) and Sagar (52 thousand tonnes) in Madhya Pradesh. India imported 6387 thousand tonnes of RP in 2010. Jordan was the largest exporter of RPs (2933 thousand tonnes) followed by Egypt (1036 thousand tonnes) and Morocco (918 thousand tonnes). Its import has been steadily increasing since 2002 (4944 to 6387 thousand tonnes in 2010).

Phosphorus sources available in the world

Most of the world RP resources are widely distributed in marine phosphorite deposits. Phosphorite is a non-detrital sedimentary rock which contains high amounts of phosphate-bearing minerals. Morocco and Western Sahara lead in reserves followed by China, Jordan, United States and Russia (Table 4)[14]. Igneous deposits occur in Brazil, Canada, Russia, Finland and South Africa. Also, the continental shelves and seamounts in the Pacific and Atlantic Oceans contain large resources of P. Currently, the total RP resources of the world are estimated to be around 300 billion tonnes and the reserves are 71 billion tonnes. The term 'resources' indicates the total estimated amounts that are in principle suitable for extraction of P as per the current technology and P concentrations, whereas the term 'reserve' refers to the accessible resources that are economically exploitable. If the current rate of production and consumption continues, the total estimated resources of 300 billion tonnes would last for the next 1500 years. However, further exploration is expected to increase the estimated amount of resources.

World RP production and demand

Access to low-cost RP is important for the success of the P fertilizer industry. However, this access is geographically restricted to countries such as Morocco, China and the US. Almost two-thirds of the world RP is produced in these countries with Morocco leading in global exports (33% share). About 30% of P fertilizer manufacturers rely on imports or domestic purchases for the supply of RP. Hence, ensuring a secure global supply of low-cost RP is of utmost importance for sustainable food security. While two-thirds of the global RP is produced by three countries, many others either do not possess sufficient reserves of RP or lack in economic means to obtain it. As per the current reserve and use estimates, only few countries can sustain them in terms of P production for long (e.g. Algeria and Morocco >1000 years), others for a shorter duration (China, Brazil and USA: 50 years), while others (e.g. Japan and Germany) cannot sustain at all. This clearly shows that not only ensuring geographically uniform long-term access to P is important, but it is also important to evolve and maintain efficient agronomic practices and P consumption patterns that minimize its wastage. India with a very limited domestic supply of RP, is the largest importer of RP in the world (about 30% of global trade). However, situation is far better in North American countries with integrated phosphate rock supplies, with imports being less than 10% of total domestic consumption (www.scopenvironment.org).

Risk of future phosphorus shortage

The only economic source of P in the world is mined RP and the global agricultural production mostly depends on

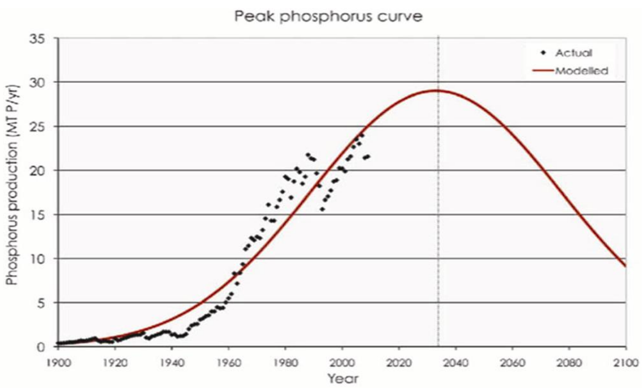

Figure 2. Availability of rock phosphate for phosphorus production in the world.

it. If the supplies of RP become unavailable, the world food production would decline significantly. Hence, analysing the risk of phosphate reserves accessibility or otherwise is a key issue and has been addressed[15,16].

Cordell *et al.*[15] identified a parallel between 'peak oil' and 'peak phosphorus', and found that phosphate reserves would be exhausted during the 21st century. They proposed a Gaussian model of phosphate availability (Figure 2). This model projects that P supply would peak around 2030, and decline to one-thirds by 2100. However, others, by calculating RP reserve longevity using current reserves and production, have indicated that the world has over 300 years of reserves. The estimates of RP reserves are subject to change with updated information and discovery, and with changes in economics and technology[16]. Whatever may be the projections, world RP reserves will get exhausted sooner or later and addressing future P supply should become one of the most urgent priorities for the future sustainability of agriculture and humanity.

What needs to be done to make India self-reliant in P consumption

Considerable potential exists both for developing lower cost P fertilizers, particularly ones using indigenous P sources, and for increasing the efficiency with which fertilizer P is utilized by the crop. Two main approaches can help achieve these objectives: (i) Developing and use of new P sources, including lower cost P forms with improved plant availability, reduced transport and spreading costs, recycling of waste materials. (ii) Improving soil, crop and fertilizer management to increase P use efficiency and mobilizing native soil P. Soil management may include improving the availability of native P by adjusting soil properties and reducing P fixation. Crop management could include selection of plant species with root system tolerant to low-P status soil, better utilization of mycorrhizae and P solubilizing organisms and better root development, and fertilizer management including balanced P fertilization with improved fertilizer application techniques.

Some practical recommendations

Promote indigenous supply and upgradation of material

Information generated amply justified the direct application of indigenous and imported RP for acid soils with low exchangeable calcium status and suitable mixtures of water soluble source such as SSP and RP in 1 : 3 and 1 : 1 proportions for neutral and slightly alkaline soils. It is recommended to apply RP well in advance if the P-sorption capacity of the soil is less. Most suitable soils

Table 5. List of districts under high soil P status and area covered in the state

State	Status	District	Area (%)
Bihar	High	Samastipur	3.2
Himachal Pradesh	High	Kinnaur	11.6
Jharkhand	High	Lohardaga	1.9
Karnataka	High	Bangalore (R), Chamrajanagar, Davanagere, Mandya	4.2
Kerala	High	Ernakulam, Kollam, Kottayam, Thiruvananthapuram	24.1
Madhya Pradesh	High	Dindori, Guna, Hoshangabad, Rajgarh, Sehore	13
Orissa	High	Bolangir, Boudh, Keonjhar, Mayurbhanj, Phulbani, Sambalpur, Sonepur	31.3
Punjab	High	Bathinda, Pategar Sahib, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Ropar	52.8
Tamil Nadu	High	Coimbatore, Pudukkottai, Madurai, Nagapattinam, Nilgiri, Peerambalur, Ramanathapuram, Thanjavur, Thiruallur, Tiruvannamalai, Tiruvarur, Vellore	37.6
West Bengal	High	Hooghly	5.8

for direct application of RP are acid soils with low exchangeable Ca and low P concentration. Also, RP application may also be promoted in high-value crops such as vegetables, fruit and pulses. Rock phosphate application may also enhance the quality of exportable produce such as mango, litchi, etc. RP is recommended for direct application in several states in India, but some constraints to its use are as follows: (i) Composition of the available RP is variable, which necessitates analysis before application. (ii) RP is not readily available in the open market. (iii) there is a limited understanding of the soils on which RP can be efficiently and economically used. (iv) Application of RP is not adequately supported by extension services[17].

Phosphorus use efficiency is 15–25%. Millions of tonnes of P have been applied in soils over the last 60 years. Where has it gone? A close look at the P dynamics and its movement in soil–plant system is required and areas where P fertility has been built up must be demarcated followed by development of strategy for need-based P application. Such areas with high soil P status are shown in Table 5 (ref. 11). Phosphatic fertilizer application can be reduced by 25% in such areas without any reduction in yield[18]. In low available P and high-responsive soils, adequate P greatly increases crop yields. However, on soils with very high P, a small maintenance dose of P may be sufficient[19].

Plantation crops such as rubber, tea, coffee, spices, etc. being perennial in nature have the capacity to utilize the P in RP most economically and hence their direct application may be encouraged.

In soils which have received repeated P applications for several years, 60% water soluble P may be sufficient in most cases and a fully water soluble form may not be needed. The use of nitrophosphates may be encouraged in such situations. Also, low water soluble nitrophosphates could be applied in acid soils. It has also been found that low to medium grade RP can be used for making products containing diammonium phosphate fertilizers with different percentage of P_2O_5 content depending on acid, particle size and nature of RP[20]. Government intervention, however, is required to ensure the availability of RP in local markets.

Some imported RPs intended for direct application are highly reactive with more than 40% total P_2O_5 soluble in 2% citric acid, highly porous, soft, have large surface area being of 60 mesh fineness, weakly crystalline and have low cadmium content. There is general agreement that material of size 60–100 mesh is optimum[21]. Citrate-soluble P in Mussoorie RP (MRP) doubles when its fineness increases from 60 to 100 mesh[22]. In an interesting report on rice in the acid soil of Assam (pH 5.0), MRP of 100 mesh produced a bigger direct response, and the 60 mesh material produced a bigger residual effect. Hence, in situations where direct response is desired, 100 mesh RP could be used, while for perennial crops 60 mesh RP will serve the purpose[23]. Some practicable recommendations on the direct application of RP are summarized in Table 6 (ref. 18).

Rock phosphate deposits with high carbonate substitution are more suitable for direct application than fluorapatite. Also, presence of the minerals such as calcite and dolomite can inhibit the release of P from RP. Partial acidulation techniques are more successful in those RP deposits having low level of Fe and Al oxides, though it may not be economical at present. New beneficiation techniques have also come up in the recent past to improve the quality of RP for direct application and manufacture of P fertilizers.

Further evaluation of any RP for its efficiency may be preferably performed not for any individual crop, rather for a cropping system where ordinarily a pulse or oilseed legume should feature. Rock phosphate application can also be done under minimum tillage condition, for example rice–wheat system under conservation agriculture in Indo-Gangetic Plain (IGP) or in organic farming systems. Since soil moisture status dictates the availability of added P, the RP application needs to be encouraged under assured irrigation supply and in high rainfall areas.

Table 6. Some practicable recommendations on the direct use of rock phosphate in India.

Region, crop/cropping system	Recommendation
Western Himalayan Region, maize-wheat system	In acid soils (pH < 6.0), apply 60 kg P_2O_5 ha^{-1} as a mixture of single super phosphate and RP in ratio of 1 : 2 to maize. This proves as effective as application of entire P as single superphosphate. However, for wheat, single superphosphate performs better than RP and single superphosphate mixture.
Eastern Himalayan Region, rice-based systems	In Entisols (pH 5.1) of Jorhat (Assam), application of 30 kg P_2O_5 ha^{-1} to summer as well as monsoon rice gives higher productivity of the system. Apply RP or a mixture of SSP and RP in 1 : 1 ratio in the strongly acid soils. Use of water-soluble fertilizer (SSP) alone is not preferable. In extremely acid soils of Brahmaputra valley, Mussoorie rock phosphate applied at 40 kg P_2O_5 ha^{-1}, 20-days before rice transplanting can effectively substitute single superphosphate in rice–rice system. In rice–wheat system, application of 30 kg P_2O_5 ha^{-1} to rice and 20 kg ha^{-1} to wheat, using half the P as fertilizers (SSP + RP in 1 : 1 ratio) and remaining half as FYM slurry improves the P use efficiency.
Lower Gangetic Plain Region, rice-based systems	In acid soils, use single superphosphate and RP in 1 : 2 ratio as basal dressing for higher productivity and fertilizer P use efficiency in rice–rice system. In alkaline soils, ammonium poly-phosphate and combination of single superphosphate and RP in 1 : 2 ratio are more efficient than single superphosphate.
Central Plateau and Hilly regions, East Coast Plains and Hilly regions, and Southern Plateau and Hilly regions, rice-based systems	Rock phosphate is suitable for acidic soils of these regions. Apply RP at least 3 weeks before transplanting of rice. Mixing of SSP with fresh cow/buffalo dung (@ 50% by weight of SSP) also helps in better utilization of P in acid soils of Central Plateau and Hilly Regions. In neutral and alkaline soils of these regions, combined application of RP and pyrites (10 : 5 W/W) enhances P use efficiency.

Organic farming is slowly gaining popularity and in that endeavour, eco-friendly natural RPs should play an effective role by their direct application not only to field crops, but also to plantation and horticultural systems.

Develop methods for efficient utilization of phosphorus from various sources

The full potential of available organic resources can be utilized by preparing phosphocompost. A study conducted by Biswas and Narayanasamy[24] revealed that addition of low-grade Indian RP along with *Aspergillus awamori* to crop residue during composting helped to enhance the mobilization of unavailable P in RP to available forms of P, which in turn helped in supplying P to mung bean. Biswas *et al.*[25] found that cow dung mobilized the insoluble P from Mussoorie RP for 15–20 days, which was reflected well in the P extracted by 2% formic acid, 2% citric acid and Olsen's reagent, confirming the role of organics in P mobilization. Also, spent wash (SP) mixed in the ratio SP : RP :: 1 : 20 has been shown to mobilize P from RPs[26]. The P in RPs can be mobilized or made available to plants by treating RPs with organic materials and composting them. This technology is found promising where: (i) 'moderate to high' reactive RPs are available, but cannot be utilized for making soluble fertilizers such as SSP or TSP. (ii) There is frequent and routine addition of organic manures in soils and (iii) Organic farming is practiced (www.fao.org/docrep/007/y5053e/y5053e00.htm). The technique of composting animal manures and organic waste materials with RP (phosphocompost) for increasing the agronomic value of RP has long been known. The results of some field evaluation tests of enriched phosphocompost in some soils is given in Table 7. The largest potential sources of organic wastes for composts in India are rice straw and husk, which presently cause disposal problems. It would be appropriate to develop composting systems capable of turning both the rice residues and local RP materials into valuable fertilizers.

Some plants, especially legumes are able to increase the solubilization of P from RP through excretion of organic acids from their roots or through higher uptake of calcium. The use of RP may be encouraged in these crops.

Till now, a vast amount of human excreta has not been utilized in the country. Urine separation techniques (e.g. struvite precipitation) for direct use on agricultural land (e.g. energy crops) and for N and P recovery are now available[27]. A huge quantity of municipal and solid waste (MSW) is generated in India annually. These wastes are simply dumped into ground that not only occupies the valuable land resources but also poses threat to our environment and health hazards to citizens. The total waste generated by urban India is estimated to be 188,500 tonnes per day (TPD) or 68.8 mt per year (TPY). A total of

Table 7. Performance of enriched phosphocompost vis-à-vis chemical fertilizers

Cropping system, soil	Research finding	Reference
Rice–wheat, Alluvial soil	Higher grain yield (7.41 t ha^{-1}) of rice was obtained in the treatment receiving half of the recommended level of inorganic P in combination with 2 t ha^{-1} of phosphocompost. Maximum wheat grain yield of 5.41 t ha^{-1} was obtained in treatment receiving recommended dose of fertilizers along with 2 t ha^{-1} of phosphocompost. The relative yield of rice and wheat was 110% and 104% respectively in the treatment each receiving 2 t ha^{-1} of phosphocompost along with inorganic fertilizers. The addition of 2 tonnes of phosphocompost each to rice and wheat saved 13 kg P_2O_5 ha^{-1} in wheat and 60 kg N ha^{-1} in rice.	34
Green gram–wheat	Phosphocompost application increased the phosphorus use efficiency of green gram (12.90%) and wheat (20.48%) over single superphosphate.	35
Green gram–sorghum, black soil	Results clearly indicated that the application of nitrogen through urea with phosphocompost applied in *kharif* season enhanced the growth of *kharif* and *rabi* crops resulting in an increase of grain and fodder yield. This is due to the application of phosphocompost in *kharif* which would have solubilized more P from phosphate rock by evolving more organic acids and meets the P needs of the *rabi* crop.	36
Soybean–wheat, black soil, sorghum–wheat	Field-testing of the phospho-sulpho-nitro compost revealed that the application of 75% recommended doses of NPK + enriched compost @ 5 t ha^{-1} was superior to 100% recommended doses of NPK for soybean–wheat and sorghum–wheat. Phosphocompost is equivalent to 4.5–6.5 kg urea and 70–90 kg SSP	37
Pigeon pea, green gram, clusterbean, wheat and pearl millet, Tropical soil	Phosphocomposts prepared by mixing farm wastes, cattle dung and soil was on par with single superphosphate	38, 39

366 cities in India which represent 70% of India's urban population generate 47.2 mt per year (TPY) at a per capita waste generation rate of 500 grams/day. At this rate, the total urban MSW generated in 2041 would be 230 million TPY (630,000 TPD) and would be occupying an area totalling the area of Mumbai, Chennai and Hyderabad. Soil scientists and other environmentalists have to play a pivotal role in converting these wastes into valuable manure, which can serve as a valuable source of P, through proper composting technology[28].

Phosphate fertilizer plants in India are designed to use high grade imported RPs. However, the Indian RPs are mostly of low grade. Even the supplies from world markets also showing decline in grade. This implies that future plants need to be specifically designed to use indigenous low grade RPs or a blend of indigenous and imported RPs. Also a higher acceptable limit of deleterious constituents may be required but this needs to be examined. So far, the recommendation for the use of RP is based mainly on P_2O_5 content (Table 3). The Indian Fertilizer (Control) Order issued in 1985 for RP is that minimum 18% of total P_2O_5; and 90% should pass through 100 mesh (0.15 mm) sieve and the remaining 10% should pass through 60 mesh (0.25 mm) sieve. Whether the phosphate present in RPs is soluble is not the criterion (www.fao.org). Suitable modifications in FCO can be made by incorporating criteria such as solubility of RP and its composition clearly specifying its suitability for either direct application, fertilizer manufacture, or beneficiation. Such information is available elsewhere (http://www.geologydata.info/non_mettalic/rock.htm), however, new research data can be generated, if needed.

Search new sources of phosphorus and improve mining efficiency

There is a need to explore and exploit any undiscovered P resources and reserves in the country. In addition to geological deposits, this may involve the recycling of P from waste water, and reclaiming the existing but non-functional mines. Information about the current recovery rates in mining is inadequate, however, the reported values range between 41% and 95%[29,30].

Research information must be generated whether high reactive imported RP could be mixed with indigenous RP of low quality to make such application cost-effective and environment friendly.

Enhance utilization efficiency of phosphorus

Application of reactive RPs to the green manure crop preceding a rice-based cropping system should be encouraged. Agronomic recommendation on the method of application of RP (side placement versus broadcast) may be tailored according to the type of root spread of the cultivar (shallow compact, shallow spreading, deep compact or deep spreading) based on results of field experiments. The equilibrium phosphate potential of plant roots and soil may be used as a diagnostic tool for evaluating the probable response of cultivars to P application in responsive soils[31].

Biotechnology can offer solutions in a number of areas, for instance, to improve uptake of P by use of microbial inoculants. Advantage of P solubilizing micro-organisms such as *Pseudomonas striata*, *Aspergillus awamori* and

VA mycorrhizae be taken for effective dissolution of RP. Understanding of biogeochemical processes associated with P uptake at and around plant roots can stimulate the development of target-specific, 'smart' agrochemical agents. More research is necessary to develop efficient phosphate solubilizing biofertilizers through recombinant DNA technology for efficient utilization of P in RP.

Develop phosphorus-efficient genotypes

Engineering of nutrient-efficient crops and varieties, utilizing molecular biology and biotechnological tools, is required to develop P-efficient genotypes. Immediate objective could be to identify some P efficient genotypes from already established cultivars, as there could be many existing geographical variations in P efficiency of cultivars[32]. Phosphorus mobilization effect of pH depends on soil P compounds, therefore, will differ with soil type. Both the enhanced release of organic acids and higher acid phosphatase activity in the rhizosphere may be useful for increasing P acquisition from inorganic and organic P pools respectively. Modification of these traits by genetic means should be considered in medium term. In long-term, the role of various root traits needs to be targeted in an integrated manner and then methods need to be developed for studying their importance under natural soil conditions, so that the genotypic variation can be explored and their ecological significance in P acquisition can be established.

Develop and implement sound phosphorus policy

Though the danger of accumulation of heavy metal through continuous application of indigenous RP is less, their accumulation is to be monitored in soils where continuously heavy doses of imported RPs are used, particularly for cadmium.

It is suggested that the issue be reconsidered to amend the prevalent FCO norm on priority for high reactive imported sources for direct application to make their use cost effective. FAO has compiled the specifications for the direct use of RP (http://www.fao.org/docrep/007/y5053e/y5053e0g.htm)[33]. Such guidelines should be incorporated in FCO norms. Such policies must ensure the availability of RP in local markets.

Conclusions

Phosphorus is essential for ensuring food security in India. Indian soils are low in available P status and would require adequate P fertilization in future in order to sustain high production of food grains and other crops. Rock phosphate is the only known source for manufacturing phosphatic fertilizers. Unfortunately, India does not have adequate reserves of RP, and those present are mainly of low grade. Guidelines, however, are available for direct use of RP under several soil–crop–climatic conditions, especially where the available P status has reached high category, in plantations and high-value crops, etc. The government must take steps to ensure the availability of RP in Indian markets for its direct use. Phosphocompost making techniques, using RP, are available and their benefit has been shown under field conditions. This needs to be promoted not only in organic farming, but also in conventional agriculture. A huge amount of organic and MSW, is generated in the country and has high manure potential. At least some of this can find a place in compost making and such availability needs to be quantified region-wise. It is also desired to reuse P from any biowastes generated in the country including human excreta, manure and food waste and increase the efficiency of P use in all sectors including agriculture. Research should be promoted to understand the biogeochemical processes associated with P uptake at and around plant roots and develop P efficient genotypes. We must on priority develop technology to recover P from all forms of waste materials or even sea water, no matter at what cost, as otherwise food production will be dictated by its supply from outside in years to come.

1. Cordell, D., Drangert, J. O. and White, S., The story of phosphorus: Global food security and food for thought. *Global Environ. Chang.*, 2009, **19**, 292–305.
2. Syers, K. *et al.*, Phosphorus and food production. In *UNEP Yearbook 2011*, UNEP, Nairobi, 2011, pp. 34–45.
3. Van Vuuren, D. P., Bouwman, A. F. and Beusen, A. F., Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. *Global Environ. Chang.*, 2010, **20**, 428–439.
4. Pathak, H., Mohanty, S., Jain, N. and Bhatia, A., Nitrogen, phosphorus, and potassium budgets in Indian agriculture. *Nutrient Cycling in Agroecosystems*, 2010, **86**, 287–299.
5. Olsen, S. R., Cole, C. V., Watanable, F. S. and Dean, L., Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939, USA, 1954.
6. Parker, F. W., Nelson, W. L., Winters, E. and Miles, I. E., The broad interpretation and application of soil test Information. *Agron. J.*, 1951, **43**, 105–112.
7. Ramamoorthy, J. B. and Bajaj, C., Available nitrogen, phosphorus and potassium status of Indian soils. *Fert. News*, 1969, **14**, 24–36.
8. Ghosh, A. B. and Hassan, R., Phosphorus fertility status of soils of India, Bulletin No. 12, ISSS, 1979, pp. 1–8.
9. Hasan, R., Phosphorus status of soils in India. *Better Crops Int.*, 1996, **10**, 4–5.
10. Motsara, M. R., Available NPK status of Indian soils as depicted by soil fertility maps. *Fert. News*, 2002, **47**, 15–21.
11. Muralidharudu, Y., Sammi Reddy, K., Mandal, B. N., Subba Rao, A., Singh, K. N. and Sonekar, S., GIS based soil fertility maps of different states of India. All India Cordinated Project on Soil Test Crop Response Correlation, Indian Institute of Soil Science, Bhopal, 2011, p. 224.
12. Fertiliser Statistics, 2010–2011, The Fertilizer Association of India, Publicity Department, FAI, New Delhi, 2011.
13. Indian Minerals Yearbook 2011 (Part-II), 50th Edition, Apatite and rock phosphate (Advance Release). Government of India, Ministry of Mines Indian Bureau of Mines Indira Bhavan, Civil Lines, Nagpur, 2011, pp. 14.2–14.18.

14. US Geological Survey, *Mineral Commodity Summaries 2012: US Geological Survey*, 2012, p. 198.
15. Cordell, D., Drangert, J. O. and White, S., The story of phosphorus: global food security and food for thought. *Global. Environ. Change*, 2009, **19**, 292–305.
16. Steven, J., Van Kauwenbergh, Stewart, M. and Mikkelsen, R., World reserves of phosphate rock – a dynamic and unfolding story. *Better Crops*, 2012, **97**, 18–20.
17. Dev, G., Use of phosphate rock in food grain production under irrigated and rainfed conditions in India. In Johnston and Syers op. cit, 1998.
18. Acharya, C. L. *et al.*, Methodologies and package of practices on improved fertilizer use efficiency under various agro-climatic regions for different crops/cropping systems and soil conditions. Indian Institute of Soil Science, Bhopal, 2003, pp. 1–74.
19. Subba Rao, A., Managing phosphorus for higher efficiency and environmental quality. *J. Indian Soc. Soil Sci*., 2010, **58**, 4–14.
20. Zafar, I. Z., Anwar, M. M. and Pritchard, D. W., Beneficial route of low grade phosphate rocks for fertilizer production. *Ind. Eng. Chem. Res*., 1995, **34**, 4501–4507.
21. Mathur, B. S., Use of indigenous rock P deposits in acid soils of Chhotanagpur plateau. *Proc. FAI (ERC) Symp*., 1980, pp. 63–88.
22. Ramaswamy, S. and Arunachalam, G., Influence of Mussoorie phos on the main and residual crop of paddy in neutral soil. *Indian J. Agric. Chem*., 1983, **15**, 125–138.
23. Sarkar, D. and Sarkar, M. C., Efficiency of MRP for rice in acid soil of Assam. *J. Ind. Soc. Soil Sci.*, 1982, **30**, 48–52.
24. Biswas, D. R. and Narayanasamy, G., Rock phosphate enriched compost: an approach to improve low-grade Indian rock phosphate. *Bioresour. Technol*., 2006, **97**, 2243–2251.
25. Biswas, D. R., Subba Rao, A. and Ganeshamurthy, A. N., Mobilization of rock phosphate phosphorus using fresh cow dung and pyrite. *Indian J. Agric. Sci*., 1996, **66**, 86–90.
26. Kumari, K. and Phogat, V. K., Solubilization of phosphorus from low grade Udaipur rock phosphate from using spent wash. *Indian J. Agric. Sci.*, 2009, **43**, 219–222.
27. Tilley, E., Atwater, J. and Mavinic, D., Recovery of struvite from stored human urine. *Environ. Technol*., 2008, **29**, 797–806.
28. Solid waste management in India (http://swmindia.blogspot.in/p/introduction.html).
29. Prud'homme, M., World Phosphate Rock Flows, Losses and Uses. Paper presented at the Phosphates, 2010, Conference and Exhibition, Brussels, March 2010.
30. Van Kauwenbergh, S., World Phosphate Rock Reserves and Resources, IFDC Technical Bulletin, 75. International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA, 2010.
31. Ramamoorthy, B., The physical chemistry of the availability of plant nutrients in soils. In *Advances in Agricultural Sciences* (ed. Krishnamurthi, S.), Agricultural College and Research Institute, Coimbatore, 1965.
32. Beebe, S., Lynch, J., Galwey, N., Tohme, J. and Ochoa, I., A geographical approach to identify phosphorus-efficient genotypes among landraces and wild ancestors of common bean. *Euphytica*, 1997, **95**, 325–336.
33. Zapata, F. and Roy, R. N., Use of phosphate rocks for sustainable agriculture, FAO Land and Water Development Division and the International Atomic Energy Agency, Food and Agriculture Organization of The United Nations, Rome, 2004.
34. Singh, J., Rani, N., Sidhu, B. S. and Beri, V., Effect of phosphocompost on rice–wheat system in a non-calcareous Typic Haplustept. *J. Indian Soc. Soil Sci*., 2009, **57**, 338–344.
35. Mishra, M. M., Kapoor, K. K. and Yadav, K. S., Effect of compost enriched with mussorie rock phosphate on crop yield. *Indian J. Agric. Sci*., 1982, **52**, 674.
36. Ghadage, H. L., Mokate, A. S. and Deshmukh, P. H., Fertilizer economy through phosphocompost for sequence cropping. *Madras Agric. J.*, **90**, 523–525.
37. Manna *et al.*, Technology Bull. No-02/2006, IISS, Bhopal, 2006, pp. 1–11.
38. Bangar, K. C., Yadav, K. S. and Mishra, M. M., Transformation of rock phosphate during composting and the effect of humic acid. *Plant Soil*, 1985, **85**, 259–266.
39. Palaniappan, S. P. and Natarajan, K., Practical aspects of organic matter maintenance in soil. In *Organics in Soil Health and Crop Production* (ed. Thampan, P. K.), Peekay Tree Crops Development Foundation, Cochin, India, 1993, pp. 24–41.