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REVIEW ARTICLE

IFDC’s fifty years of research and development on the use of phosphate rock as fertilizer

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Abstract Phosphate rock (PR) is the key raw material in phosphatic fertilizers. However, the phosphorus (P) in PR is generally unavailable for crop nutrition. Currently, direct application of PR (DAPR) to crops accounts for less than 1% of the global annual P consumption of 21.4 million metric tons (Mt) of P equivalent. This paper reviews the International Fertilizer Development Center’s (IFDC) fifty years of research on DAPR as an alternative or supplement to water-soluble phosphate (WSP) fertilizers in acidic soils of the sub-humid and humid tropics. It highlights the significant advancements IFDC made in identifying basic principles determining the effectiveness of PR fertilizers including mineralogy, chemical reactivity, surface area and influential soil and crop factors. It also summarizes agronomic outcomes and identified economic factors impacting PR use. Examples of the use of the PR decision support system (PRDSS) developed by IFDC to integrate soil, crop, PR source and site factors to predict the relative agronomic effectiveness (RAE) and economic feasibility of the PR source are presented. Finally, the paper summarizes specific farming strategies and ongoing research that will influence the direct application of PR in the future.

Keywords Phosphate rock · Water-soluble phosphate fertilizers · Direct application phosphate rock · Agronomic effectiveness · Economic considerations · Phosphate rock decision support system (PRDSS) · Decentralized/localized production

Introduction

Phosphorus (P) is a critical nutrient for soil fertility and sustainable crop production in all agricultural systems. For many years, the need for P has been primarily met by using highly water-soluble P (WSP) fertilizers, including single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), and diammonium phosphate (DAP), produced from phosphate rock (PR) minerals. Recent global annual consumption of these fertilizers is about 21.4 million metric tons (Mt) of P equivalent (IFA 2022). However, high cost and limited accessibility pose significant challenges for smallholder farmers, particularly in sub-Saharan Africa and other resource constrained regions. Since its establishment in 1974, the International Fertilizer Development Center (IFDC) has addressed these challenges by advancing research on phosphate rock (PR) as a cost-effective

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and locally available alternative to WSP fertilizers with special emphasis on the use of indigenous PR on acidic soils in low-income countries (Stangel 1978). This review of IFDC's research on the direct application of PR (DAPR) is structured to present the evolution of the research from initial activities to identify inherent PR characteristics and external physical and economic factors affecting P availability, followed by a summary of hundreds of global agronomic trials, important impacts and a case study highlighting recent research. The final component notes current and future opportunities that may increase the use of PR (Barreto et al. 2018; Chtouki et al. 2022; de Amaral Leite et al. 2020).

Despite its potential, global PR consumption for direct application remains below 1% primarily due to its lower solubility compared to WSP fertilizers, variability in mineralogical properties, and logistical challenges associated with local availability and processing (IFA 2022). Adoption rates are further constrained by limited awareness of PR's agronomic benefits, inconsistent policy support, and the need for tailored recommendations based on soil and crop characteristics. In the past 50 years, IFDC has identified, characterized, modified, and chemically analyzed over 60 PRs and conducted agronomic evaluations of direct application of indigenous PRs on acidic soils in sub-humid and humid tropics in Latin America, Southeast Asia and sub-Saharan Africa (SSA). Several in-depth reviews on IFDC's global research on the agronomic effectiveness of PRs and modified PRs have been published (Chien 2003a, b; Mokwunye 1991; Chien and Menon 1995; Chien et al. 2010; Hammond et al. 1986b; Mokwunye and Vlek 1986). Thus, this paper highlights IFDC's research that identified factors determining the ability of PRs to supply plant-available P, while noting pertinent non-agronomic factors that influence adoption of DAPR for annual crops.

This review also seeks to identify the possible roles of PR sources in addressing the present-day conundrum of simultaneous deficiencies and excesses of P across global agricultural systems. In SSA, P deficiencies severely limit crop production and contribute to land and water degradation via nutrient mining and erosion (Craswell and Vlek 2010; Henao and Baanante 1999, 2006; MacDonald et al. 2011). In other regions with intensive crop production, large legacy P loads have been identified as a major cause of eutrophication and leaching of soluble P in sandy soils, resulting in degradation of surface and groundwater quality (Maguire and Sims 2002). Together, these two very different P nutrient use scenarios present major challenges to sustaining food and fiber production while addressing the increasing environmental concerns associated with land and water degradation (Mikkelsen et al. 2014; Scholz et al. 2014). They also highlight the need for sustainable P management strategies. Phosphate rock offers a potential solution by providing a cost-effective and environmentally friendly alternative for addressing P deficiencies in SSA (Iseki et al. 2024; Lompo et al. 2018; Traore et al. 2019) while reducing dependency on WSP fertilizers in regions with excess legacy P (Syers et al. 2008). However, addressing these challenges requires a nuanced understanding of the agronomic, economic and environmental factors influencing PR use.

Agronomic effectiveness of phosphate rock for direct application

Phosphate rock is a general term used to describe naturally occurring mineral assemblages with high concentrations of phosphate minerals. Almost all global production of phosphate fertilizers is based on PR containing mineral apatite. Figure 1 presents the two major types of PR deposits (sedimentary and igneous) and identifies other phosphorite occurrences resulting from coastal upwellings that deposit P-rich water on continental shelves and along coastlines (blue bands) and seamounts (blue circles) in the Atlantic and Pacific oceans (Pufahl and Groat 2017). Sedimentary PR deposits provide 80–90% of the total annual global production of PR and, depending on the level of carbonate substitution, vary in reactivity from low to high. It is the highly reactive sedimentary PRs that have the potential to substitute directly for WSP in annual crops. Igneous deposits in Brazil, Finland, Russia, South Africa, and Zimbabwe account for the remaining 10–20% of global PR production. These apatite varieties are relatively unreactive and are unsuitable for direct application (Puhafl and Groat 2017; Van Kauwenbergh 2010).

Prior to the early 1960s, researchers operated under the incorrect assumption that all PRs behave similarly when directly applied to the soil. However,

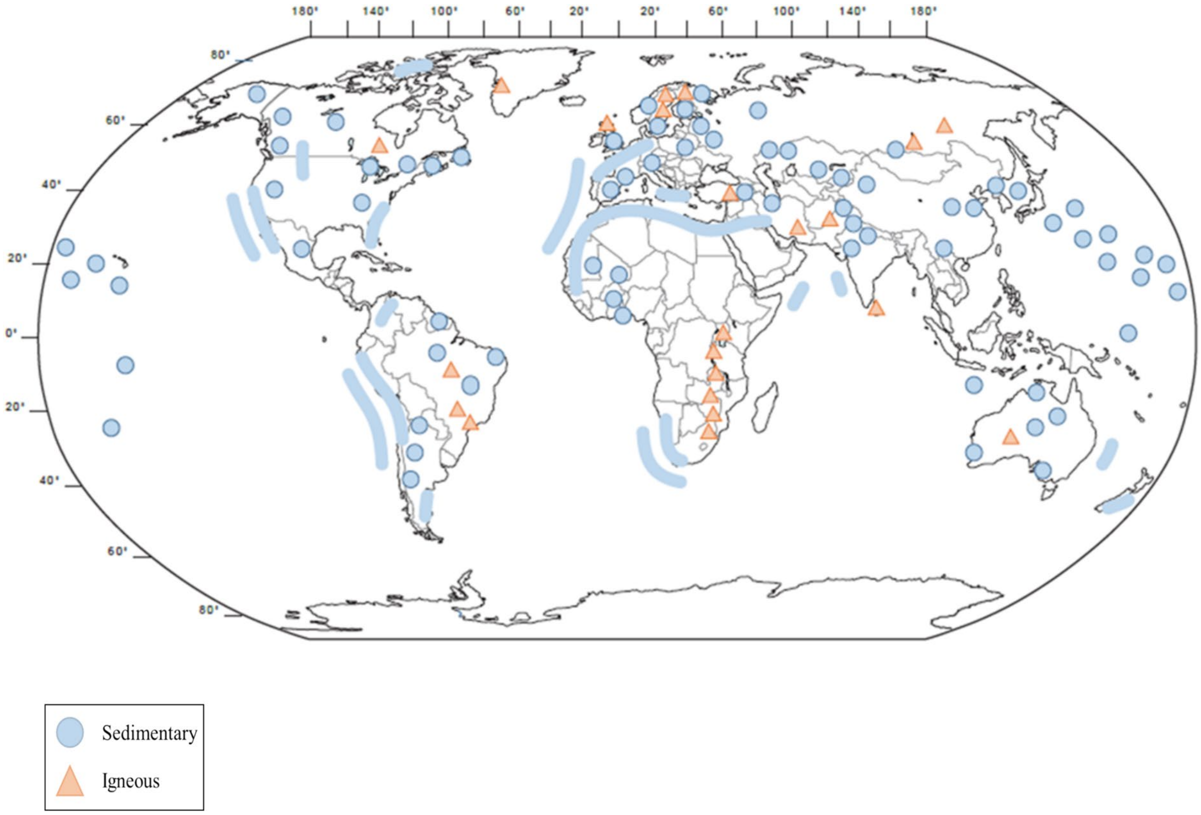

Fig. 1 Global phosphate rock deposits (Source: Pufahl and Groat 2017)

subsequent studies, including work done by IFDC demonstrated that the agronomic effectiveness of PR varies significantly depending on its mineralogical and chemical composition, as well as the influence of soil, crop, environment, and management factors.

Mineralogy and chemical composition of phosphate rock

An early report by Lehr and McClellan (1972) revealed that X-ray diffraction research indicated the mineral of most importance in PRs was apatite. Apatite varies in physical, chemical, and crystallographic properties but generally is in the form of carbonate apatite (francolite), with varying degrees of isomorphic substitutions in an empirical formula as $Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{2+0.4x}$, where a, b, and x are mole fractions of substituted ions. These results indicated the degree of isomorphic substitution of carbonate for phosphate in the apatite structure was the key factor in determining the reactivity of PR. X-ray diffraction studies also revealed that the unit cell *a*-dimension of apatite decreased as the mole ratio of CO_3:PO_4 increased. Results also confirmed earlier findings that the unit cell *a*-dimension of apatite could be used to estimate the mole fraction of carbonate substitution for phosphate. Finally, a correlation plot of neutral ammonium citrate (NAC) soluble P versus the mole ratio of CO_3 to PO_4 of the apatite in 49 different PRs demonstrated the solubility of those PRs increased as the carbonate substitution for phosphate in the apatite structure increased.

Building on these foundational studies, IFDC has undertaken detailed analyses of over 60 PR deposits located in the tropics. The mineralogy of the PRs was analyzed using X-ray diffraction, infrared spectroscopy, and electron microscopy. Comprehensive chemical analysis by extraction was used to determine the distribution of chemical species (e.g., total P_2O_5, citrate-soluble P_2O_5, CaO, SiO_2, and F content) within the mineral components (McClellan 1980; Van Kauwenbergh 2010).

Chemical reactivity of phosphate rock

Phosphate rock solubility is a critical determinant of its agronomic effectiveness. Widely used chemical extractants include neutral ammonium citrate (NAC) in the USA, 2% citric acid (CA) in most countries, and 2% formic acid (FA) in European countries. IFDC's early research disclosed that interpretation of solubility measurements could be affected by the presence of accessory minerals in association with the apatite. Chien and Hammond (1978) compared the solubility of seven PRs varying widely in apatite reactivity and free carbonate (calcite and dolomite) content. Among methods assessed, NAC2 (second extraction) and 2% FA were better correlated with crop data than NAC1 (first extraction) and 2% CA. The poorer correlation of NAC1 was attributed to depressed solubility due to the presence of free carbonates (calcite and dolomite) in some of the PRs, culminating in an underestimation of PR solubility because free carbonates are more soluble than apatite. When NAC2 was used, the solubility of the PRs correlated well with crop data.

IFDC's research on PR solubility produced three major observations: (1) recognition that the effectiveness of PR source under field conditions is impacted by climatic and environmental conditions; therefore, solubility measurements cannot be used to predict yield but can be used to predict the performance of one PR source relative to another; (2) results related to the efficient use of a particular PR can be expected to produce similar responses by other PRs of comparable solubilities under similar management scenarios; and (3) for countries with one or more PR deposits, these measurements can provide guidance on the feasibility of and priorities for resource development (Hammond et al. 1986b).

Numerous IFDC greenhouse and field studies were conducted to rank indigenous PRs located in tropical countries in terms of agronomic potential. Initial studies focused primarily on the use of Latin American PRs for crops (maize, cassava, beans, guinea grass, and ryegrass) grown on Oxisols. Hammond (1977) ranked PRs as having low, medium, or high agronomic effectiveness when used for direct application. Here, the agronomic effectiveness was significantly correlated with the solubility of the PR as indicated by NAC2. However, other factors influencing crop response were found to prevent a definitive relationship between agronomic effectiveness and solubility and only a relative ranking of PR source behavior could be predicted by solubility measurements. Of the three Latin American PRs used in the study, the agronomic effectiveness of Bayovar from Peru was classified as high, Huila from Colombia as medium, and Pesca also from Colombia as low relative to WSP (TSP). These rankings corresponded to NAC2-soluble P solubility in the range of 2.4–3.0% (high), 1.4–2.0% (medium), and 0.84–1.2% (low) (Diamond 1979).

In an expanded study, Leon et al. (1986) conducted a greenhouse trial with guinea grass (*Panicum maximum*) that included additional PRs varying in solubility along with the PRs previously used by Hammond

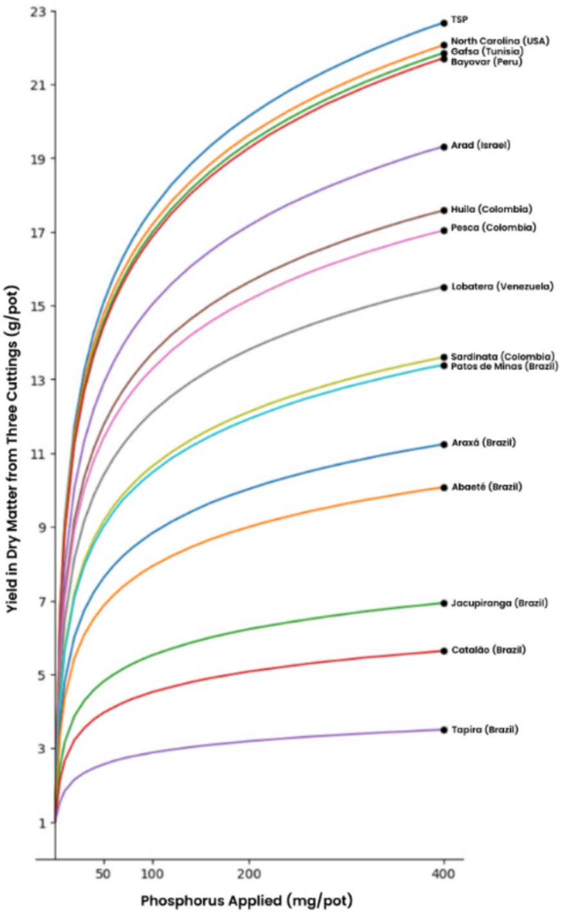

Fig. 2 Response by guinea grass to application of phosphate rock (Leon et al. 1986)

(1977). Response curves obtained from this study are illustrated in Fig. 2 and demonstrate the significant differences in the ability of the various PRs to supply plant-available P. Based on the poor yield response obtained from the inclusion of several PRs, Leon et al. (1986) proposed an additional grouping of very low (NAC2). Today, PRs designated as having very low, low, medium, and high agronomic effectiveness are commonly referred to as very low-, low-, medium-, and highly reactive PRs. By refining solubility measurement techniques and linking them to field performance, IFDC has provided critical insights for the direct application of PR. These advancements enable agronomists and policymakers to make informed decisions ensuring the sustainable use of PR as a P source in diverse agricultural systems.

Physical factors impacting the agronomic effectiveness of phosphate rock

While reactivity is a critical indicator in determining the ability of PRs to provide plant-available P, other external factors influence the agronomic effectiveness of PR, including the physical condition of PR. Since PR is water insoluble, the first step in supplying plant-available P is its partial dissolution in the soil. The physical form of the PR influences both the rate of dissolution, because of the role of surface area contact in promoting dissolution, and spatial availability of P following dissolution (Lehr and McClellan 1972).

Early recommendations on particle-size for PRs, regardless of PR solubility, called for grinding 80% through 100 mesh, thereby increasing contact of PR particles with soil for dissolution. Yet, IFDC-led research was the first to report that reactivity had a significant impact on the need for grinding. In Indonesia, multi-year trials conducted on various crops (Fig. 3) revealed that finely ground and unground highly reactive North Carolina phosphate rock (NCPR) were equally effective as TSP (Chien and Friesen 1992) due to porous apatite structures within the unground PR particles, which facilitated dissolution in acid soils (Lehr and McClellan 1972). These findings suggest the need for grinding can be minimized for highly reactive PRs, reducing processing costs and improving the feasibility of direct application in tropical agriculture. Conversely, efforts to increase the use of finely ground medium-reactive Tilemsi Valley PR resulted in farmers complaining the material was being blown away (Bationo et al. 1997). Expanding this approach to other regions and PR sources requires further evaluation under diverse agroecological conditions.

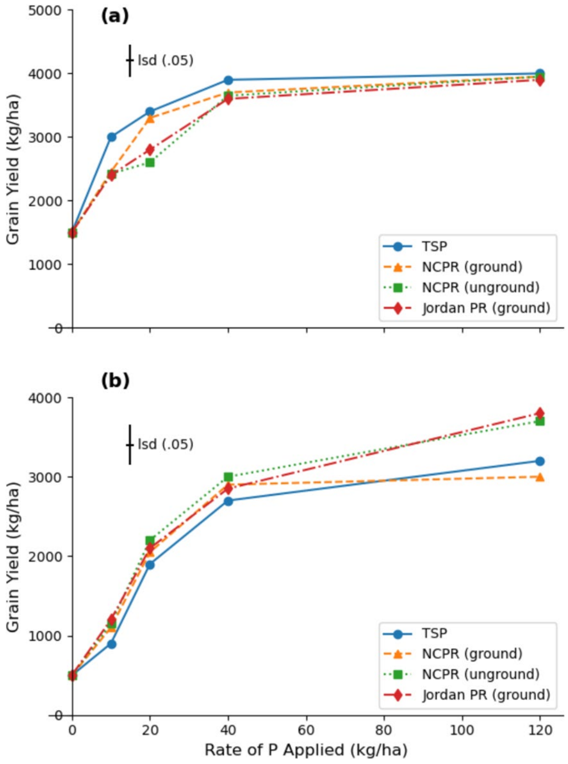

Fig. 3 Effects of P sources and rates on grain yield of (**a**) upland rice at Terbanggi and (**b**) maize at Palembang. Ground refers to – 100 mesh and unground refers to – 35 mesh (Chien and Friesen 1992)

Soil factors impacting phosphate rock use

Dissolution of PR is favored by conditions where soil pH, exchangeable Ca, and P concentration in the soil solution are low and PR contact with the soil is optimized. Additionally, soils with high organic matter content may enhance PR dissolution through the production of organic acids, which chelate Ca and maintain P in solution. Understanding these interactions is critical for optimizing PR use in diverse agricultural systems.

Soil pH: Unlike TSP, the effectiveness of PRs is highly dependent upon soil pH. Field trials by IFDC

Table 1 Effect of liming on the response of maize (grain yield) to P sources applied at 120 kg P ha^{-1} at two locations in Sumatra (Chien and Friesen 1992)

P source[a]	Kuamang Kuning		Sitiung	
	−Lime	+Lime	−Lime	+Lime
	(kg ha^{-1})			
Control	723	2332	2233	2004
TSP	1172	4924	5047	6064
NCPR (ground)	960	4380	4772	4162
NCPR (unground)	1062	3665	6976	5636
Jordan PR (ground)	1214	3404	6599	5485

[a] Ground refers to −100 mesh and unground refers to −35 mesh

in Sumatra comparing the performance of highly reactive NCPR and medium reactive Jordan PR to TSP on maize assessed the effect of liming on PR dissolution (Table 1). While liming can help reduce aluminum (Al) toxicity and improve maize growth with WSP or PR, liming provides Ca ions that decrease PR dissolution because of negative Ca common-ion effect on PR dissolution. Data in Table 1 shows liming increased maize yield with TSP or PRs at Kuamang Kuning site (pH = 5.4) whereas liming increased maize yields with TSP but decreased the maize yield with PRs at the Sitiung site (pH = 6.0). These results indicate that while liming is necessary for food crop production on highly acidic soils, lime rates should be carefully chosen to prevent significant adverse pH effects on PR dissolution (Chien and Friesen 1992).

Phosphorus sorption: The relationship of P sorption to PR dissolution was less understood and resulted in seemingly contradictory results prior to the early 1980s. To address this inconclusive information, Hammond et al. (1986a) were the first to use iron (Fe) gel to adjust the P-sorption capacity of a soil while maintaining all other soil properties (e.g., soil pH) constant (Fig. 4). The results showed that a high P-sorption capacity decreased the RAE of PR compared with WSP in short-term annual crops. However, when considering that the residual available P from WSP decreases more rapidly than that from PR, the RAE of PR increased for long-term crops. Therefore, PR can be more effective than WSP for long-term crops, such as pastures, oil palm and rubber, in tropical soils.

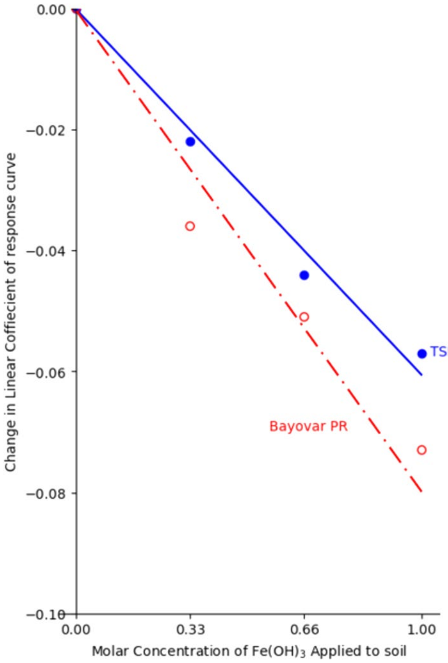

Fig. 4 Change in linear coefficients of response curves as influenced by iron-gel treatment (Hammond et al. 1986a)

Soil organic matter (SOM): Chien (1979) first demonstrated evidence of Ca^{2+} chelation by the hydrolyzed SOM upon urea addition. Results revealed that a significant amount of soluble P was released from the PR despite the extracted SOM suspension having a pH = 9.0. However, the amount of water-soluble free Ca^{2+} was very low, meaning the Ca^{2+} ions were complexed with the SOM. When the SOM was flocculated with hydrochloric acid and centrifuged, a significant amount of free Ca^{2+} was measured in the solution, suggesting release of the Ca^{2+} ions once the Ca-organic matter complex was decomposed. This mechanism, along with organic acids produced from manure, is believed to be responsible for increased P dissolution when PR is composted with manure or used in organic farming systems.

Management practices: Since the pH of acid soils increases upon flooding, it is important to manage PR application for acid soils and flooded rice. In a greenhouse study, Hellums (1991) evaluated three PR sources representing low (Hahotoe, Togo), medium (Tilemsi, Mali) and high (Bayovar, Peru) reactivity versus TSP in an acid soil (pH 4.8) for flooded rice in three management schemes: (1) Pre-flooded the soil followed by P application and rice transplanting, (2) Both P application and rice transplanting at flooding, and (3) P sources were applied to the soil at field moisture capacity two weeks prior to flooding and rice transplanting. The results showed that while TSP was not influenced by water management, all PRs performed poorly in producing rice under management scenarios (1) and (2), but scenario (3) significantly increased PR effectiveness, especially the highly reactive Bayovar PR which proved to be 83% as effective as TSP in rice production. The poor results with scenarios (1) and (2) were due to increased soil pH upon flooding whereas dissolution of PRs at field capacity for 2 weeks prior to flooding provided sufficient P to support rice production (Hellums 1991; Chien and Menon 1995; Chien et al. 1990). Therefore, management of PR applications for acid flooded rice is very important.

Crop species and PR use

The capacity of PR-based fertilizers to provide adequate P nutrition is positively influenced by crop species with extensive root systems, acidification in the root rhizosphere, long growth periods (Chien and Friesen 1992; Chien et al. 1990), and a warm moist climate (Hammond et al. 1986b). Generally, the RAE of PRs relative to WSP is higher for long-term or perennial crops compared to short-term annual crops. As noted, PR has been widely used in Asia for decades on tree crops, especially rubber and oil palm in Malaysia and Indonesia (Chien et al. 1990).

For many years, the understanding was that PR use should be restricted to acid soils, but Habib et al. (1999) reported that canola (*Brassica napus)* could utilize a medium-reactive Ain Layloun PR (Syria), even in calcareous soils. Production of organic acids in the root rhizosphere of canola was suggested as the driver for PR dissolution. In a subsequent greenhouse trial, Chien et al. (2003) found that the RAE of nine PR sources (relative to TSP) used for canola grown on an alkaline soil (pH 7.8) increased from 0 to 88% as the 2% CA solubility of the PR sources increased from 0.92 to 5.8% P. The correlation of PR solubility and RAE was highly significant ($r^2 = 0.947$). These findings indicate medium- and highly reactive PRs can be used for canola in alkaline soils.

Issues associated with the use of phosphate rock

All PRs contain heavy metals, e.g., cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and lead (Pb), and radioactive elements, e.g., uranium (U), with amounts varying among sources and even within the same deposit. Table 2 shows the results of an IFDC study of potentially hazardous heavy metals present in major deposits used for global WSP fertilizer production and in indigenous deposits evaluated

Table 2 Chemical analysis of potentially hazardous elements in selected sedimentary phosphate rocks (Van Kauwenbergh 1997)

Country	Deposit	Reactivity	P (%)	As	Cd	Cr (mg kg^{-1})	Pb	Se	U	V	Hg (µg kg^{-1})
Algeria	Djebel Onk	High	12.9	6	13	174	3	3	25	41	61
Angola	Cabinda	High	14.3	6	13		5.5			260	
Burkina Faso	Kodjari	Low	11.2	6	< 2	29	< 2	2	84	63	90
Jordan	El Hassa	Medium	14.0	5	4	127	2	3	54	81	48
Mali	Tilemsi	Medium	12.7	11	8	23	20	5	123	52	20
Morocco	Khouribga	Medium	14.7	13	3	188	2	4	82	106	566
Niger	Parc W	Low	14.7	4	< 2	49	8	< 2	65	6	99
Peru	Bayovar	High	12.9	30	11	128	8	5	47	54	118
Senegal	Taiba	Low	16.2	4	87	140	2	5	64	237	270
Tanzania	Minjingu	High	12.6	8	1	16	2	3	390	42	40
Togo	Hahotoe	Low	16.1	14	48	101	8	5	77	60	129
Tunisia	Gafsa	High	12.9	5	34	144	4	9	12	27	144
USA	Central Florida	Medium	13.6	6	6	37	9	3	59	63	371
USA	North Carolina	High	13.2	13	33	129	3	5	41	19	146

as possible substitutes for imported WSP fertilizers (Van Kauwenbergh 1997).

Among the heavy metals, Cd is of greatest concern with respect to contamination of the food chain. Several studies have indicated acid soils with high SOM (e.g., pastures) and fertilization with WSP fertilizers containing significant amounts of Cd over an extended period were conducive to increases in Cd levels in crops (Johnston and Jones 1992; Mortvedt 1992, 2005).

IFDC studies indicate that PR reactivity and soil pH are important determinants of available Cd to plants. In a greenhouse experiment with rice grown on two acid soils, Cd uptake in grain from the low-reactive Hahotoe PR (Togo) (Cd 48 mg kg^{-1}) was 80% of that obtained from the high-reactive NCPR (Cd 33 mg kg^{-1}) on soil with pH = 5.0. On soil with pH = 5.6, Cd uptake from Hahotoe PR was only 52% of that obtained with the NCPR, indicating that Cd uptake decreased with increasing pH. Results also showed that Cd uptake for rice grains increased with acidulation and most of the Cd uptake was localized in the rice roots and straw, with less than 10% in the grain. Overall, Cd uptake by the rice plant (grain, straw, and root) was higher from the NCPR treatments than from Hahotoe PR treatments (Iretskaya et al. 1998).

In a follow-up greenhouse study to determine the impact of crop species on Cd uptake (applied at a rate of 200 µg Cd kg^{-1}) in three soils varying in pH (5.0–7.7), results revealed on the more acid soil (pH = 5.0), Cd concentration in the grain followed the order of wheat = soybean > oat > flooded rice > cowpea. On the more neutral soils (pH 6.2 and pH 7.7), Cd uptake followed the order of wheat > soybean = flooded rice > oat = cowpea. These results indicate that Cd uptake varies by crop species as well as soil pH. Notably, only the cowpea grain did not exceed the maximum permissible concentration (0.100 mg Cd kg^{-1}) adopted by several European countries (Iretskaya and Chien 1999).

While there is no immediate concern related to soil and crop contamination from heavy metals in PR when P is applied at recommended rates, long-term issues may exist, warranting periodic assessment. Also, there is increasing concern related to fluorine (F) associated with PR and P fertilizers leaching into groundwater. Currently, the World Health Organization (WHO) suggests a guideline value of 1.5 mg L^{-1}. While P fertilizer production and use have been identified as the largest anthropogenic sources of F in the environment, most of this F is strongly retained in soils. Again, there is limited concern related to food contamination and groundwater contamination from the F associated with PR use, but possible leaching from the phosphogypsum ponds is a concern that requires constant monitoring (Fuge 2019; Tiwari 2023).

Highlights of IFDC findings on direct application of phosphate rock

The RAE of DAPR sources proved to be highly variable in regional field trials established by IFDC and its partners in Asia, Latin America, and West Africa. Such results were expected given the differences in the chemical solubility and reactivity of the indigenous PR sources and the great diversity in soils and cropping systems of the tropical areas of emphasis. IFDC and its many partners made a concerted effort to identify specific conditions where indigenous PRs could be agronomically effective and equally important, to identify conditions in which direct application of PR should not be recommended. Highlights of the regional research include the following:

- Direct application of medium- to highly reactive PR on long-term crops (pastures, rubber, oil palm, cocoa, and tea) is an established practice in Southeast Asia, but little is used on food crops. Beginning in 1977, IFDC as part of the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER), established a series of trials on P sources for flooded rice. Between 1977 and 1981, 84 trials were conducted on 24 sites in several Asian countries (Bangladesh, India, Indonesia, Philippines, Sri Lanka, Thailand, and Vietnam). Of the 58 trials producing a P response, the highly reactive PRs produced yields equivalent to WSP.
- Experiments in Indonesia showed that unground highly reactive NCPR was as effective as TSP in both annual and residual maize and soybean trials (Chien and Friesen 1992). The concept of using unground reactive PR (e.g., Bayovar [Peru] and Gafsa [Tunisia]) is now widely accepted (Chien and Friesen 1992).

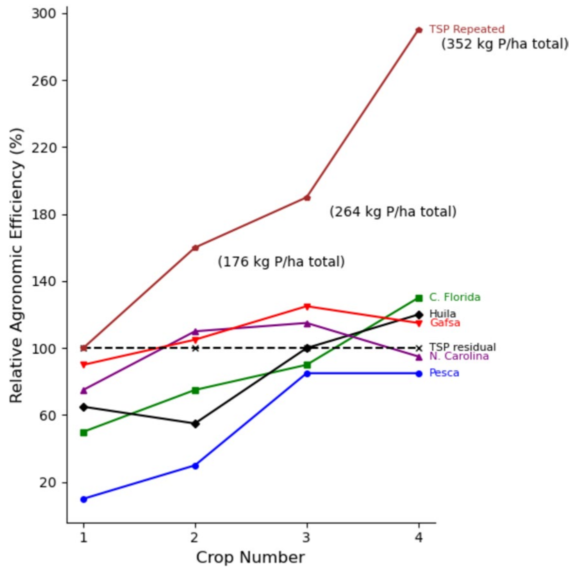

Fig. 5 Relative agronomic effectiveness of five phosphate rock sources as compared with residual and fresh triple superphosphate at 88 kg P ha^{-1} during four consecutive crops of beans (Los Guacas, Popayan, Colombia) (Hammond and Leon 1983)

- In Latin America, primary target areas for direct application of PR sources were the lowland tropics, where soils have extremely low levels of P. IFDC researchers conducted field studies in Bolivia, Colombia, Ecuador, and Peru on grain, cereal, bean crops, and pastures on Oxisols in the Colombian Llanos region and Ultisols in the Peruvian Amazon basin. The results revealed the highly reactive Bayovar PR, NCPR, and Gafsa PR were as effective as TSP across all rates for most crops. Additionally, studies conducted on cassava (three years) and signal grass (five years) that initially received a one-time application of 176 kg P ha^{-1} as highly reactive PRs or TSP showed a strong residual response, with no significant differences between sources (Hammond 1977; Hammond and Leon 1983).

  Field trials with beans as an indicator crop on Andepts in Colombia revealed that the highly reactive imported PR sources, Gafsa and North Carolina, produced yields comparable to those observed with the TSP treatment for the first cropping. The medium-reactive Huila PR (Colombia) was 66% as effective as TSP, and the low-reactive Pesca PR (Colombia) was 7% as effective. Residual studies (without additional P fertilization) showed the highly reactive PRs (Gafsa and North Carolina) were equal to or better than TSP in providing plant available P (Fig. 5). Medium-reactive PRs (Huila and Central Florida [USA]) increased in residual effectiveness until they equaled TSP in the third crop, while the residual value of low-reactive Pesca PR was 27 and 82% as effective as residual TSP for the second and third bean crop, respectively. However, overall yields were significantly improved with repeated annual application of TSP compared to cumulative yields associated with residual P (Hammond et al. 1986b).
- In 1982, IFDC scientists and national collaborators initiated evaluation of low-reactive Hahotoe PR as an annual fertilizer relative to SSP in numerous trials in Burkina Faso, Gambia, Kenya, Niger, Nigeria, Sierra Leone, and Togo. Overall, SSP was superior to Hahotoe PR at every location. Mokwunye and Vlek (1986) reported continued applications of both P sources (Hahotoe PR and SSP) at one-half the initial rate of P for two additional years raised the mean yield of the Hahotoe PR treatments to 96% of the yield obtained with SSP.
- In an Oxisol in the Gambia, the RAE of the medium-reactive Tilemsi PR (Mali) was similar to SSP for both maize and groundnut (Bationo et al. 1990).
- Observations from a three-year field study in Niger assessing the agronomic effectiveness of various P fertilizers for millet production concluded: (1) low-reactive Parc W PR (Niger) was only 48% as effective as SSP and was not recommended for direct application for annual crops; (2) finely ground medium-reactive Tahoua PR (Niger) was 82–92% as effective as SSP across all three seasons of maize cropping; (3) Tahoua PR (like Tilemsi Valley PR) should not be acidulated due to its high levels of Fe and Al oxides; and (4) over a period of three years, one initial application of a large basal dose (three times the annual dose) of P fertilizers was more effective than three annual applications in terms of total grain yield (Bationo et al. 1990).
- Low-reactive and some medium-reactive PRs are not suitable for direct application. For these PRs, IFDC developed two processes: (1) partial acidulation of PR with sulfuric or phosphoric acid and/or (2) compaction of PR with WSP to improve

agronomic effectiveness. Generally, the resulting products (containing approximately 50% of total P as WSP) increased yields significantly, but there are specific caveats for some PRs (e.g. PRs containing > 10% Fe-Al oxides). While the focus of this paper is DAPR, details of these two processes and a summary of associated agronomic results are available (Chien and Hammond 1988; Menon and Chien 1996).

- As previously noted, IFDC researchers were the first to identify canola's ability to effectively utilize P from medium-reactive PR (Ain Layloun from Syria) even on calcareous soils. IFDC scientists were also the first to report the additional benefit of PR dissolution providing Ca nutrition for plant growth on acid soils (Hellums et al. 1989).
- Because conventional soil tests for P were developed to generate fertilizer recommendations for WSP fertilizers in temperate climates, they were inadequate for evaluating the bioavailability of P in tropical soils fertilized with water-insoluble PR or modified forms of PR (Chien 1978; Hammond et al. 1986b). IFDC initiated a research program to develop a suitable soil test to enable fertilizer recommendations based on the use of PR products across a wide range of crops and soils. The designated Pi test (built on the work by Van der Pauw (1971) and Sissingh (1971)) utilized an Fe hydroxide-impregnated paper strip as a sink to sorb and retain the P mobilized in the soil suspension (Chardon and Chien 1996; Menon et al. 1989). Ultimately, the Pi test proved to be a better indicator of plant-available P, regardless of P source, over a wide range of soils, crops, and moisture regimes (Ibrikci et al. 1991; Kleinman et al. 2001; Lin et al. 1991; Sharpley 1993; USDA 2024). The Pi test (now commonly referred to as the Fe–O, FeO–P, or IIP method to reflect its use beyond soils) has proved to be an important tool for monitoring P loss in runoff, leachates, and watersheds (Maguire and Sims 2002; Wang et al. 2015).
- With funding from the World Bank and in collaboration with the French Agricultural Research Centre for International Development (CIRAD), the Norwegian Agency for Development Cooperation (NORAD), and World Agroforestry (ICRAF), IFDC contributed to the development of a methodology to evaluate the feasibility of using indigenous PRs to rebuild soil P stocks in SSA (World Bank 1994, 1997).
- The knowledge gained from IFDC's PR research (agronomic and economic) was instrumental in developing the IFDC Phosphate Rock Decision Support System (PRDSS) which enables researchers and extension agents to provide robust recommendations on where various PRs can be substituted for commercial WSP fertilizers. The PRDSS (Chien et al. 1999; Singh et al. 2003; Smalberger et al. 2006) has evolved over time based on hundreds of agronomic trials conducted globally by numerous research institutions. IFDC's latest version of the PRDSS mathematical model provided the basis for IFDC's partnership with the Food and Agriculture Organization of the United Nations (FAO) and IAEA to develop the web-based PRDSS tool that is globally available (https://prdss.ifdc.org/). It allows for the selection of crops, soils, PRs, sites/locations, and crop management practices to calculate the RAE of a specific PR for a specific area, where latitude and longitude are provided by the user. In addition to the web-based platform, IFDC developed a PRDSS app designed to calculate RAE for broader geographic scales. The app also determines the economic feasibility (relative economic effectiveness) of PR versus WSP by including prices and cost associated with both sources (Smalberger et al. 2006). While both tools share similar objectives, the app enables large-scale analyses, offering flexibility for policymakers and researchers working on regional fertilizer strategies. This dual approach ensures the PRDSS can cater to both localized and macro-level decision making needs.

Figure 6 shows the RAE prediction for maize in Tanzania, comparing two planting seasons (November 2022 and March 2023), for two indigenous PRs, sedimentary highly reactive Minjingu PR and igneous low-reactive Panda Hill PR. The results confirm that Minjingu PR has a high RAE relative to WSP fertilizers in most of the locations with its solubility and effectiveness being better during November than March, due to rainfall. In

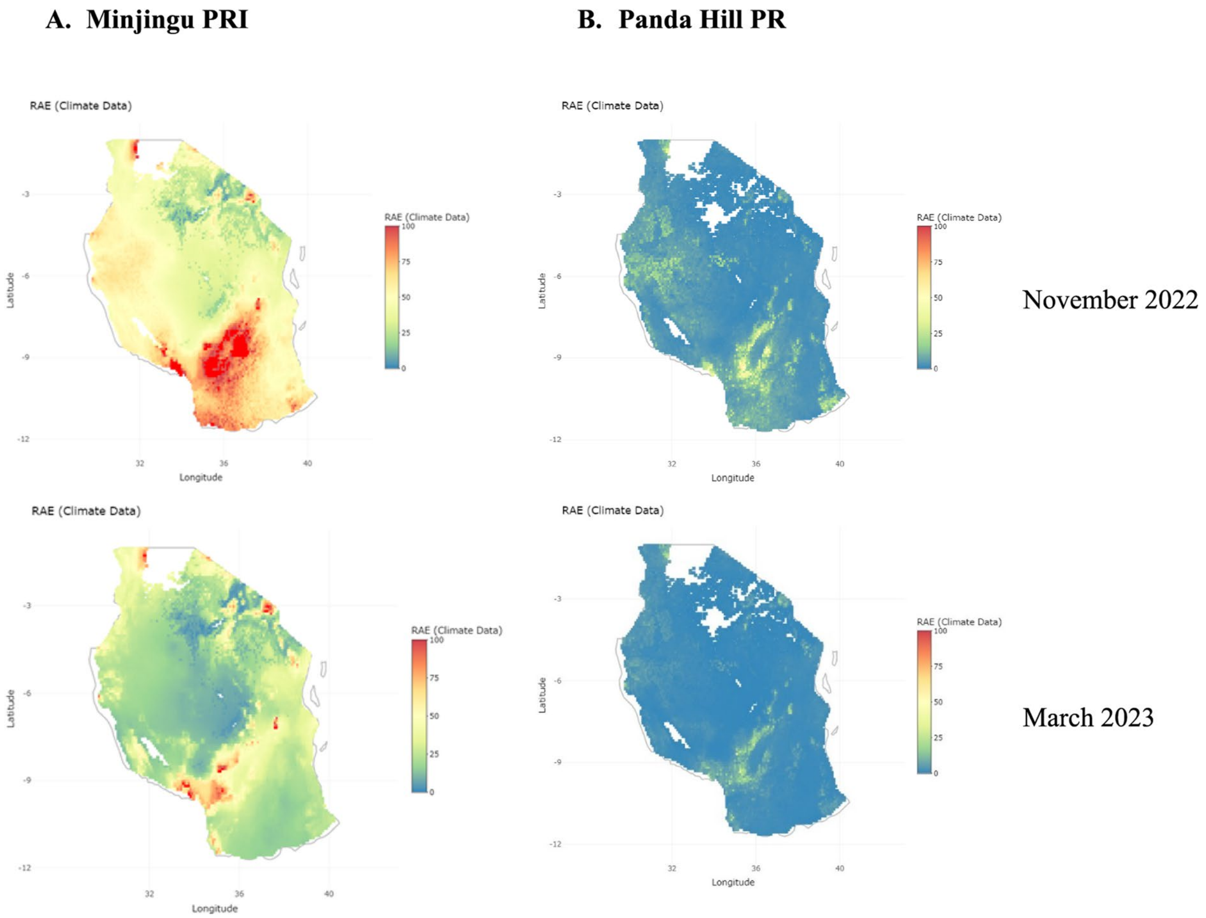

Fig. 6 Relative agronomic efficiency of Minjingu PR and Panda Hill PR, as predicted by the PRDSS app

contrast, the low-reactive Panda Hills has a very low RAE, and its suitability is limited to very few areas. These findings highlight the PRDSS's potential to guide PR use by accounting for site-specific climatic conditions, ensuring efficient and cost-effective fertilizer application. Information on agronomic performance combined with a full socio-economic evaluation that considers the size of the deposit, all production and distribution costs, socioeconomic and environmental impacts, and government policy determines whether an indigenous PR can be effectively developed and utilized. This information is critical in assisting low-income countries with indigenous PR deposits how best to address their need to improve soil P fertility.

Constraints on the use of phosphate rock for direct application

Many low-income countries possess PR deposits, but few are exploited commercially (Hellums 1992; 1995; Van Kauwenbergh 2001, 2006; Lompo et al. 2018). In many instances, there are issues related to PR availability. For example, in Peru the highly reactive Bayovar PR is primarily exported and not available to local farmers, who rely on WSP fertilizers. In West Africa, the medium reactive Tilemsi Valley deposit (Mali) has not been mined for over 20 years due to political unrest. Prior to its closure, the deposit was facing significant financial constraints due to the distance from the mine to important agricultural areas, the lack of supporting infrastructure (reliable roads), and complaints about the dustiness of the PR product (Bationo et al. 1997). Currently, the medium-reactive

Tahoua PR mine (Niger) is being operated by a private company, and the PR product is being scaled out by IFDC. While initial yield results are promising, the long-term economic viability is questionable due to the limited size of the deposit. In Burkina Faso, the low- to medium-reactive Kodjari PR has been mined on a small scale of 1000–2000 mt yr^{-1} for over 30 years. The PR is utilized in-country for maize, rice, and sugarcane. Other deposits in SSA (Minjingu in Tanzania and Cabinda in Angola), which perform well agronomically (Bationo 2024 personal communication; Prochnow 2024, personal communication), may continue to face significant competition from WSP fertilizers when considering total cost per unit of P. It is important to recognize that costs associated with mining, processing, transportation/distribution, and modification quickly drive up the farm-gate price of locally produced PR fertilizers. Additionally, policy-related factors that favor WSP fertilizers, such as fertilizer subsidies and regulations, negatively impact PR use (Bumb et al. 1994; Henao and Baanante 1999).

In SSA, only 20–40% of attainable yield is achieved for food grains due to water and multi-nutrient deficiencies (Mueller et al. 2012). As a result, agronomic response to inputs is limited, requiring a more complex integrated strategy for improving overall agricultural productivity (Bationo 2008; Breman and Debrah 2003; Mokwunye and Bationo 2002). Finally, an often-overlooked additional factor is that sustainable expansion of farmers' marketable outputs is a necessity for the adoption of fertilizers, including PR. In SSA, the lack of marketable surpluses in subsistence farming regions remains a serious hurdle to the adoption of fertilizers. In turn, sustainable marketable surpluses by farmers require market outlets and a consistent demand for their products to ensure stable and suitable prices. True valuation of these costs and benefits often results in a cost–benefit ratio unfavorable to PR (IFDC 2011).

Examples of the Impact of IFDC's phosphate rock research and development work

Work done by IFDC on PR research and development during the past 50 years has established IFDC as a leading institute on the potential use of PR for crop production in agriculture. Through collaborative efforts with governments, research institutions, and industry stakeholders, IFDC has advanced the agronomic, economic and policy frameworks for PR use. This research has resulted in significant impacts on PR use for several countries importing and exporting PR for direct application. Examples of significant impacts include:

- Prior to 1976, Malaysia only imported Christmas Island PR to address the P requirements of oil palm and rubber plantations. Later, the country began importing other PRs, creating a state of confusion for growers. Between 1976 and 1985, IFDC conducted several national and international seminars to provide accurate and scientific information on PR use. In 1986, based on IFDC's recommendations, the government revised the fertilizer regulations to state: (1) the solubility of PR should be expressed as percentage of P (P_2O_5) in the rock, rather than as a percentage of total P (P_2O_5) to ensure solubility values reflected only the plant-available P in the PR, (2) the minimum total P requirement was lowered from 13.2 to 12.3%, since total P did not impact the effectiveness of PR; and (3) unground, as-received highly reactive PRs could be used without additional grinding. The revised Malaysian regulations were later adopted by Indonesia.
- IFDC was the first to report that highly reactive unground, as-received NCPR and finely ground NCPR performed equally well in increasing maize and rice yields during three years of field trials in Indonesia. Published results provided new information to NCPR marketers that allowed them to realize significant cost savings through: (1) greatly reduced grinding cost; (2) avoidance of the dust issues associated with finely ground NCPR, which previously prevented lower-cost bulk shipping; (3) virtual elimination of adulteration and the need for hand application allowing for mechanized application; and (4) greatly reduced dust-related health issues along the production and use chain. This IFDC breakthrough result of using unground highly reactive PR for direct application has been successfully adopted by several exporting countries (Algeria, Morocco, Peru and Tunisia) and importing countries (Brazil, Indonesia, Malaysia, and New Zealand) for field crops.

- IFDC's research reported, for the first time in scientific literature: (1) canola's ability to extract plant-available P from sufficiently reactive PRs, even on alkaline soils; (2) dissolution of reactive PR provided Ca nutrition for plants; and (3) Cd uptake by upland rice from a highly reactive PR containing Cd to be much lower than that from the fully acidulated WSP produced from the same PR.
- The web-based PRDSS, resulting from the combined efforts of IFDC and FAO/IAEA, is freely available for use and has been further modified to be accessible as an app.
- In 1995 and 2001, IFDC organized two international workshops on appropriate technologies for PR use in Asia, with representatives from over 30 countries attending.
- In 2005, IFDC initiated a comprehensive study of raw materials (including PR) in Africa that could be used to increase local and regional fertilizer production (Van Kauwenbergh 2006).
- Because PR is essential to food security, the longevity of global supplies is of great interest and a source of considerable debate. In a detailed global review of PR reserves and resources, IFDC determined that, at production levels of 160–170 million Mt of PR concentrate per year, current usable reserves of PR could last 300–400 years (Van Kauwenbergh 2010).
- IFDC has conducted research and development work on PR deposits in Africa, Latin America, and Southeast Asia ranging from identification of appropriate mining and processing technologies to possible use of indigenous PRs to increase crop productivity and food security Countries include Algeria, Angola, Australia (Christmas Island), Bolivia, Brazil, Burkina Faso, Chile, China, Colombia, Ecuador, Egypt, India, Indonesia, Israel, Jordan, Kazakhstan, Mali, Morocco, Namibia, Niger, Nigeria, Pakistan, Peru, Russia, Senegal, Sri Lanka, Syria, Tanzania, Thailand, Togo, Tunisia, Uganda, USA, Venezuela, and Zimbabwe.
- For the past two decades, IFDC has been commissioned by private sector companies interested in the developing the highly reactive Namibia PR (trade name Namphos) located along the coast of Namibia (2010–2015) and the medium- to highly reactive Cabinda PR in Angola (2015–present). Research focused on (1) characterization of the apatite minerals by X-ray diffraction, (2) total chemical analysis of apatite mineral composition, (3) agronomic (greenhouse and field trials) evaluation with different soils and crops and, in the case of Cabinda PR, production of products via wet granulation of PR mixed with WSP at different ratios. In Namibia, despite very positive crop responses to direct application of Namphos on acid soils, development of the deposit remains uncertain due to environmental concerns associated with negative impacts on associated fishing grounds. A more detailed summary of activities in Angola is presented below.

Case study—Angola

Currently, Angola uses very low amounts of fertilizer (approximately 120,000 mt annually imported at a high cost) and produces average yields that are significantly below potential yields. Beginning in 2017, the private sector company Minbos launched a comprehensive nationwide effort to promote the use of indigenous Cabinda PR (via direct application) as an effective P source to address soil nutrient depletion and improve regional agricultural production. The strategy involved a thorough agronomic research strategy at various levels (laboratory, greenhouse, and field trials) in collaboration with IFDC, Plant Nutrition Science and Technology (NPCT) in Brazil and Angola's Agronomic Research Institute (IIA).

Based on the results of these activities, Cabinda PR's reactivity is classified as medium to high with most soil (average pH < 5.8, low P and Ca availability) and climatic conditions (average rainfall of 1000 mm) being suitable for direct application. However, soil pH and rainfall vary considerably in Angola, decreasing from north to south and from east to west. This suggests that Cabinda PR cannot be substituted for WSP countrywide due to limiting rainfall and pH higher than 5.8 in some areas. This result was supported by simulations using the PRDSS, which also indicated potential for this P source to be used in other low-income countries in the region with similar soil and climatic conditions. As shown in Fig. 7, the RAE was favorable and as expected, influenced by soil and climatic conditions. According to PRDSS predictions, direct application of Cabinda PR has greater potential for dry beans than maize.

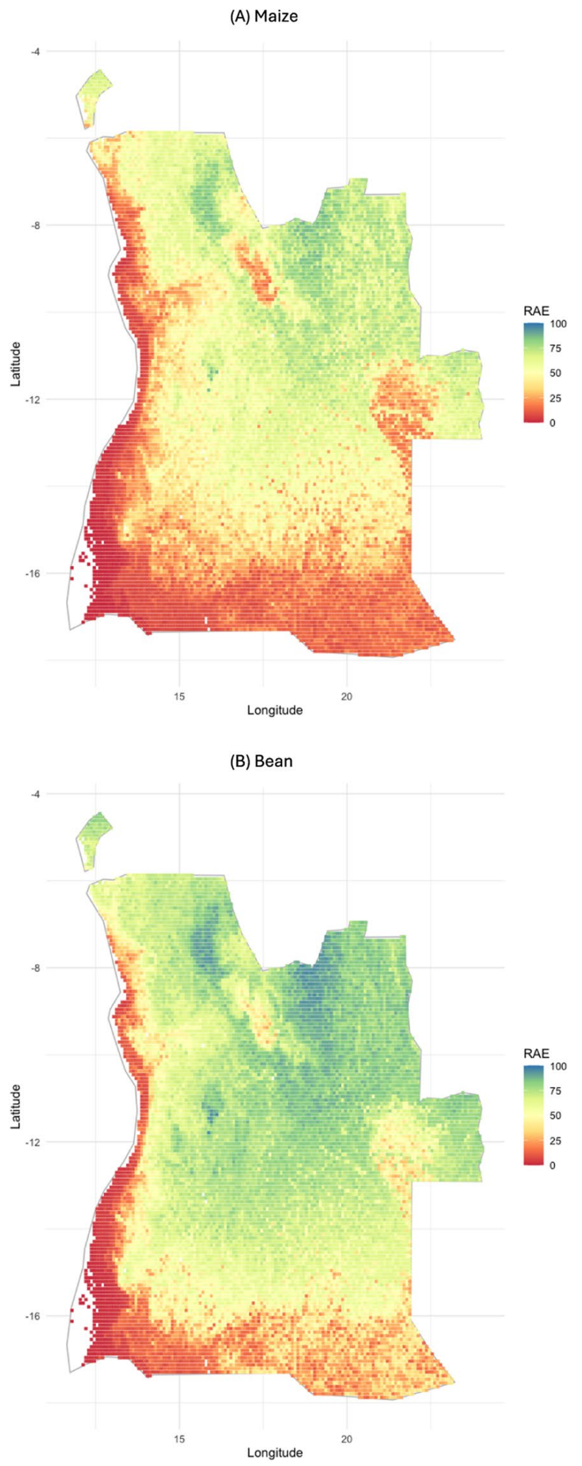

Fig. 7 Effect of soil and climatic conditions on RAE of Cabinda PR when applied on **A** maize and **B** bean for September planting in Angola

Recent field experiments compared P sources at recommended rates of P for various crops against a control treatment. The rate selected was defined by crop and soil condition, with annual (maintenance) P application ranging from 35 to 50 kg P ha^{-1}, whereas higher P-fixing soils received 40–180 kg P ha^{-1}. The sources tested were standard WSP sources (MAP or TSP), Cabinda PR, and Cabinda PR plus additional low rates of WSP. Nitrogen and K were applied at a blanket rate across all treatments. Application of Cabinda PR in all the field trials was broadcast with incorporation at 20 cm soil depth. WSP fertilizers were applied in the furrow during seeding. In total, 43 field trials were conducted (2019–2024) with 16 trials for beans, 15 for maize, 6 for potatoes, 2 for soybean and 1 each for wheat, sorghum, peanuts and sugarcane. Some of the field trials were designed to assess the effect of a large initial basal application of the Cabinda PR across four seasons to four annual applications of WSP at the recommended rate, resulting in the P applied as Cabinda PR or WSP being equal at the end of four years.

Figure 8 presents the results of some of the field trials individually, showing in general the comparative performance of the Cabinda PR source. The conclusions from the 43 field trials can be summarized as: (1) the Cabinda PR, is a medium to high reactivity PR, producing an average RAE of 75% of the RAE for WSP, and (2) surface application and incorporation (20 cm) of Cabinda PR, plus small amounts of WSP (20% of the total P applied) in furrow at seeding, increased yields over the Cabinda PR only treatments to yield levels comparable to those obtained in WSP treatments.

The results indicate Cabinda PR can be used by smallholders of Angola, to increase yields 2–3 × current levels, when combined with reasonable amounts of N and K fertilizers. Also, the results indicate that Cabinda PR combined with some WSP can be an excellent P source for intensive farming systems. In summary the Cabinda PR is a good agronomic alternative to imported WSP fertilizers for Angola and surrounding countries, but economic analysis to determine farmers' costs and benefits for each cropping system management strategy will be necessary (Prochnow 2024 personal communication).

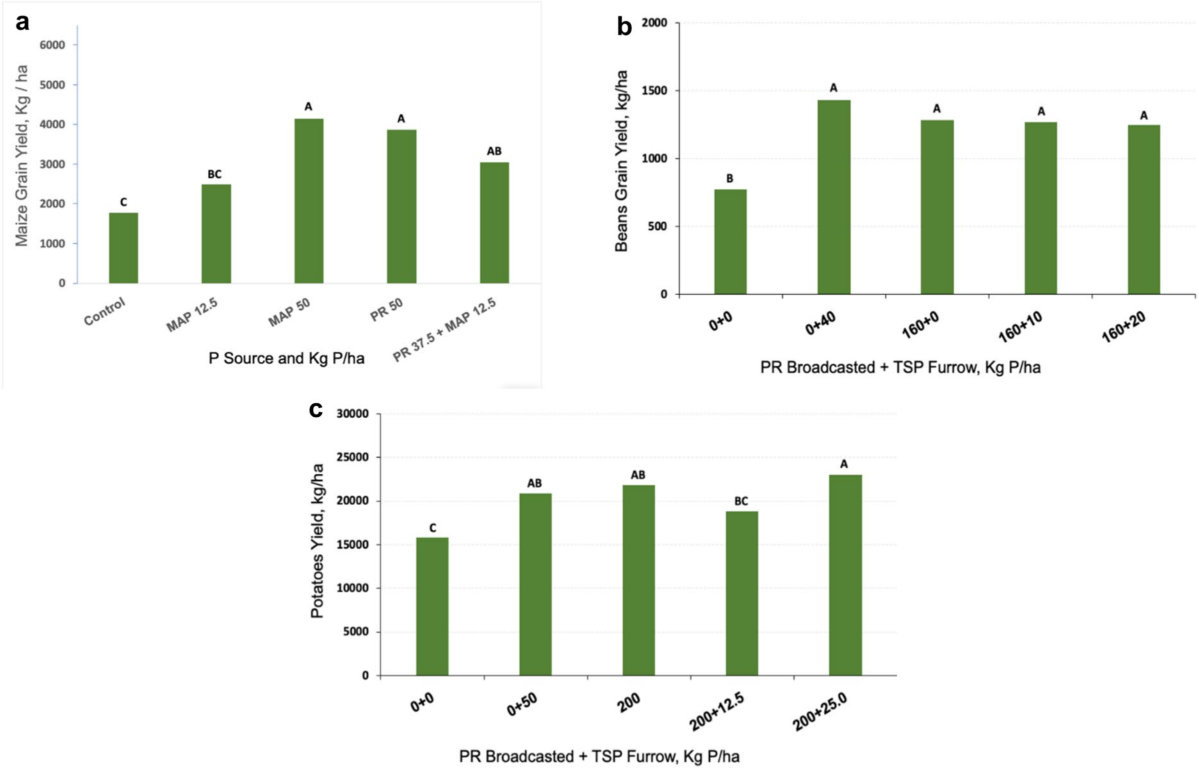

Fig. 8 Effect of P source on yields (kg ha^{-1}) of **a** maize grain at Mbaue, Huambo, Angola (pH of 5.2); **b** bean grain at Cela, Waku Kungo, Angola (pH of 5.4); and **c** potato at Humpata, Huila, Angola (pH of 6.2). Treatments designated by the same capital letter are not significantly different (Duncan test at $p < 0.10$)

Current and future opportunities for direct application of phosphate rock for improved soil health

Despite the extensive research and numerous encouraging results on the use of direct application of PRs on food crops in the tropics, few examples of farmer adoption exist outside tree crops and pastures in Southeast Asia. For the foreseeable future, this will remain the primary market, in part due to the limited availability of reactive PRs for direct application, the mature nature of the WSP market, and the current full cost–benefit ratio of WSP relative to reactive PR, including non-agronomic costs. Due to extensive PR research, additional PR sources have been commercialized for export from Algeria, Australia, China, Egypt, Israel, Jordan, Morocco, and Tunisia to Brazil, Indonesia, Malaysia, and New Zealand. In some low-income countries, indigenous PR sources are being successfully marketed for local use in Burkina Faso, Chile, Colombia, Niger, and Tanzania. Angola PR (Cabinda) is scheduled to be available in late 2025. In the future, emerging opportunities in organic farming, decentralized P fertilizer production, soil remediation, and integrated soil fertility management (ISFM) present promising avenues for expanding PR utilization beyond the foundational work of IFDC and others previously noted.

Organic farming, now practiced on over 96 million hectares worldwide (Willer et al. 2025), is expected to increase the demand for PR. Approved P sources for organic farming include PR, manure, and compost. Factors affecting the agronomic effectiveness of PR in organic farming are virtually the same as those for conventional farming, except for PR combined with composting. Here, initial research suggests that chelation of organic matter with Ca ions derived from apatite is the main mechanism driving PR dissolution in organic systems (Chien 1979) rather than soil acidity, as in the case of conventional farming (Chien et al. 2009). Combining PR with organic amendments such as compost, manure and biochar (Chtouki et al. 2022; Viana et al. 2024) can create synergistic effects to enhance soil health. Co-composting PR with plant residues or manure can increase microbial activity and produce organic acids that help dissolve apatite, accelerating the release of P (Kpomblekou and Tabatabai 1994; Sagnon et al. 2024). These integrated approaches maximize PR's agronomic effectiveness by providing slow-release P, enhancing soil fertility, and promoting a more resilient and sustainable cropping system (Tumbure et al. 2020; Zhang et al. 2022).

Organic farmers utilizing manure and compost as primary N inputs will most likely see high soil P tests, due to these inputs having high P availability. Here, management strategies must focus on minimizing P buildup and prevention of surface water P losses. Conversely, producers limiting use of manures and composts will experience higher rates of P removal and will need reactive PR inputs to sustain profitable crop production. For all producers, recognition that PRs are not equal in agronomic effectiveness is important. Thus, soil testing and knowledge of management history will be critical to overall P management (Nelson and Janke 2007).

Phosphate fertilizers (including reactive PRs) are unique in that they function as fertilizers and as an amendment through the provision of annual or labile P for the first crop and residual P for subsequent cropping. Thus, P fertilizers play a significant role in IFDC's ISFM approach utilized in SSA to increase food production while improving soil health (Bationo and Mokwunye 1991; Bationo et al. 2020; Breman and Debrah 2003; Vanlauwe et al. 2023; Winterbottom et al. 2013). Here, the importance of residual P in rebuilding soil P levels cannot be overstated. The residual effect is evidence that P fertilizers provide a flow of benefits to farmers and the soil resource base over several years and should be considered a capital investment (Baanante 1998; Buresh et al. 1997; IFDC 1997; Jama et al. 1997; Syers et al. 2008; Teboh 1995). While this investment would contribute to sustainable increases in crop production and prevent environmental degradation (particularly in sub-Saharan Africa [SSA]), there are significant barriers to replenishing soil P and using PR, as revealed in studies funded by the World Bank (1994, 1997). These include (1) substantial cost of inputs, regardless of source or option (one-time basal or gradual moderate applications); (2) additional labor, erosion prevention, and equipment costs associated with a one-time basal application; (3) land tenure issues, which preclude farmers' interest in long-term benefits (Bumb and Baanante 1996); and (4) specific to SSA, only a few indigenous PR deposits currently being mined that could be utilized in a replenishment strategy.

Conversely, in countries with a long history of P fertilizer use, many soils are at or near the critical level for P. For these soils, the current recommendation is that a maintenance level of P be applied annually to replace the P removed by the harvested crop (Syers et al. 2008). This situation (assuming favorable economics and PR availability) could offer an opportunity to replace WSP with reactive PRs for annual crops on acid soils in intensive farming areas in the East Asian floodplains, North America, Europe, and Latin America. For intensive farming systems with moderate to high soil P fertility, future research should evaluate reactive PRs' ability to maintain crop productivity (Chien and Friesen 1992).

Currently, the potential exists for the use of direct application of PR to reclaim acid mine spoils and to remediate soils contaminated with Pb. The highly acidic pH of acid mine spoils suggests that low-reactive PR sources may also be viable. Research associated with this use should examine the long-term reactions of PR with these soils in terms of available P, type of P compounds formed, and rate of PR decomposition. The agronomic value of Ca from PR should also be considered because these soils are low in Ca and usually require liming.

Pb contamination in soil is of concern not only because of its toxicity to animals and humans, but also because of its ease of exposure through ingestion or inhalation. Early research noted the use of P fertilizers to immobilize Pb by converting the less stable Pb compounds (e.g., cerussite [$PbCO_3$]) to more stable Pb compounds with very low solubility and bioavailability (e.g., chloropyromorphite [$Pb_5(PO_4)_3Cl$]) (Lindsey 1979). Generally, WSP fertilizers are more effective than PRs in reducing soluble Pb. However, assuming lower costs, PR may be more economical for large-scale soil remediation. Again, the effectiveness of PR in immobilizing Pb is determined by the reactivity of the PR used (Chien et al. 2009, 2010).

For less reactive PRs in SSA, compaction with WSP, N, and K needs further consideration.

One-step dry granulation/compaction offers several benefits, including increased PR dissolution and agronomic effectiveness, a means of delivering a multi-nutrient fertilizer, and the elimination of dust issues at the distribution and farm levels (Traore et al. 2019). Also, the effect of mini-granulation (process to produce relatively small PR granules from finely ground PR) on the agronomic effectiveness of less reactive PRs is not known and needs to be examined.

In addition to partial acidulation and granulation/compaction processes, there is interest in using acid waste effluents to produce P fertilizers. Initial findings indicate the reaction between low-reactive igneous PRs (Araxa and Patos from Brazil) and acid mine waste produced more soluble P, thus improving plant P uptake and yield, with an insignificant increase in heavy metal content. This study suggests the recycling of acid metallurgical waste may be an effective means to increase the agronomic potential of low-reactive igneous PR (Mattiello et al. 2016; Barreto et al. 2018), but issues with by-product waste remain and heavy metal content should be monitored.

The integration of PR and green ammonia presents a transformative opportunity for decentralized production to produce sustainable fertilizers. Phosphate rock can react with green ammonia derived from nitric or phosphoric acid to produce fertilizers like MAP or DAP. Additionally, partially acidulated PR created using diluted acid from green ammonia processing offers a cost-effective opportunity. This synergy supports the development of tailored compound fertilizers, such as NP and NPK formulations to address specific soil and crop needs, facilitating decentralized production models and reducing transportation costs.

Biological means of improving the agronomic effectiveness of low-reactive PRs continue to be explored. Much research is being conducted to capture the benefits of soil microorganisms that enhance nutrient acquisition, particularly P acquisition using phosphate-solubilizing microorganisms (PSB) and arbuscular mycorrhiza fungi (AMF) (de Amaral et al. 2020; Goenadi et al. 2000; Koele et al. 2014). Most notable is the significant amount of research dedicated to the identification of PSB strains capable of improving PR solubilization through the secretion of various organic acids. Bacteria from numerous genera (*Pseudomonas, Agrobacterium, Bacillus,* etc.) are capable of solubilizing unavailable P. While multiple PSB inoculants have been used in agriculture, many exhibit insignificant effects due to low adaptive capacity in the field. Research has also shown difficulties in reproducing bacterial P solubilization (Elhaissoufi et al. 2022).

Most plants have a symbiotic relationship with AMF, with AMF accounting for 5–50% of the total biomass of soil microbes (Olsson et al. 1999). These fungi are known for scavenging soil P under P-limiting conditions. Conversely, research has shown that soils with sufficient or excessive amounts of P limit the efficacy of AMF inoculation, thereby implying targeted AMF inoculation should be more effective in low fertilizer input systems utilizing less soluble PR sources (Ryan and Graham 2002).

Despite the significant advances in agricultural microbiology, the development of cost-effective large-scale production of PSB and VMF inoculum is complex, with commercial exploitation being limited to soybean and possibly sugarcane in Brazil. There are also patent law issues with the commercial use of indigenous inoculum (considered to belong to the global commons) being converted to private property (Kothamasi et al. 2011).

Further research is needed to determine the effects of management practices and different cropping systems on the performance of PRs. Since PR dissolution is influenced by the amount of surface area brought into direct contact with the soil, complete incorporation is considered the most suitable method of application. However, on soils with high P retention, incorporation reduces the effectiveness of WSP fertilizers and PRs. While band application reduces P retention from WSP fertilizers, it would also reduce PR dissolution. A similar effect would be expected with the use of the strategic application of fertilizer via microdosing, a technique developed for and widely adopted in the Sahelian countries (Bationo et al. 2020). This approach involves the application of small doses of commercial N, P, and K fertilizers close to the plant as a means of increasing nutrient use efficiency while reducing fertilizer investment cost. The microdosing approach of feeding the plant was designed for use with WSP fertilizers; replacement of WSP with reactive PR could result in a reduction of soluble P due to reduced surface area contact with the soil and needs additional study.

Application method is also an important consideration in the viability of reactive PR use in no- or low-till scenarios, where surface broadcast application reduces contact with the soil, particularly in annual cropping systems. The use of direct application of reactive PRs in flooded rice cropping systems requires more investigation. Because acidic soils trend to neutral pH on flooding, soil pH conditions would not be conducive to PR dissolution. Engelstad (1974) reported that highly reactive NCPR was not comparable to TSP in flooded rice systems, while Hellums (1991) reported highly reactive Bayovar PR was 83% as effective as TSP when P fertilizers were added to the soil two weeks prior to flooding. Since rice-based cropping systems are diverse and extensive, further research is necessary to identify the management practices that most improve PR viability (Chien and Friesen 1992).

Most published research has focused on the relationship between conventional WSP fertilizers and eutrophication. Little information is available in the literature on the use of non-conventional P sources, such as reactive PR, and their impact on P runoff. Preliminary research found that the use of reactive PRs minimized eutrophication compared to WSP sources because of lower P availability from PRs for algal growth. Shigaki et al. (2007) presented results revealing that P losses from surface runoff were significantly lower on three soils with reactive NCPR compared with TSP. Additional work, including field studies, is needed to validate this finding and to more clearly define the edaphic and climatic conditions under which directly applied PR will effectively substitute for WSP in soils with significant P reserves.

Concerns remain about the impact of prolonged use of PRs containing hazardous elements on global agricultural soils. Research on recovering hazardous elements, such as U and rare earth elements, from PR is warranted. When demand for U was high in the past (1980s–1990s), it was commercially recovered as a byproduct of wet phosphoric acid production in Florida (USA). Extracting U during phosphate fertilizer production is desirable since otherwise lost resources (U) are conserved and the fertilizer (and byproducts) produce less radiotoxic heavy metals. However, removing U from PR presents technological and economic challenges, since heavy metal removal requires additional processing (e.g., direct leaching) prior to the usual processing steps. The increasing need for clean energy options, such as nuclear power, and rare earth element technologies is resulting in a resurgence of interest in recovery from PRs, as global demand exceeds supply (Haneklaus et al. 2017; Haneklaus et al. 2024; Mwalongo et al. 2023; Steiner et al. 2020; Ulrich et al. 2014). Cost-effective removal of these elements could have positive benefits for PR use, particularly in SSA.

Summary

All farmers have a deep appreciation for the physical, biological, and socio-economic elements of their environment. They do not willingly degrade their soil resources but apply soil fertility improvement strategies that are within their reach. For smallholders, gaining access to affordable P nutrients is crucial for improving food production, livelihoods, and soil health. Under these circumstances, direct application of indigenous or regional reactive PRs is proposed as a possible alternative to annual WSP fertilizer, assuming availability of a cost-effective reactive PR as well as appropriate soil properties and cropping systems. While direct application of medium- or highly reactive PRs may offer opportunities for the agronomic use of a limited number of these deposits, many factors must be considered in determining whether domestically produced PRs offer a competitive advantage over commercial WSP fertilizers, particularly for annual crops. While potential markets do exist, several factors other than RAE have historically influenced the use of PR sources. It should not be assumed that the presence of an indigenous PR deposit will result in a lower-cost solution to soil P infertility.

For farmers practicing intensive or organic agriculture, reactive PR could substitute for WSP in supplying maintenance doses of P. However, a caveat to be considered is the limited availability of reactive PR in the market. Highly reactive NCPR, Bayovar PR, and Gafsa PR have consistently provided plant-available P comparable to WSP sources, but only Gafsa PR is being used in significant amounts for direct application. NCPR is only used for production of processed phosphate concentrates, as is much of the Bayovar PR exported from Peru. Because WSP fertilizer production is a mature industry resilient to disruption, the use of reactive PR for direct application in intensive cropping systems appears limited in the foreseeable future.

Future research to determine whether PRs will have an expanded role as P fertilizers will require additional investigation of physical and chemical processes to improve solubility and produce NPKs containing PR, the biological means to improve PR solubility, effective management practices for PRs in various cropping systems, impacts on eutrophication, and identification of cost-effective means of removing heavy metals from reactive sedimentary PRs.

Like all fertilizer use, the underlying and linked considerations that should govern PR use must be agronomic performance, nutrient use efficiency, cost effectiveness, and environmental impacts. The best practices of ISFM should be implemented when applying reactive PRs or WSP fertilizers to P-deficient acid soils, especially in SSA, while intensive farming systems call for the use of the 4R Principles of Nutrient Stewardship (right source, right rate, right time, and right application method) to be given priority. Improving P recovery and efficiency while reducing negative environmental effects are important short-term goals and will require a sensible strategy to produce more food while minimizing P losses. Only techniques which are logistically, technically, and economically feasible should be adopted.

Author contributions DTH and SHC wrote the main manuscript text, while LP, MD and US provided figures 6-8 along with descriptive text. All authors reviewed the manuscript.

Declarations

Author contributions DTH and SHC wrote the main manuscript text, while LP, MD and US provided Figs. 6–8 along with descriptive text. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Conflict of interest The authors declare no competing interests.

References

Baanante CA (1998) Economic evaluation of the use of phosphate fertilizers as capital investment. In: Johnston AE, Syers JK (eds) Nutrient management for sustainable agriculture in Asia. CAB International, Wallingford, pp 109–120

Barreto WSC, Mattiello EM, Santos WO, Melo LCA, Vergütz L, Novais RF (2018) Agronomic efficiency of phosphate fertilizers produced by the re-use of metallurgical acid residue. J Environ Manag 208:1–7. https://doi.org/10.1016/j.jenvman.2017.11.075

Bationo A (2008) Integrated soil fertility management options for agricultural intensification in the Sudano-Sahelian zone of West Africa. Academy Sci Pub/TSBF/CIAT, Amsterdam

Bationo A, Mokwunye AE (1991) Role of manures and crop residue in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. In: Mokwunye AE (ed) Alleviating soil fertility constraints to increased crop production in West Africa. Kluwer Academic, Dordrecht, pp 217–226

Bationo A, Chien SH, Henao J, Christianson CB, Mokwunye AE (1990) Agronomic evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. Soil Sci Soc Am J 54:1772–1777. https://doi.org/10.2136/sssaj1990.03615995005400060045x

Bationo A, Ayuk E, Ballo D, Koné M (1997) Agronomic and economic evaluation of Tilemsi phosphate rock in different agroecological zones of Mali. Nutr Cycl Agroecosyst 48:179–189

Bationo A, Singh U, Dossa E, Wendt J, Agyin-Birikorang S, Lompo F, Bindraban P (2020) Improving soil fertility through fertilizer management in Sub-Saharan Africa. In: Lal R (ed) Soils and fertilizers. CRC Press, Boca Raton, FL, pp 67–102. https://doi.org/10.1201/9780429471049-4

Breman H, Debrah SK (2003) Improving African food security. SAIS Rev 23:153–170. https://doi.org/10.1353/sai.2003.0002

Bumb BL, Baanante CA (1996) The role of fertilizer in sustaining food security and protecting the environment to 2020. IFPRI, Washington DC

Bumb BL, Teboh JF, Atta JK, Asenso-Okyere WK (1994) Ghana policy environment and fertilizer sector development. Tech Bull T-41, International Fertilizer Development Center, Muscle Shoals, AL

Buresh RJ, Smithson PC, Hellums DT (1997) Building soil phosphorus capital in Africa. In: Buresh RJ et al. (ed)

Replenishing soil fertility in Africa. Soil Sci Soc Am J, Madison WI, pp 111–149. https://doi.org/10.2136/sssaspecpub51.c6

Chardon WJ, Chien S (1996) Iron oxide impregnated filter paper (Pi test): a review of its development and methodological research. Nutr Cycl Agroecosyst 46:41–51. https://doi.org/10.1007/BF00210223

Chien SH (1978) Interpretation of Bray 1 extractable phosphate from acid soil treated with phosphate rock. Soil Sci 144:34–39

Chien SH (1979) Dissolution of phosphate rock in acid soils as influenced by nitrogen and potassium fertilizers. Soil Sci 127:371–376

Chien SH (2003a) IFDC's evaluation of modified phosphate rock products. In: Rajan SSS, Chien SH (eds) Proceedings of international meeting on direct application of phosphate rock and related technology: Latest developments and practical experiences, Kuala Lumpur, Malaysian Soc Soil Sci and IFDC, Muscle Shoals, AL, USA, pp 66–77

Chien SH (2003b) Factors affecting the agronomic effectiveness of phosphate rock: a general review. In: Rajan SSS, Chien SH (eds) Proceedings of international meeting on direct application of phosphate rock and related technology: Latest developments and practical experiences, Kuala Lumpur, Malaysian Soc Soil Sci and IFDC, Muscle Shoals, AL, USA, pp 50–62

Chien SH, Friesen DK (1992) Phosphate rock for direct application. In: Sikora FJ (ed) Future directions for agricultural phosphate research. TVA-NFERC, Muscle Shoals, AL, pp 47–52

Chien SH, Hammond LL (1978) A comparison of various laboratory methods for predicting the agronomic potential of phosphate rocks for direct application. Soil Sci Soc Am J 42:935–939. https://doi.org/10.2136/sssaj1978.03615995004200060022x

Chien SH, Hammond LL (1988) Agronomic evaluation of partially acidulated phosphate rocks in the tropics. Paper series P-7, International Fertilizer Development Center, Muscle Shoals, AL

Chien SH, Menon RG (1995) Factors affecting the agronomic effectiveness of phosphate rock for direct application. Fert Res 41:227–234. https://doi.org/10.1007/BF00748312

Chien SH, Singh U, Van Reuler H, Hellums DT (1999) Phosphate rock decision support systems for sub-Saharan Africa. Special issue on soil fertility. Afr Fert Mark 12:15–22

Chien SH, Carmona G, Henao J, Prochnow LI (2003) Evaluation of rape response to different sources of phosphate rock in an alkaline soil. Comm Soil Sci Plant Anal 34:1825–1835. https://doi.org/10.1081/CSS-120023217

Chien SH, Prochnow LL, Canatarella H (2009) Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. Adv Agron 102:267–322. https://doi.org/10.1016/S0065-2113(09)01008-6

Chien SH, Prochnow LI, Tu S, Snyder CS (2010) Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: an update review. Nutr Cycl Agroecosyst. https://doi.org/10.1007/s10705-010-9390-4

Chien SH, Sale PWG, Hammond LL (1990) Comparison of effectiveness of various phosphate fertilizer products. In: Proceedings of international symposium on phosphorus requirements for sustainable agriculture in Asia and Oceania. IRRI, Manila, pp 143–156

Chtouki M, Bargaz A, Lyamlouli K, Oukarroum A, Zeroua Y (2022) A phospho-compost biological-based approach increases phosphate rock agronomic efficiency in faba bean as compared to chemical and physical treatments. Environ Sci Pollut Res Int 49:74012–74023. https://doi.org/10.1007/s11356-022-21087-z

Craswell ET, Vlek PLG (2010) Nutrient mining in African soils due to agricultural intensification. In: Lal R, Stewart BA (eds) Principles of sustainable soil management in agroecosystems, Adv Soil Sci. CRC Press, Boca Raton, pp 401–421

de Amaral Leite A, de Souza Cardoso AA, de Almeida Leite R, de Oliveira-Longatti SM, Filho JFL, de Souza Moreira FM, Melo LCA (2020) Selected bacterial strains enhance phosphorus availability from biochar-based rock phosphate fertilizer. Ann Microbiol 70(1):6. https://doi.org/10.1186/s13213-020-01550-3

Diamond RB (1979) Views on marketing of phosphate rock for direct application. In IFDC (ed) Seminar on phosphate rock for direct application, IFDC, Muscle Shoals, AL USA, pp 448–463

Elhaissoufi W, Ghoulam C, Barakat A, Zeroual Y, Bargaz A (2022) Phosphate bacterial solubilization: a key rhizosphere driving force enabling higher P use efficiency and crop productivity. J Adv Res 38:13–28. https://doi.org/10.1016/j.jare.2021.08.014

Engelstad OP, Jugsujinda A, De Datta SK (1974) Response by flooded rice to phosphate rocks varying in citrate solubility. Soil Sci Soc Am J 38:524–529

Fuge R (2019) Fluorine in the environment, a review of its sources and geochemistry. Appl Geochem 100:393–406. https://doi.org/10.1016/j.apgeochem.2018.12.016

Goenadi D, Siswanto H, Sugiarto Y (2000) Bioactivation of poorly soluble phosphate rock with a phosphorus-solubilizing fungus. Soil Sci Soc Am J 64:927–932. https://doi.org/10.2136/sssaj2000.643927x

Habib L, Chien SH, Carmona G, Henao J (1999) Rape response to a Syrian phosphate rock and its mixture with triple superphosphate on a limed alkaline soil. Commun Soil Sci Plant Anal 30:449–456

Hammond LL (1977) Effectiveness of phosphate rocks in Colombian soils as measured by crop response and soil phosphorus levels. Dissertation, Michigan State University

Hammond LL, Leon A (1983) Agronomic effectiveness of natural and altered phosphate rocks from Latin America. In: IMPHOS (ed) 3rd international congress on phosphorus compounds, Brussels, pp 503–518

Hammond LL, Chien SH, Easterwood GW (1986a) Agronomic effectiveness of Bayovar phosphate rock in soil with induced phosphorus retention. Soil Sci Amer J 50:1601–1606

Hammond LL, Chien SH, Mokwunye AU (1986b) Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. Adv Agron 40:89–140

Haneklaus N, Bayok A, Fedchenko V (2017) Phosphate rocks and nuclear proliferation. Sci Glob Secur 25:143–158. https://doi.org/10.1080/08929882.2017.1394061

Haneklaus NH et al (2024) Rare earth elements and uranium in Minjingu phosphate fertilizer products: plant food for thought. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2024.107694

Hellums DT (1991) Factors affecting the efficiency of nonconventionalphosphorus fertilizers in lowland and upland-cropping systems. Dissertation, Auburn University

Hellums DT (1992) Role of nonconventional phosphate fertilizers in tropical agriculture: IFDC's research perspective. In: Schultz J (ed) Phosphate fertilizers and the environment. IFDC, Muscle Shoals, AL, pp 89–95

Hellums DT (1995) Environmental aspects of phosphate fertilizer production and use. In: Dahanayake K, Van Kauwenbergh SJ, Hellums DT (eds) Direct application of phosphate rock and appropriate technology fertilizers in Asia-What hinders acceptance and growth. IFDC, Muscle Shoals, AL, pp 105–113

Hellums DT, Chien SH, Touchton JT (1989) Potential agronomic value of calcium in some phosphate rocks from South America and West Africa. Soil Sci Soc Am J 53:459–462

Hellums DT, Baanante CA, Chien SH (1992) Alternative phosphorus fertilizers for the tropics: An agronomic and economic evaluation. In: Yost RS (ed) Proceedings of the Trop Soils phosphorus decision support system, Texas A&M College Station, TX, pp 147–154

Henao J, Baanante CA (1999) Estimating rates of nutrient depletion in soils of agricultural lands of Africa. IFDC, Muscle Shoals, AL

Henao J, Baanante CA (2006) Agricultural production and soil nutrient mining in Africa: implications for resource conservation and policy development. IFDC, Muscle Shoals, AL

Ibrikci H, Hanlon EA, Rechcigl JE (1991) Initial calibration and correlation of inorganic-phosphorus soil test methods with bahiagrass field trial. Commun Soil Sci Plant Anal 23:2569–2579

IFA and Argus Media Group (2023) Phosphate rock resources and reserves. International Fertilizer Association

IFA (2022) IFASTAT consumption (Plant Nutrition) database. International Fertilizer Association. https://www.ifastat.org/database/plant nutrition

IFDC (1997) International workshop on development of national strategies for soil fertility recapitalization in sub-Saharan Africa. Summaries of presentations and deliberations and framework for National Soil Fertility Improvement Action Plans. IFDC, Lome, Togo

IFDC (2011) Improving productivity along the agricultural value chain. IFDC, Muscle Shoals AL

Iretskaya SN, Chien SH (1999) Comparison of cadmium uptake by five different food grain crops grown on three soils of varying pH. Commun Soil Sci Plant Anal 30:441–448

Iretskaya SN, Chien SH, Menon RG (1998) Effect of acidulation on high cadmium containing phosphate rocks on cadmium uptake by upland rice. Plant Soil 201:183–188

Iseki K, Ikazaki K, Nakamura S, Sidibe H (2024) Effect of phosphate rock direct application on tropical legumes under different soil types of Sudan Savanna. Plant Prod Sci 27:272–282. https://doi.org/10.1080/1343943X.2024.2400084

Jama B, Swinkels A, Buresh R (1997) Agronomic and economic evaluations of organic and inorganic phosphorus in western Kenya. Agron J 89:597–604

Johnston AE, Jones KC (1992) The cadmium issue—Long-term changes in the cadmium content of soils and the crops grown on them. In: Phosphate fertilizers and the environment, IFDC, Muscle Shoals, AL USA, pp 255–298

Kleinman PJA et al (2001) Interlaboratory comparison of soil phosphorus extracted by various soil test methods. Commun Soil Sci Plant Anal 32:2325–2345

Koele N, Kuyper TW, Bindraban PS (2014) Beneficial organisms for nutrient uptake. VFRC/IFDC, Muscle Shoals, AL

Kothamasi D, Spurlock M, Kiers T (2011) Agricultural microbial resources: private property or global commons? Nat Biotechnol 29:1091–1093. https://doi.org/10.1038/nbt.2056

Kpomblekou AK, Tabatabai MA (1994) Effect of organic acids on release of phosphorus from phosphate rocks. Soil Sci 158:442–453. https://doi.org/10.1097/00010694-199415860-00006

Lehr JR, McClellan GH (1972) A revised laboratory reactivity scale for evaluating phosphate rocks for direct application. Bull. 43, National Fertilizer Development Center, Tennessee Valley Authority, Muscle Shoals, AL

Leon LA, Fenster WE, Hammond LL (1986) Agronomic potential of eleven phosphate rocks from Brazil, Colombia, Peru, and Venezuela. Soil Sci Soc Am J 50:798–802

Lin TH, Ho SB, Houng KH (1991) The use of iron oxide-impregnated filter paper for the extraction of available phosphorus from Taiwan soils. Plant Soil 133:219–226

Lindsey WL (1979) Chemical equilibria in soils. Wiley-Interscience, New York

Lompo F, Bationo A, Sedogo MP, Bado VB, Hien V, Ouattara B (2018) Role of local agro-minerals in mineral fertilizer recommendations for crops: examples of some West Africa phosphate rocks. In: Bationo A et al (eds) Improving the profitability, sustainability, and efficiency of nutrients through site specific fertilizer recommendations in West Africa agroecosystems. Springer International Publishers, Princeton, NJ, pp 157–180. https://doi.org/10.1007/978-3-319-58789-9_9

MacDonald GK, Bennett EM, Potter PA, Ramankutty N (2011) Agronomic phosphorus imbalances across the world's croplands. Proc Natl Acad Sci USA 108:3086–3091. https://doi.org/10.1073/pnas.1010808108

Maguire RO, Sims JT (2002) Soil testing to predict phosphorus leaching. J Environ Qual 31(5):1601–1609. https://doi.org/10.2134/jeq2002.1601

Mattiello EM, Resende Filho IDP, Barreto MS, Soares AR, da Silva IR, Vergütz L, Melo LCA, Soares EMB (2016) Soluble phosphate fertilizer production using acid effluent from metallurgical industry. J Environ Manage 166:140–146. https://doi.org/10.1016/j.jenvman.2015.10.012

McClellan GH (1980) Mineralogy of carbonate fluorapatites. J Geol Soc 6:675–681

Menon RG, Chien SH (1996) Compaction of phosphate rocks with soluble phosphates. Tech. Bull. T-44, International Fertilizer Development Center Muscle Shoals, AL

Menon RG, Chien SH, Sissingh HA (1989) Determination of plant-available phosphorus by the iron hydroxide-impregnated paper (Pi) soil test. Soil Sci Soc Am J 53:110–115

Mikkelsen RL, Binder CR, Frossard E, Brand FS, Scholz RW, Vilsmaier U (2014) Use: what is needed to support sustainability? In: Scholz RW, Roy AH, Brand FS, Hellums DT, Ulrich AE (eds) Sustainable phosphorus management-a global transdisciplinary roadmap. Springer, Dordrecht, pp 207–246

Mokwunye AU (1991) Alleviating soil fertility constraints to increased crop production in West Africa. Kluwer Academic, Dordrecht. https://doi.org/10.1007/978-94-011-3224-4

Mokwunye AU, Bationo A (2002) Meeting the phosphorus needs of the soils and crops of West Africa: the role of indigenous phosphate rocks. In: Vanlauwe B, Diels J, Sanginga N, Merckx R (eds) Integrated plant nutrient management in Sub-Saharan Africa. CAB Int., Wallingford, pp 209–224

Mokwunye AU, Vlek PLG (1986) Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa. Martinus Nijhoff, Dordrecht

Mortvedt JJ (1992) The radioactivity issue—Effects on crops grown on mined phosphate lands, P-fertilized soils and phosphogypsum-treated soils. In: Phosphate fertilizers and the environment, IFDC, Muscle Shoals, AL USA, pp 271–278

Mortvedt JJ (2005) Heavy metals in fertilizers: Their effects on soil and plant health. International Fertilizer Society, Proceedings No. 575, York, UK

Mueller N, Gerber J, Johnston M, Ray D, Ramankutty M, Foley J (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257. https://doi.org/10.1038/nature11420

Mwalongo DA, Haneklaus NH, Lisuma JB, Kivevele TT, Mtei KM (2023) Uranium in phosphate rocks and mineral fertilizers applied to agricultural soils in East Africa. Environ Sci Pollut Res Int 30:33898–33906. https://doi.org/10.1007/s11356-022-24574-5

Nelson N, Janke RR (2007) Phosphorus sources and management in organic production systems. J Am Soc Hortic Sci 17:42–454. https://doi.org/10.21273/HORTTECH.17.4.442

Olsson PA, Thingstrup I, Jakobsen I, Bååth E (1999) Estimation of the biomass of arbuscular mycorrhizal fungi in a linseed field. Soil Biol Biochem 31(13):1879–1887. https://doi.org/10.1016/S0038-0717(99)00119-4

Pufahl P, Groat LA (2017) Sedimentary and igneous phosphate deposits: formation and exploration. An invited paper. Econ Geol 112:483–516. https://doi.org/10.2113/econgeo.112.3.483

Ryan MH, Graham JH (2002) Is there a role for arbuscular mycorrhizal fungi in production agriculture? Plant Soil 244:263–271. https://doi.org/10.1023/A:1020207631893

Sagnon A, Traore M, Tibiri EB, Zongo S, Bonkoungou IJO, Nakamura S, Barro N, Tiendrebeogo F, Sarr PS (2024) Enhancing the use of phosphate rock through microbially-mediated compost transformation to improve agronomic and economic profitability in Sub-Saharan Africa. Front Sustain Food Syst. https://doi.org/10.3389/fsufs.2024.1445683

Scholz RW, Roy AH, Hellums DT (2014) Sustainable phosphorus management: transdisciplinary challenge. In: Scholz RW, Roy AH, Brand FS, Hellums DT, Ulrich AE (eds) Sustainable phosphorus management–a global transdisciplinary roadmap. Springer, Dordrecht, pp 1–128

Sharpley AN (1993) An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide impregnated paper. J Environ Qual 22:597–601

Shigaki F, Sharpley A, Prochnow LI (2007) Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soi trays. Sci Total Environ 373:334–343. https://doi.org/10.1016/j.scitotenv.2006.10.048

Singh U et al (2003) An expert system for estimating agronomic effectiveness of freshly applied phosphate rock. In: Rajan SS, Chien SH (eds) Direct application of phosphate rock and related appropriate technology—latest developments and practical experiences. Special Publication SP-37. IFDC, Muscle Shoals, AL, pp 214–224

Sissingh HA (1971) Analytical technique of the Pw method used for the assessment of the phosphate status of arable soils in the Netherlands. Plant Soil 34:483–486. https://doi.org/10.1007/BF01372800

Smalberger SA, Singh U, Chien SH, Henao J, Wilkens PW (2006) Development and validation of a phosphate rock decision support system. Agron J 98:471–483. https://doi.org/10.2134/agronj2005.0244

Stangel PJ (1978) The IFDC phosphate program. In: Seminar on phosphate rock for direct application, IFDC Muscle Shoals, AL USA, pp 3–35

Steiner G, Geissler B, Haneklaus N (2020) Making uranium recovery from phosphates great again? Environ Sci Technol 54:1287–1289. https://doi.org/10.1021/acs.est.9b07859

Syers JK, Johnston AE, Curtin D (2008) Efficiency of soil and fertilizer phosphorus use. Fertilizer and Plant Nutrition Bulletin 18, FAO, Rome, Italy

Teboh JF (1995) Phosphate rock as a soil amendment: who should bear the cost? In: Gerner H, Mokwunye AU (eds) Use of phosphate rock for sustainable agriculture in West Africa. IFDC, Muscle Shoals, AL, pp 142–149

Tiwari KK, Raghav R, Pandey R (2023) Recent advancements in fluoride impact on human health: a critical review. Environ Sus Indic. https://doi.org/10.1016/j.indic.2023.100305

Traore L, Kone M, Bouhsane M, Richardson J, France M, Hosanee J (2019) Valorization of the natural phosphate of Tilemsi (PNT) for the development of the agricultural productions in Mali. Int J Sci 8:12–23

Tumbure A, Bishop P, Bretherton M, Hedley M (2020) Co-pyrolysis of maize stover and igneous phosphate rock to produce potential biochar-based phosphate fertilizer with improved carbon retention and liming value. ACS Sustain Chem Eng 8(10):4178–4184. https://doi.org/10.1021/acssuschemeng.9b06958

Ulrich AE, Schnug E, Prasser HM, Frossard E (2014) Uranium endowments in phosphate rock. Sci Total Environ 478:226–234. https://doi.org/10.1016/j.scitotenv.2014.01.069

US Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) (2024) Testing methods for phosphorus and organic matter. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/testing-methods-for-phosphorus-and-organic

Van der Pauw F (1971) Effective water extraction of method for the determination of plant available soil phosphorus. Plant Soil 34:467–481

Van Kauwenbergh SJ (1997) Cadmium and other minor elements in world resources of phosphate rock. International Fertilizer Society Proceedings, No. 400, York, UK

Van Kauwenbergh SJ (2001) Overview of world phosphate rock production. In: Rajan SSS, Chien SH (eds) Proceedings of international meeting on direct application of phosphate rock and related technology: latest developments and practical experiences, Kuala Lumpur, Malaysian Soc Soil Sci and IFDC, Muscle Shoals, AL, USA, pp 28–49

Van Kauwenbergh SJ (2006) Fertilizer raw materials resources of Africa. IFDC, Muscle Shoals, AL

Van Kauwenbergh SJ (2010) World phosphate rock reserves and resources. IFDC, Muscle Shoals, AL

Vanlauwe B et al (2023) Fertilizer and soil health in Africa—the role of fertilizer in building soil health to sustain farming and address climate change. IFDC, Muscle Shoals, AL

Viana RDSR, de Figueiredo CC, Chagas JKM, Paz-Ferreiro J (2024) Combined use of biochar and phosphate rocks on phosphorus and heavy metal availability: a meta-analysis. J Environ Manage 353:120204. https://doi.org/10.1016/j.jenvman.2024.120204

Wang YT et al (2015) Agronomic and environmental soil phosphorus tests for predicting potential phosphorus loss from Ontario soils. Geoderma 241:51–58

Willer H, Trávniček J, Schlatter B (2025) The world of organic agriculture 2024. FiBL and IFOAM-Organics Int., Frick

Winterbottom R et al. (2013) Improving land and water management. Installment 4 of creating a sustainable food future. WRI, Washington DC, pp 1–43. https://www.wri.org/research/improving-land-and-water-management

World Bank (1994) Feasibility of phosphate rock as a capital in sub-Saharan Africa: Issues and opportunities. Washington DC

World Bank (1997) PR Initiative case studies: synthesis report. An assessment of phosphate rock as a capital investment: evidence from Burkina Faso, Madagascar, and Zimbabwe. IFDC/CIRAD/ICRAF/NORIAGRI, Washington, DC

Zhang Z, Liu B, He Z, Pan P, Wu L, Lin B, Li Q, Zhang X, Wang Z (2022) The synergistic effect of biochar-combined activated phosphate rock treatments in typical vegetables in tropical sandy soil: results from nutrition supply and the immobilization of toxic metals. Int J Environ Res Public Health 19(11):6431. https://doi.org/10.3390/ijerph19116431