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Agronomic Evaluation of Partially Acidulated Phosphate Rocks in the Tropics

IFDC's Experience

International Fertilizer Development Center

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S. H. Chien & L. L. Hammond

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Abstract

Phosphorus (P) is critically needed to improve the soil fertility for crop production in a large area of developing countries. The high cost of conventional, water-soluble P fertilizers constrains their use by resource-poor farmers. Finely ground phosphate rock (PR) for direct application has been tested and used on tropical acid soils as a low-cost alternative where indigenous deposits of PR are located. However, direct application of PR with low reactivity or with inappropriate soil/crop combinations does not always give satisfactory results. Partial acidulation of PR (PAPR) represents a technology that can be used to produce highly effective P fertilizers from those indigenous deposits. The International Fertilizer Development Center (IFDC) has developed a continuous process that combines partial acidulation and granulation into a single step. Numerous field trials conducted by IFDC in Asia, sub-Saharan Africa, and Latin America have demonstrated that PAPR at 50% acidulation with H_2SO_4 or at 20% with H_3PO_4 approaches the effectiveness of SSP or TSP in certain tropical soils and crops. This paper also discusses important factors in the agronomic effectiveness of PAPR. These include (1) mineralogical composition and reactivity of PR used and (2) soil properties and soil reactions.

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Agronomic Evaluation of Partially Acidulated Phosphate Rocks in the Tropics—IFDC's Experience

Introduction

One of the major problems that has inhibited the development of an economically successful agriculture in the tropics is the poor soil fertility for crop production. Many of the agricultural soils in the tropical regions are low in both total and available phosphorus (P), which is an essential plant nutrient. Furthermore, there are vast areas of Oxisols, Ultisols, and Andosols in the tropics that are characterized by having low pH and high levels of iron and aluminum oxides. These soils generally have good physical properties and are well suited for agriculture, but in many cases they have a relatively high P-fixing capacity. Thus, a proper management of P fertilizers is critically needed to improve the soil fertility in the tropics.

Use of conventional, water-soluble P fertilizers such as triple superphosphate (TSP) and single superphosphate (SSP) by the resource-poor farmers in the tropics has been limited primarily by the high cost (*5*). Indigenous finely ground phosphate rock (PR) for direct application has been tested and used on some tropical soils because of lower capital investment and production costs. However, direct application of PR with low reactivity does not always give satisfactory results, especially if used for short-term crops, e.g., maize, beans, and potatoes. Partial acidulation of PR represents an alternative means of producing agronomically effective P fertilizers from indigenous PR resources that may otherwise be unsuited for use as a fertilizer (*5*).

The main advantages of partially acidulated phosphate rock (PAPR) over superphosphates are as follows:

1. In agronomic terms, PAPR can provide a portion of the P in a readily plant-available form and the remainder in a form that should enhance residual value.
2. When H_3PO_4 is used, the PAPR increases the concentration of P above that of the unacidulated PR.
3. When H_2SO_4 is used, sulfur (S) is included in quantities appropriate for many nutritional demands.
4. The quantity of acid required is reduced, and therefore the cost of raw materials (H_2SO_4 or H_3PO_4) for PAPR will be less than for locally produced TSP or SSP.
5. Rocks that are unsuited chemically for the production of superphosphates can be used for PAPR.
6. PAPR products have better physical and chemical properties than superphosphates for bulk blending with urea.

During the past 10 years, the International Fertilizer Development Center (IFDC) has conducted a comprehensive research program on the production and use of PAPR. Numerous field trials on PAPR have been carried out by IFDC in Latin America, Asia, and sub-Saharan Africa. This paper is intended to summarize the research highlights to date.

Production and Characteristics of PAPR

In this paper, the "% PAPR" refers to the proportion of acid used to prepare the PAPR relative to the quantity of acid that would have been required to produce superphosphate from that particular PR. Thus, SAB-PAPR-50% refers to sulfuric acid-based PAPR using 50% of the H_2SO_4 required to produce SSP, and PAB-PAPR-50% refers to phosphoric acid-based PAPR using 50% of the H_3PO_4 required for TSP. The relationship between effective acidulation levels with H_2SO_4 and H_3PO_4 is shown in Figure 1. As illustrated with Pesca PR from Colombia, the effective level of acidulation with 50% H_2SO_4 is approximately the same as that with 20% H_3PO_4.

The commercial production of SAB-PAPR is similar to that for SSP, and in some cases both products are manufactured in the same plants. The conventional SSP process steps are acidulation, denning (for about 15-60 minutes), curing (for a few weeks), granulating,

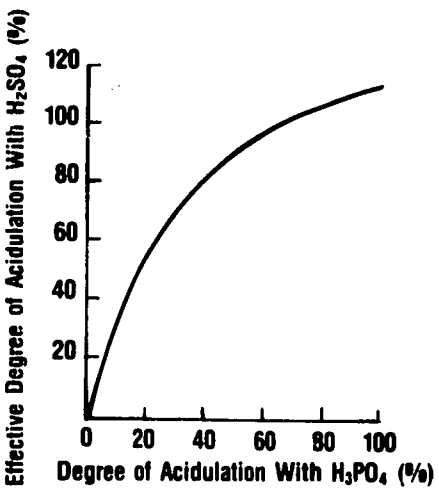

Figure 1. Relationship Between Effective Levels of Acidulation With H_2SO_4 and H_3PO_4 on Pesca Phosphate Rock (*4*).

and drying. This conventional process is suitable for the commercial PRs that are reactive and relatively low in impurities; however, it is not suitable for some unreactive PRs that contain relatively high amounts of Fe_2O_3 and Al_2O_3 because it results in low efficiency of the acid for partial acidulation of the PRs and can result in a product with poor physical properties. A continuous process using a single step for acidulation and granulation in the drum or pug mill-type granulator has been recently developed by IFDC for the production of PAPR (Figure 2). The liquid added during the granulation acts as the acidulation medium and prevents precipitation of part of the gypsum on the surface of the unreacted PR, thereby allowing the reaction to proceed toward complete utilization of the acid. In this process a closely sized, durable, and nondusty granular (-3.35 +1.18 mm or -6 +14 mesh) product resembling granular SSP or TSP is produced in a single step without curing.

The PAB-PAPR is essentially a mixture of monocalcium phosphate (MCP), which is water-soluble, and unreacted PR, which is slightly soluble in citrate solution. In SAB-PAPR, $CaSO_4$ is also present with MCP and PR. The actual amounts and forms of water-soluble, citrate-soluble, and citrate-insoluble P in the final PAPR products, however, vary widely among PR sources used and the degree of acidulation. The chemical characteristics of PAPR produced greatly depend on (1) the reactivity of the PR used, (2) the form and the quantity of acid used, (3) the impurities in the rock, and (4) the process conditions used.

PAPR products prepared with H_3PO_4 always contain more total and water-soluble P_2O_5 than those with H_2SO_4 (Table 1). Partial acidulation of PR with H_2SO_4 always results in a decrease of total P_2O_5 and an increase of water-soluble P_2O_5 as the degree of acidulation increases (Table 2). On the other hand,

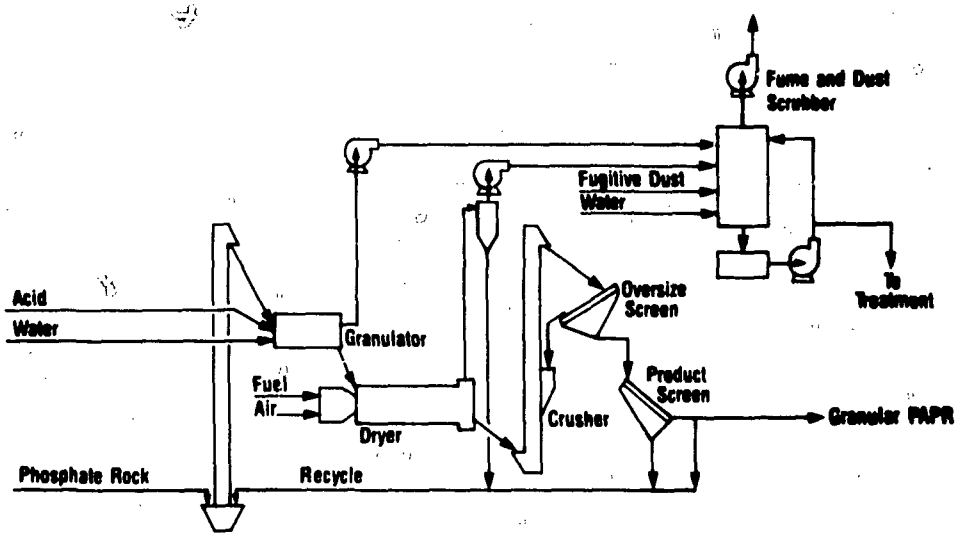

Figure 2. IFDC's Single-Step Process for Making PAPR With H_2SO_4 (18).

citrate-soluble P_2O_5 of PAPR products appears to be less changed, irrespective of the type of acid and the degree of acidulation used (Tables 1 and 2). These results showed that the major P_2O_5 components in the PAPR products are in the form of MCP and unreacted PR.

Table 1. Chemical Analyses of PAPR Products Prepared From Two PRs With Two Types of Acid (4,11)

PR Source	Type of Acid	Percent of Acidulation	P_2O_5, % of Weight: Total	Water-Soluble	Citrate-Soluble
Pesca (Colombia)	-	0	19.5	0	3.3
	H_2SO_4	20	17.5	4.3	2.2
	H_3PO_4	20	25.1	8.8	3.9
Mussoorie[a] (India)	-	0	25.0	0	2.2
	H_2SO_4	50	18.2	9.0	1.0
	H_3PO_4	50	36.3	20.0	1.5

a. Concentrated PR.

Table 2. Chemical Analyses of PAPR Products Prepared From Two PRs With H_2SO_4 at Various Acidulation Levels (18)

PR Source	Percent of Acidulation	P_2O_5, % of Weight: Total	Water-Soluble	Citrate-Soluble
Kodjari (Burkina Faso)	0	25.3	0	1.9
	20	21.2	2.4	3.4
	30	20.5	3.5	2.9
	40	19.2	5.3	3.0
	50	18.0	6.5	2.8
Hahotoe (Togo)	0	35.9	0	3.0
	25	28.6	7.2	3.4
	50	25.0	11.7	2.2

Recently, researchers at IFDC conducted a systematic investigation to evaluate the influence of Fe_2O_3 + Al_2O_3 content in PR on the solubility and agronomic effectiveness of PAPRs made from several sources that vary widely in chemical and mineralogical compositions. Data in Table 3 show that a significant reversion of water-soluble P_2O_5 to citrate-soluble or citrate-insoluble P_2O_5 occurred during aging (3 weeks to 12 months) in those products containing a relatively large quantity of Fe_2O_3 + Al_2O_3. Accordingly, total available P_2O_5 (water- plus citrate-soluble) also declined upon aging in those PAPR products. The products made from those PRs with low Fe_2O_3 + Al_2O_3 content were not significantly affected by aging (Table 3). Water- and citrate-soluble P_2O_5 contents were maintained at relatively constant levels during aging.

The single-step process was then modified by adding a cooler, whereby ambient air was used to cool the hot PAPR materials coming out of the dryer. It was found that this modification, which provided an immediate cooling effect, reduced the reversion of water-soluble P_2O_5 to citrate-soluble or citrate-insoluble P_2O_5 during aging for those PAPRs prepared from PRs containing high Fe_2O_3 + Al_2O_3 (Table 4). For example, water-soluble P_2O_5 of fresh Kodjari-PAPR (50% acidulation) decreased from 35.9% to 17.5% upon aging when a cooler was not used (Table 3). With cooling, water-soluble P_2O_5 was about the same for both fresh and aged (31.1% and 30.3%, respectively) PAPR products (Table 4).

When the cooling process was used, the water-soluble P_2O_5 was higher in the products made from PRs with low Fe_2O_3 + Al_2O_3 than in those from PRs with high Fe_2O_3 + Al_2O_3 at the same degree of acidulation (Figure 3). The effect of Fe_2O_3 + Al_2O_3 was more pronounced at 50% acidulation than at 30% acidulation, presumably because the presence of H_2SO_4 caused more Fe_2O_3 + Al_2O_3 to react with water-soluble P to form water-insoluble forms such as Fe-P and Al-P. Therefore, in the selection of PR for making PAPR with H_2SO_4, the Fe_2O_3 + Al_2O_3 content in the rock should be considered.

Table 3. Total, Water-Soluble, and Citrate-Soluble P_2O_5 of Various PAPR Products Made With H_2SO_4 Before and After Aging (*18*)

PAPR Product	Fe_2O_3+ Al_2O_3 in PR	Percent of Acidulation	P_2O_5[a] Total	Water-Soluble	Citrate-Soluble	Water- + Citrate-Soluble
	(%)		(%)			
El-Hassa (Jordan)	0.7					
Fresh		30	26.2	29.8	11.4	41.2
Aged		30	26.2	28.9	11.4	40.3
Central Florida (U.S.A.)	2.3					
Fresh		50	23.7	47.6	12.6	60.2
Aged		50	23.5	51.0	16.2	67.2
Kodjari (Burkina Faso)	7.1					
Fresh		50	17.9	35.9	16.7	52.6
Aged		50	18.4	17.5	28.8	46.3
Tilemsi Valley (Mali)	8.5					
Fresh		30	22.8	29.3	21.2	50.5
Aged		30	23.0	11.0	25.0	36.0
Tahoua (Niger)	12.4					
Fresh		50	22.5	28.8	12.8	41.6
Aged		50	23.0	10.9	20.0	30.9

a. Total P_2O_5 as percent of weight of PAPR; water- and citrate-soluble P_2O_5 as percent of total P_2O_5.

Table 4. Total, Water-Soluble, and Citrate-Soluble P_2O_5 of PAPR Products Made With H_2SO_4 (Cooling Process) From PRs With High Fe_2O_3 + Al_2O_3 Content (*6*)

PAPR Product	P_2O_5 Total	Water-Soluble	Citrate-Soluble	Water- + Citrate-Soluble
	(%)			
Kodjari				
Fresh	20.7	31.1	8.9	40.0
Aged	20.5	30.3	10.1	40.4
Tilemsi Valley				
Fresh	25.1	22.0	17.4	39.4
Aged	25.1	21.1	16.5	37.6
Tahoua				
Fresh	21.4	29.4	17.8	47.2
Aged	20.9	31.6	16.3	47.9

a. Total P_2O_5 as percent of weight of PAPR; water- and citrate-soluble P_2O_5 as percent of total P_2O_5.

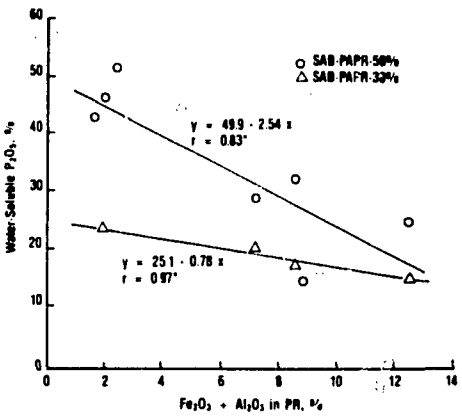

Figure 3. Water-Soluble P_2O_5 of SAB-PAPRs as Influenced by Fe_2O_3 + AL_2O_3 Content in the PRs Used at Two Acidulation Levels (*6*).

Laboratory and Greenhouse Evaluation of PAPR

IFDC conducted two greenhouse experiments to study the influence of chemical reactivity of PR (as expressed by citrate solubility) on the agronomic effectiveness of PAPR with 50% H_2SO_4. Data in Table 5 show that water-soluble P_2O_5 contents of various PAPRs used were more or less independent of the PRs' reactivity, whereas the citrate-soluble P_2O_5 of PAPR made from high-reactivity PR (Bayovar) was higher than that of PAPR made from PRs with lower reactivity. Because the P availability from PAPR was found to correlate well with water solubility (Figure 4), but not with citrate solubility, it would be expected that the agronomic effectiveness of PAPR would be little influenced by the rock's reactivity. For example, as shown in Table 5, SAB-PAPR-50% made from low-reactivity Media Luna (Colombia) or from Hahotoe (Togo) was as effective as that made from high-reactivity Bayovar PR (Peru) in increasing dry-matter yield of maize. It should be pointed out, however, these were short-term results obtained under greenhouse conditions. Long-term tests under field conditions are needed to verify the greenhouse results.

Unlike chemical reactivity of PR, the impurities such as Fe_2O_3 + Al_2O_3 present in PR were found to have significant effects on water-soluble P_2O_5 content (Figure 3) and the subsequent agronomic effectiveness (Table 6) of the PAPR produced from the PR. In general, those PAPRs made from PRs with low Fe_2O_3 + Al_2O_3 content were agronomically more effective than those from PRs with high Fe_2O_3 + Al_2O_3 content (Table 6). Several field trials conducted in Niger, West Africa, showed that granular SAB-PAPR-50% made from Tahoua PR, which contains 12.4% Fe_2O_3 + Al_2O_3, did not perform as well as the finely ground PR in increasing millet grain yield (Figure 5). Thus, PRs with high Fe_2O_3 + Al_2O_3 content may not be suitable for PAPR production. Alternatively, compacting these PRs (high Fe_2O_3 + Al_2O_3 content) with TSP can produce PAPR-equivalent products with good physical and chemical quality. As Figure 6 shows, when Capinota PR, which has 8.8% Fe_2O_3 + Al_2O_3, was compacted with TSP, in which 50% of total P_2O_5 is water-soluble P_2O_5, the product was as effective

Table 5. Chemical Characteristics and Dry-Matter Yield of Maize (6 Weeks) Obtained With Various PAPR Products in Two Greenhouse Experiments (6)

	PR		PAPR-50% H_2SO_4[a]				
			Percent of Total P_2O_5				
Soil Used	Source	Citrate-Soluble P_2O_5	Total P_2O_5	Water-Soluble	Citrate-Soluble	Total Available	Dry-Matter Yield
		(%)	(%)				(g/pot)
Mountview	Media Luna (Colombia)	2.3	23.7	38.0	5.5	43.5	20.4
	Huila (Colombia)	3.5	18.2	45.1	7.1	52.2	23.9
	Bayovar (Peru)	5.3	24.1	40.2	22.8	63.0	21.9
	Check (No P)	-	-	-	-	-	2.2
						LSD(0.05)	3.4
Hartsell	Hahotoe (Togo)	3.0	26.5	46.0	10.2	56.2	25.4
	Huila (Colombia)	3.5	17.3	51.4	9.8	61.2	26.9
	Bayovar (Peru)	5.3	22.8	42.7	17.2	59.9	25.3
	Check (No P)	-					3.6
						LSD(0.05)	3.0

a. PAPR materials used in two greenhouse experiments were prepared at different times, and hence, their chemical compositions were not identical.

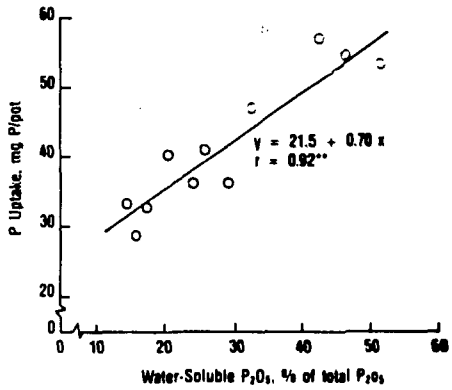

Figure 4. Phosphorus Uptake by Maize (6 weeks) From Various SAB-PAPRs as Related to Water-Soluble P_2O_5 Content (6).

Table 6. Dry-Matter Yield of Maize (6 Weeks) Obtained With Various PAPR Products Made From PRs Varying in Fe_2O_3 + Al_2O_3 Content (6)

PAPR-50% H_2SO_4	Fe_2O_3 + Al_2O_3 in PR	Dry-Matter Yield
	(%)	(g/pot)
Bayovar (Peru)	1.5	25.3
Hahotoe (Togo)	1.9	25.4
Huila (Colombia)	2.3	26.9
Kodjari (Burkina Faso)	7.1	16.4
Tilemsi Valley (Mali)	8.5	22.1
Capinota (Bolivia)	8.8	18.4
Tahoua (Niger)	12.4	15.2
Check (No P)	-	3.6
		LSD (0.05) (3.0)

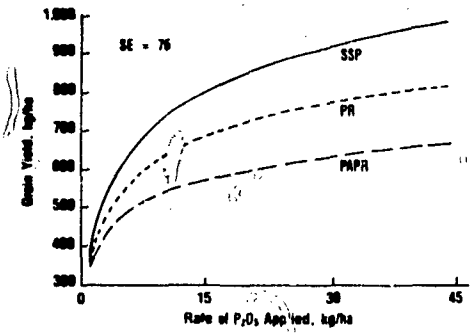

Figure 5. Grain Yield of Millet Obtained With SSP, Finely Ground Tahoua PR, and Granular Tahoua SAB-PAPR 50% at Gobery, Niger in 1985 (*13*).

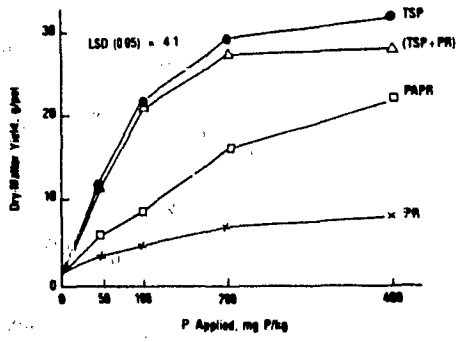

Figure 6. Dry-Matter Yield of Maize (6 weeks) Obtained With TSP, Compacted (PR+TSP), SAB-PAPR 50%, and PR. Source of PR Used Was Capinota, Bolivia (*15*).

as TSP, and both were more agronomically effective than Capinota SAB-PAPR-50% under greenhouse conditions.

It has been suggested that PAPR can be as effective as or sometimes better than superphosphates on acid soils possessing high P-fixing capacity. The chemistry of soil reactions can be explained as follows.

When MCP, which is the P component in SSP or TSP, dissolves in soil solution, it is hydrolyzed to dicalcium phosphate dihydrate (DCPD) and H_3PO_4 as follows:

$$\underset{\text{(MCP)}}{Ca(H_2PO_4)_2 \cdot H_2O} + H_2O \rightarrow \underset{\text{(DCPD)}}{CaHPO_4 \cdot 2H_2O} + H_3PO_4$$

The released H_3PO_4 can lower soil pH to as low as 1.5 and thus can dissolve Fe and Al minerals that in turn react with water-soluble P to form water-insoluble Fe-Al phosphates:

$$H_3PO_4 + \text{Fe-Al minerals} \rightarrow \text{Fe-Al ions} \xrightarrow{H_3PO_4} \text{Fe-Al phosphates}$$

The consequence of the soil reactions is that the P availability from SSP or TSP is decreased because of the so-called P-fixing process by Fe-Al minerals. With PAPR, which contains both water-soluble P (MCP) and water-insoluble P (PR) components, part of the H_3PO_4 produced by MCP hydrolysis will be neutralized by the unacidulated PR. This reaction of H_3PO_4 with unacidulated PR not only protects the water-soluble P of PAPR from reacting with Fe-Al minerals but also allows additional P to be released into the water-soluble P pool. This hypothesis has been recently verified by IFDC researchers who found that soil solution P concentrations obtained with PAPR, relative to TSP, increased with increasing P-fixing capacity of three tropical soils (Figure 7). It also can be seen clearly in Figure 8 that the agronomic effectiveness of PAPR with respect to SSP increased with increasing P-fixing capacity. The calculated values of relative agronomic effectiveness (RAE) of PAPR with respect to SSP obtained on three soils with low, medium, and high P-fixing capacity were 84%, 101%, and 124%, respectively (Figure 8). Thus, the relative effectiveness of PAPR with respect to superphosphates should be maximized on soils with very high P-fixing capacity.

It is well known that the agronomic effectiveness of PR for direct application always decreases as soil pH increases upon liming. However, the effect of soil pH on the agronomic effectiveness of PAPR is less known. In a greenhouse study, an acid soil (Mountview) was limed to raise soil pH from 4.5 to 7.0. As

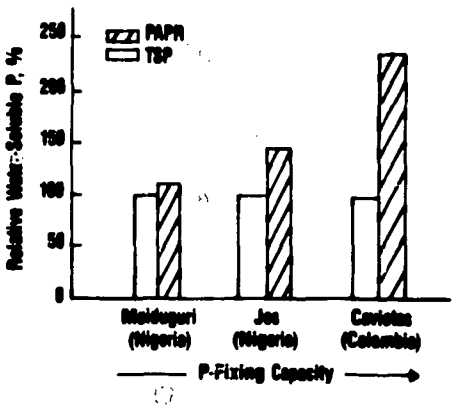

Figure 7. Effect of P-Fixing Capacity on the Relative Water Solubility of North Carolina PAB-PAPR-20% and TSP in Three Soils (*17*).

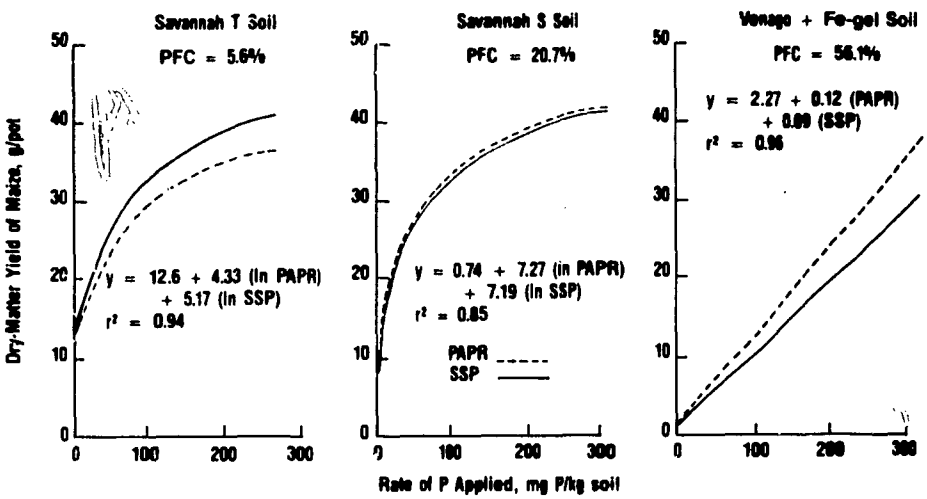

Figure 8. Dry-Matter Yield of Maize (6 weeks) Obtained With Pesca SAB-PAPR-50% and SSP on Three Soils Varying in P-Fixing Capacity (PFC) (*3*).

Figure 9 shows, although dry-matter yields obtained with TSP and Pesca PAB-PAPR-20% were influenced by pH, the RAE of PAPR with respect to TSP was relatively constant (approximately 62%), suggesting that the pH effect on PAPR was similar to that on TSP.

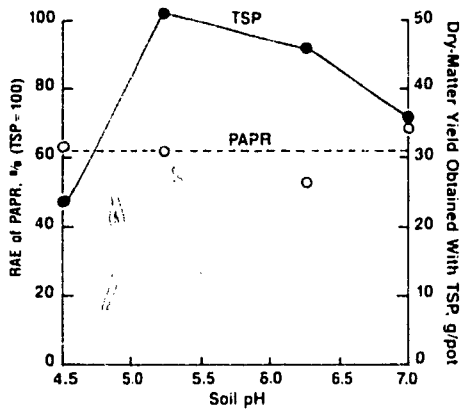

Figure 9. Relative Agronomic Effectiveness (RAE) of Pesca PAB-PAPR-20% and Dry-Matter Yield of Maize (6 Weeks) Obtained With TSP on Soil With Different pH Values Adjusted by Liming (7).

Recently, IFDC's researchers have found that PAPR can also be agronomically effective on semiarid soils in West Africa. These soils are characterized by having low Fe-Al minerals and, hence, low P-fixing capacity. Previous discussions on the chemical reactions of PAPR with Fe-Al minerals in high P-fixing soils cannot be used to explain the observed good results obtained with PAPR in West Africa. There is another explanation that might account for the effective performance of PAPR in low P-fixing soils. It is hypothesized that the water-soluble P component of PAPR encourages early plant-root development, which enables the plant to use the unacidulated PR component more effectively than could a plant treated with PR alone. IFDC conducted a unique greenhouse experiment to demonstrate this "starter effect" of the water-soluble P on the utilization of PR by the plant. In the study, maize seedlings were grown for 14 days on an acid soil (50 g) treated with different levels of TSP. The maize seedlings were then transplanted to the same soil (3 kg) that had received PR (Central Florida) alone and were grown for another 30 days. It was found that P uptake by the plant increased with increases in the weight of the maize seedling (Figure 10). Thus, the utilization of the PR component in PAPR by the plant can be increased by the associated water-soluble P component in the PAPR granules.

One of the problems likely to be encountered in using PAPR is in soil testing for fertilizer recommendations. The soil tests that are currently in use were developed to measure plant-available P in soils treated with water-soluble fertilizers and therefore may not be suitable when partly water-soluble or water-insoluble P fertilizers are applied. Acid extractants like Bray I or double acid can overestimate P from soils by dissolving more P than what would be plant available (2). Water extraction and Olsen-$NaHCO_3$ will underestimate P by not dissolving P from water-insoluble P fertilizer such as PR. IFDC has worked on a new P_i soil test, which uses a strip of filter paper impregnated

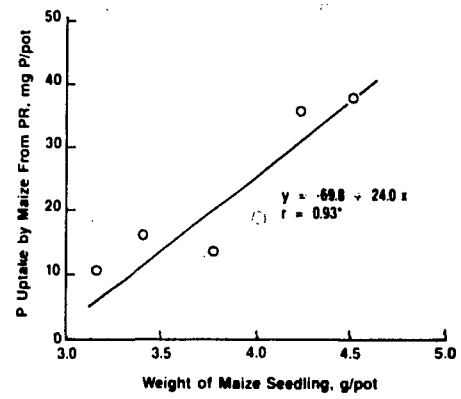

Figure 10. Phosphorus Uptake By Maize (30 days) From Central Florida PR After Transplanting as Related to Weight of Maize Seedling (14-day old) Used Before Transplanting (9).

with iron hydroxide to measure plant-available P in soils treated with nonconventional P fertilizers such as PR and PAPR. The P_i paper does not exert any harsh influence on the soil but only acts as a sink to adsorb the P that is in the soil suspension. Figure 11 shows that the Bray I test was less effective than the P_i soil test in evaluating P availability from different PAPRs applied to the soil in a greenhouse study. More work is needed to test the P_i method under field conditions.

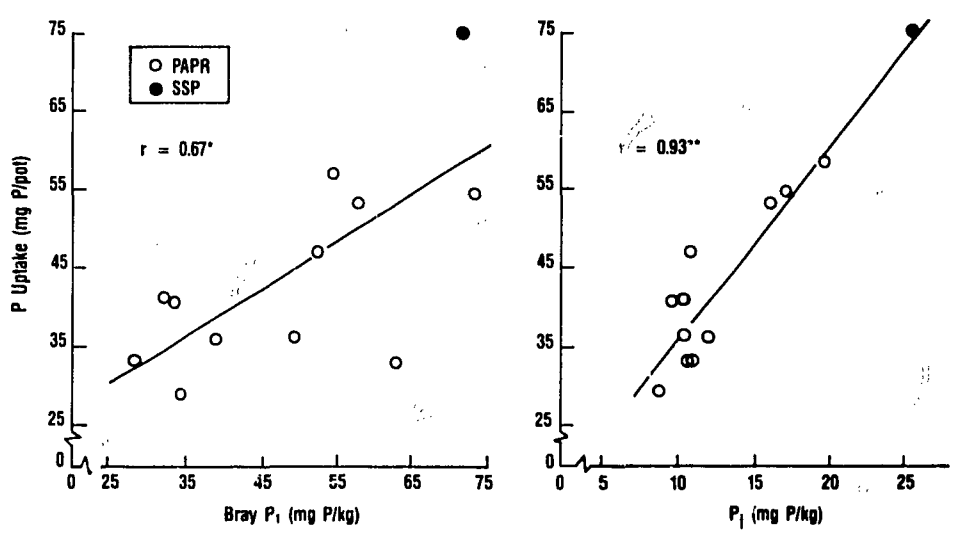

Figure 11. Phosphorus Uptake by Maize (6 weeks) as Related to P Extracted by Bray I and P_i Methods From Soil Treated With Various SAB-PAPR-50% Products and SSP (16).

Field Evaluation of PAPR in the Tropics

Latin America

Testing of PAPR was carried out in experiments on high P-fixing Andepts in Tulcan and Canar, Ecuador. It was observed that, although finely ground PR (Central Florida) was ineffective in increasing potato yield, SAB-PAPR-40% was as effective as TSP (Figure 12). Work is now in progress on the evaluation of partial acidulation of the locally available Napo PR in Ecuador.

Most of IFDC's field evaluations of PAPRs in Latin America were concentrated in Colombia during 1978-86 and used two locally available PRs (Pesca and Huila). Extensive farm-site trials were conducted in varied cropping systems and agroclimatic zones. The Pesca SAB-PAPR-40% was as effective as TSP in increasing bean yields on an Andept soil (Figure 13). However, Huila SAB-PAPR-50% was found to be less effective than TSP on yield of rainfed upland rice on an Oxisol (Figure 14). Considerable farm-to-farm variation was observed in over 60 on-farm trials; nevertheless, it was concluded that there was no statistically significant difference between the effectiveness of TSP and that of the PAPR products irrespective of the crop/soil combination (all were acid soils).

Field evaluation of PAPR was also conducted in Latin America through IFDC's Latin American PR Network involving the countries of Bolivia, Colombia, Ecuador, Peru, Costa Rica, Venezuela, and Mexico. Special emphasis has been placed on the partial acidulation of locally available PRs, e.g., Pesca, Huila, Media Luna, and Sardinata PRs in Colombia; Capinota PR in Bolivia; Bayovar PR in Peru; Baja California PR in Mexico; and Lobatera and Riecito PRs in Venezuela.

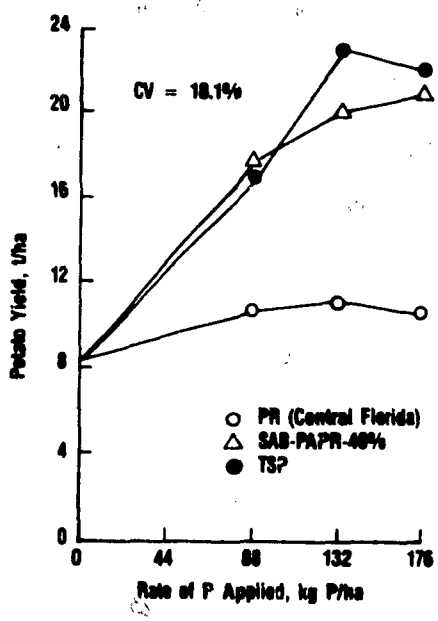

Figure 12. Effect of Partial Acidulation of Central Florida PR on the Production of Potatoes on an Andept in Ecuador (*14*).

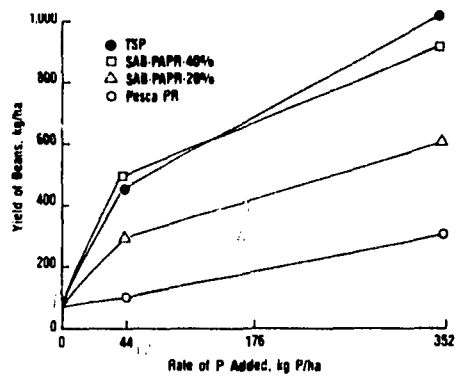

Figure 13. Effect of Partial Acidulation of Pesca PR on the Production of Beans on an Andept in Colombia (*14*).

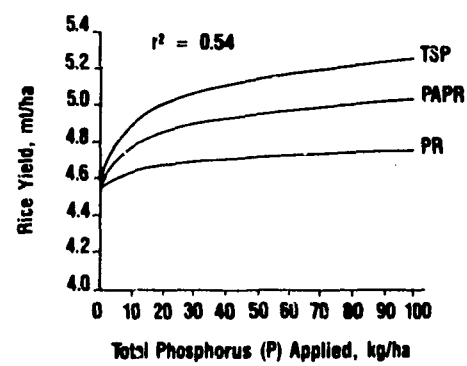

Figure 14. Effect of Partial Acidulation of Huila PR on Yield of Rainfed Upland Rice on an Oxisol in Colombia (*14*).

Asia

Many field trials on PAPR were conducted in India during 1984/85 using locally available Mussoorie PR. In all crops grown following fresh applications of fertilizer, there were no significant yield differences between TSP and PAPR produced from Mussoorie PR. This was observed on soils ranging in pH from 5.8 to 7.9, in P-fixing capacity from 2% to 18%, and in extractable P from 6.1 ppm to 10.6 ppm (Bray I) or 20.7 ppm (Olsen). Figure 15 shows the results obtained with Mussoorie SAB-PAPR-40%, unacidulated PR, and TSP in two locations for rice and wheat production. Under the same set of conditions, finely ground Mussoorie PR was found to be more variable and less effective than PAPR and TSP due to its low chemical reactivity. It should be pointed out that all the soils used were found to be relatively low in P-fixing capacity, and yet PAPR was found to be agronomically as effective as TSP.

In the Philippines, field testing of Central Florida PAB-PAPR-20% was conducted on an Andept soil in southeastern Luzon. It was found that finely ground Central Florida PR was ineffective in increasing grain yield of maize during the first cropping (Figure 16). Partial acidulation of the PR with 20% H_3PO_4 greatly increased P availability although the PAPR was still less effective than TSP. The effectiveness of PAPR was lower than that of TSP on this high P-fixing soil probably because the PAPR used was minigranulated (-0.30 +0.15 mm or -48 +100 mesh), whereas the TSP used was in a larger granular size (-3.35 +1.18 mm or -6 +14 mesh). It has been known that the agronomic

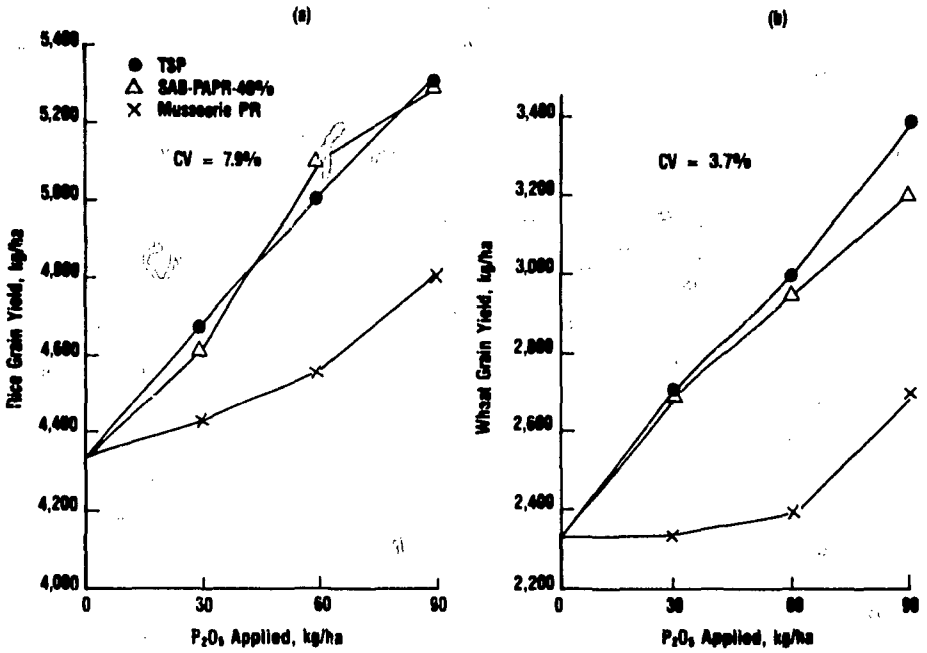

Figure 15. Effect of Partial Acidulation of Mussoorie PR (India) on Yields of (a) Rice Grain in Kampur, Uttar Pradesh and (b) Wheat Grain in Ranchi, Bihar, India (*11*).

effectiveness of water-soluble P fertilizer decreases with decreasing particle size on high P-fixing soils. During the second cropping with maize (Figure 16), the residual values of TSP, PAPR, and PR showed no significant differences in increasing grain yields.

In Indonesia long-term field trials of PAPR were conducted on an Ultisol in Nakau, Sumatra, during 1982-84. PAB-PAPR products made from Central Florida PR at 10%, 25%, and 45% were compared with PR and TSP in a rice-maize intercropping system. Data in Table 7 show that PAB-PAPRs with 25% and 45% acidulation tended to be more effective than TSP in increasing rice grain yields in 1982. However, they were much less effective than TSP for the maize crop. During the subsequent 2-year cropping period, all the PAPRs as well as PR were found to be as effective as TSP.

Field testing on PAPR for flooded rice is in progress in Asia through the collaboration between IFDC and the International Rice Research Institute (IRRI). Several countries, e.g., Indonesia, India, the Philippines, Thailand, and China, are involved in the network testing.

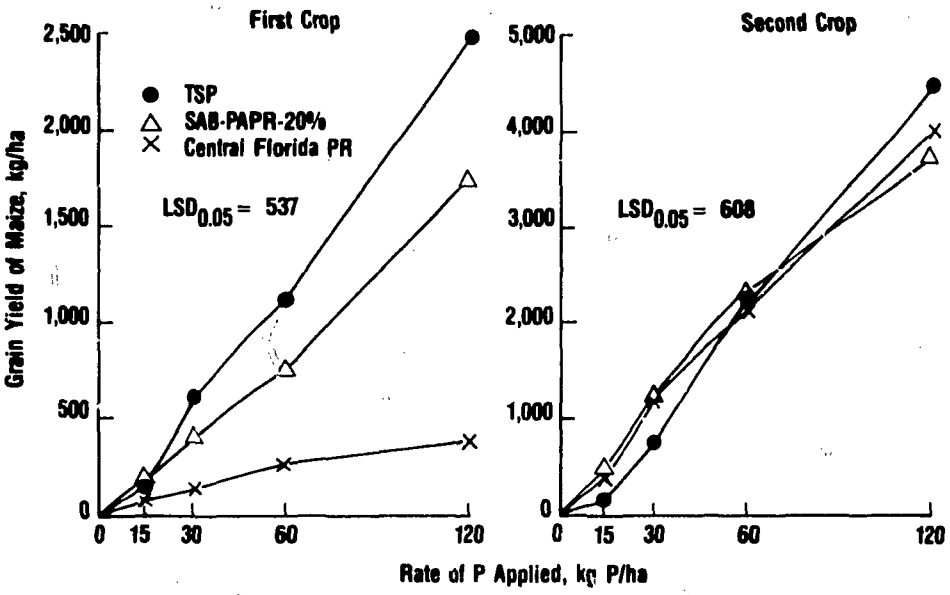

Figure 16. Grain Yields of Maize (first and second) Obtained With Various P Fertilizers on an Andept in the Philippines (*10*).

Africa

Most of IFDC's field trials on PAPR in Africa were conducted in the sub-Saharan region in West Africa using locally available PRs, e.g., Hahotoe PR in Togo, Kodjari PR in Burkina Faso, Parc W and Tahoua PRs in Niger, and Tilemsi Valley PR in Mali.

During 1983 and 1984 the evaluation of Togo PR and SAB-PAPR was carried out on Alfisols in northern Nigeria and Togo and on Ultisols in Sierra Leone. At every site, the Togo PR, due to its low reactivity, performed poorly compared with SSP in increasing grain yields of maize (Figure 17). Partial acidulation increased the agronomic effectiveness. At 50% acidulation, the agronomic efficiencies were 72%, 82%, and 103% of that with SSP in Nigeria, Togo, and Sierra Leone, respectively (Figure 17).

At Sapu, on an Oxisol in the dry region of Gambia, the agronomic effectiveness of Tilemsi PR and PAPR-H_2SO_4 products was found to be comparable with that of SSP in increasing yields of maize and groundnut (Figure 18). Tilemsi PR is known to be relatively high in reactivity for direct application. Partial acidulation of this PR may not necessarily achieve maximum benefits in either agronomic or

Table 7. Grain Yields of Rice and Maize Obtained With Various Fertilizers in Ultisols During 3-Year Cropping System in Nakau, Indonesia (*12*)

P Source	Acidulation With H_3PO_4 (%)	Grain Yield[a] 1982 Rice	1982 Maize	1983 Rice	1983 Maize	1984 Rice	1984 Maize
		(t/ha)					
PR	0	2.1	0.3	1.1	1.3	0.6	1.5
PAPR	10	2.0	0.7	1.4	1.5	0.7	1.7
PAPR	25	2.9	0.8	1.4	1.7	0.3	1.6
PAPR	45	3.2	0.6	1.3	1.8	0.6	1.7
TSP	100	2.6	1.4	1.6	2.0	0.3	1.8
No P	-	1.4	0	0.5	0.1	0.3	0.2

a. Yield obtained at 20 kg P applied to the soil each year.

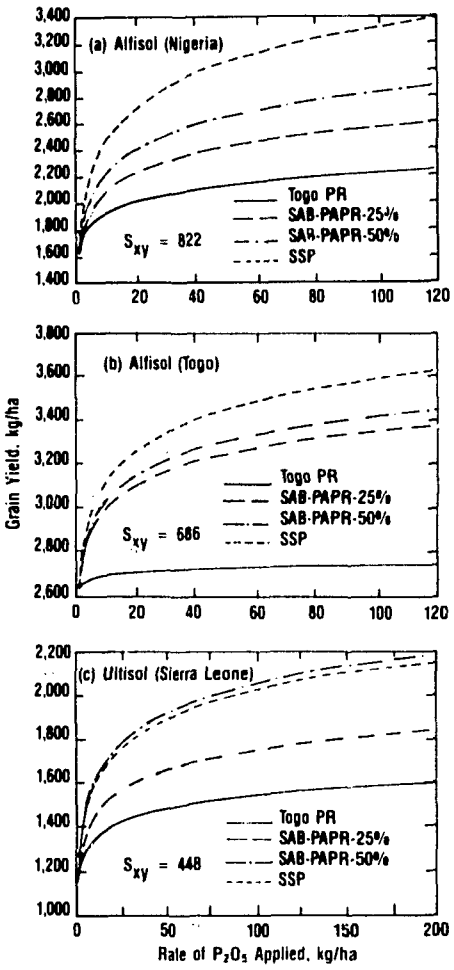

Figure 17. Grain Yields of Maize Obtained With Togo PR, Togo SAB-PAPRs, and SSP at Three Sites in West Africa (*1*).

economic effectiveness for crop production. Furthermore, the high Fe_2O_3 + Al_2O_3 content (8.5%, Table 3) in this PR may present technical problems for producing effective PAPR products.

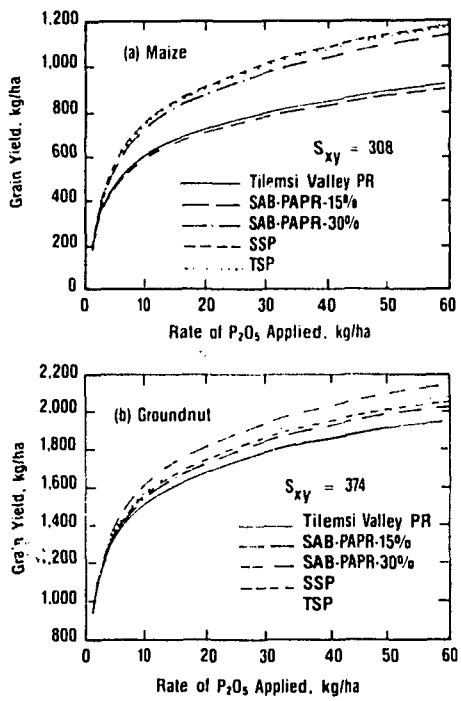

Figure 18. Yields of (a) Maize and (b) Groundnuts Obtained With Tilemsi Valley PR (Mali), Tilemsi SAB-PAPRs, SSP, and TSP on an Oxisol at Sapu in Gambia (*1*).

In Niger, Parc W PR was not effective in increasing grain yield of millet on an Alfisol, again due to its low reactivity (Figure 19). Partial acidulation with 40% H_2SO_4 dramatically increased its agronomic effectiveness to 75% of that with SSP (Figure 19). Similarly, in Burkina Faso, Kodjari PR was less effective than SSP in increasing sorghum yields on an Alfisol, whereas SAB-PAPR-50% was almost as good as SSP (Figure 20).

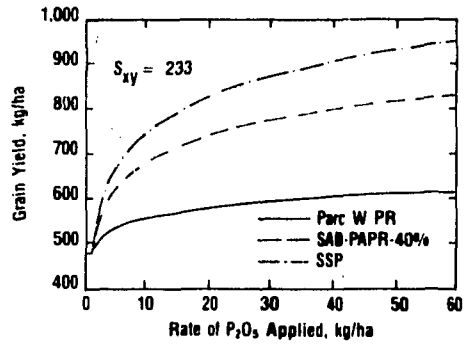

Figure 19. Grain Yield of Millet Obtained With Parc W PR (Niger), Parc SAB-PAPR-40%, and SSP on an Alfisol at Sadore, Niger (*1*).

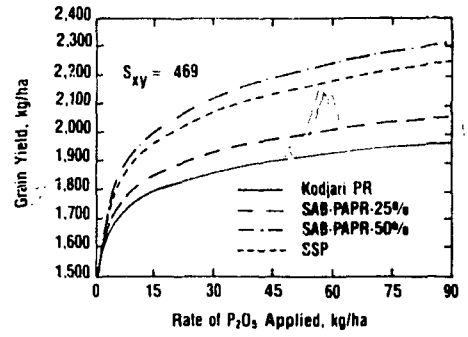

Figure 20. Grain Yield of Sorghum Obtained With Kodjari PR (Burkina Faso), Kodjari SAB-PAPRs, and SSP on an Alfisol in Burkina Faso (*1*).

While the field evaluation of PAPR in sub-Saharan West Africa continues, field trials on PAPR have been initiated by IFDC in East and Southeast Africa using locally available PRs, e.g., Sukulu PR in Uganda, Dorowa PR in Zimbabwe, Chilembwe PR in Zambia, and Matongo PR in Burundi. Future results will undoubtedly provide useful information on the benefit of producing PAPR products from locally available PRs for increasing crop production in tropical Africa.

Conclusion

IFDC's primary purpose in initiating research on PAPR was to determine if this technology could provide a means whereby indigenous PR deposits in developing

countries with limitations for direct application or conventional processing could be converted to agronomically effective fertilizers. The results obtained indicate that, under many conditions, partial acidulation of the PR is all that is required to dramatically improve the agronomic effectiveness. The agronomic effectiveness of the PAPR products is greater than that of unacidulated PR and often is comparable to that of completely soluble fertilizers. While not necessarily producing a class of fertilizers directly competitive with world-market fertilizers, partial acidulation (or compaction of PR with small quantities of soluble P) shows promise as an appropriate technology for local utilization by resource-poor farmers in developing countries.

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