

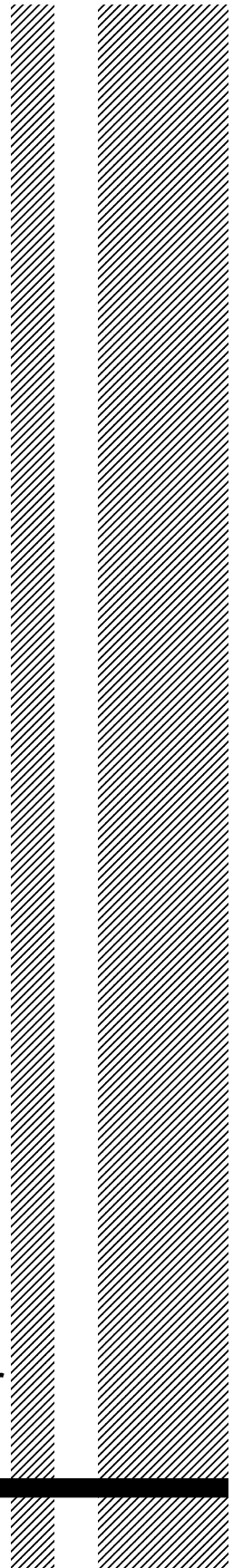
Compaction of Phosphate Rocks With Soluble Phosphates

***An Alternative Technology to
Partial Acidulation of
Phosphate Rocks
With Low
Reactivity***

IFDC Experience



IFDC International Fertilizer Development Center



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Abstract

Compaction with soluble phosphates is an alternative technology to partial acidulation in increasing the agronomic effectiveness of phosphate rocks (PRs) that have a low reactivity and are not suitable for direct application. Greenhouse trials conducted by the scientists of the International Fertilizer Development Center (IFDC) have shown that compacted products of triple superphosphate (TSP) and low reactive PRs such as Hahotoe PR from Togo, Dorowa PR from Zimbabwe, and Pesca PR from Colombia, in which PR and TSP each contribute 50% of the total P in the mixture, were as effective a P source as partially acidulated PRs (PAPRs) at 50% acidulation with H_2SO_4 for maize (*Zea mays*), beans (*Phaseolus vulgaris*), and rice (*Oriza sativa*). Both the compacted mixtures and PAPR showed an agronomic effectiveness that was similar to that of TSP.

Phosphate rocks that have low reactivity and contain large amounts of Fe and Al oxides may be unsuitable for partial acidulation but can be made more effective by mixing with soluble phosphates and compacting into granules. PAPR prepared from Capinota PR from Bolivia with 8.8% $Fe_2O_3 + Al_2O_3$ was only half as effective as TSP for maize compared with PR + TSP, which showed the same effectiveness as TSP. Compacting the PR with TSP on a 50:50 total P basis increased the relative effectiveness of the PR from 43% before treatment to 80% afterwards for rice grain production and from 50% before treatment to 92% afterwards for bean biomass yield, assuming a 100% effectiveness for TSP. On the other hand, the PAPR at 50% acidulation with H_2SO_4 was only 78% as

effective as TSP for beans and 70% as effective as TSP for rice.

In greenhouse trials the agronomic effectiveness of PAPRs from five low-reactive PRs with Fe and Al oxides ranging from 1.9% to 32.0% at 50% acidulation with H_2SO_4 was compared with that of compacted mixtures of PR + TSP with 50% of the total P from TSP in Hartsellis silt loam (pH 4.8). Three successive crops consisting of maize followed by maize followed by rice were grown. For the first maize crop, both the biomass yield and P uptake decreased with an increase in the $Fe_2O_3 + Al_2O_3$ contents of the PR. The PAPRs were 12%-86% as effective as TSP in increasing biomass yield of maize and 16%-72% in increasing P uptake. The compacted mixtures, however, were 86%-104% as effective as TSP in increasing biomass and 78%-94% as effective in increasing P uptake. The residual effect of PAPR and PR + TSP was not widely different for maize or rice.

The series of trials conducted thus far proves that if a PR has low reactivity and does not contain significant amounts of Fe and Al oxides, both partial acidulation and compaction with soluble phosphates are effective in increasing phosphorus availability for crops. On the other hand, if the PR contains large amounts of $Fe_2O_3 + Al_2O_3$, compaction with soluble P sources would be a better alternative to partial acidulation in making the best use of such PRs. The soluble-P content in the compacted mixtures should not be less than 50% of the total P. Future agronomic trials under field conditions are needed to validate this conclusion.

I. Introduction

At the present growth rate, world population is expected to increase from the present 5.2 billion to more than 8.4 billion by the year 2025 (World Bank, 1992). To provide this burgeoning population with basic food and fiber, agricultural production will have to be increased more than twofold (World Bank, 1992). Furthermore, with an increase in technological advancement and purchasing power, the dietary habits of the world's poor will shift more from the present plant-based to animal-based protein and this will, in turn, put more pressure on the land. Agriculture in the next century, therefore, should be geared to meet these demands without seriously endangering the environment.

Agricultural production can be increased by bringing more land under cultivation or by intensifying agriculture in the land presently under cultivation. In Asian countries where population pressure is expected to be most intense, the possibility of bringing more land under the plow is limited, and an increase in production to meet national needs must result from intensified production from existing agricultural lands. Such an intensification on a sustainable and environmentally friendly basis requires higher and more efficient use of fertilizers, integrated nutrient management, appropriate crop species, effective irrigation, and sound management practices.

Nearly 43% of the tropics is covered by acid, low fertility soils (Sanchez and Logan, 1992); therefore, economic and sustainable crop production requires

fertilizer application. However, fertilizers are expensive, and for many of the resource-poor farmers from developing countries, investment in fertilizers is a luxury beyond their means. One way to reduce dependence on expensive, imported fertilizers is to use indigenous resources, if available.

Phosphate rock (PR) deposits occur in several countries of Asia, Africa, and Latin America. If the PR is of good quality, it may be used effectively as a substitute for soluble P fertilizers. However, most PR deposits in developing countries are of poor quality, have low reactivity, and may not be suitable as direct application P fertilizers. The effectiveness of such PRs can be improved by partial acidulation, mixing with water-soluble P sources, or compaction of the physically mixed PR with soluble phosphates with or without other nutrients (Chien and Hammond, 1988; Menon and Chien, 1990).

Information about partially acidulated phosphate rocks (PAPRs) abounds in the literature (Hammond et al., 1986). On the other hand, data about compacted mixtures of PR and soluble phosphates are scanty. The purpose of this review is to compile the available information generated by the International Fertilizer Development Center (IFDC) on the chemical and agronomic evaluation of P fertilizers produced by mixing or compacting PR with superphosphates as an alternative to PAPR. It is hoped that such information would be useful in planning future phosphate fertilizer programs in the tropics.

II. Processes and Products

PAPRs and phosphate rocks compacted with superphosphates, hereafter referred to as PR + SSP or PR + TSP, depending on whether single superphosphate (SSP) or triple superphosphate (TSP) was used, consist essentially of a mixture of monocalcium phosphate (MCP) that is water soluble and the unreacted PR that is not water soluble but is

slightly soluble in a citrate solution. While PAPR is prepared by partial acidulation of the PR with sulfuric or phosphoric acid, in the compacted mixture, PR and SSP or TSP are thoroughly mixed, compacted, and granulated.

Partial Acidulation

Sulfuric acid-based PAPR (SAB-PAPR) is prepared by the same method used in the manufacture of SSP. The process consists of the acidulation of PR, denning, and curing. In the single-step process developed at IFDC (Schultz, 1986), the acid, mixed with the PR in a drum or pugmill-type granulator, acts as the acidulation medium and prevents the 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 (Chien and Hammond, 1988). The materials are then transferred to a dryer, and the hot PAPR materials coming out are cooled by ambient air. The single-step process produces closely sized, nondusty, granular PAPR of 1.18- to 3.35-mm size (minus 6- plus 14-mesh), which resembles TSP or SSP granules.

Compaction Granulation

Compaction granulation is a process that has been used for decades in metallurgy, ceramics, and pharmaceuticals, but its use in the fertilizer industry is of a more recent origin. Dry granulation by compaction is used as an alternative to steam granulation to produce granular potash, mixed fertilizers, and agricultural chemicals.

Compaction granulation consists of two processes, compaction of the powdered mix and granulation of the compacted material. Compaction is based on the principle that when a finely powdered material is forced through a pair of counter-rotating rolls,

the air between the particles is expelled, the material is densified, and flakes or sheets are formed. The compacted sheets are then crushed and screened to produce the desired particle size (Lupin and Le, 1983).

Compaction granulation of PR-superphosphate mixtures involves mixing the feeds, compacting, crushing, and screening. The finely ground PR and superphosphate are fed into feed bins equipped with a weigh feeder for metering of raw materials. Superphosphate and PR are metered according to the desired ratio and thoroughly mixed; the finely mixed powder is transferred to the compactor with the aid of forced feeders and forced between two counter-rotating rolls at a pressure of 1 tonne cm^{-1} . As the powder passes between the rolls, air between the particles is expelled, and the densification causes close contact between individual particles; consequently, solid, dense flakes are formed. The flakes are broken up into smaller pieces and fed into a crusher, crushed, and taken by bucket elevators to the screen, which has 1.18- to 3.35-mm (minus 6- plus 14-mesh) size openings. The crushed pieces are separated into onsize, oversize, and undersize fractions. The undersize fraction is returned to the compactor, and oversized material is returned to the crusher (Lupin and Le, 1983).

The compacted granules are more angular than the products from drum or pan granulation. A polishing drum designed to remove the sharp edges from the granules can be added to the product's treatment section to make the granules smoother.

III. Chemical Composition and Solubility

Phosphate rocks are essentially apatites in association with various mineral impurities. The apatites occur largely as carbonate apatites (francolites) with differing degrees of isomorphous substitution of the ionic components. Phosphates in the apatite structure are generally substituted to varying degrees by carbonates during the formation of the apatite. The stability and reactivity of the PR are largely determined by the

degree of substitution of carbonates for phosphates. The higher the carbonate substitution, the greater will be the reactivity of the PR (Lehr and McClellan, 1972).

When the two major raw materials for the manufacture of phosphate fertilizers—PR and sulfuric acid—are mixed together, the insoluble apatite is converted into MCP; the resulting product is called SSP. If phosphoric acid is used instead of sulfuric acid,

TSP is formed. If the amount of acid is less than the stoichiometric amount required to produce fully acidulated SSP or TSP, PAPR is produced. PAPR, therefore, is virtually a mixture of MCP and unacidulated PR.

Compacted mixtures of PR and superphosphate are produced by mechanically mixing the ground PR with SSP, TSP, or other soluble phosphates and then granulating the mixture by compaction. Basically there is no difference between a PR-superphosphate mixture obtained by mechanically mixing the two components and PAPR produced by partial acidulation of the PR. This has been demonstrated by the identical x-ray diffraction patterns of the two materials obtained before and after soil incubation (Hagin and Katz, 1985) (Figure 1). Characterization work done by the Tennessee Valley Authority (TVA) on samples of PAPR-H₂SO₄ and PAPR-H₃PO₄ produced by IFDC from Pesca (Colombia) and North Carolina PRs showed that the major P components in the samples were MCP and unacidulated apatite. No other P components were identified.

If the PR has little or no accessory minerals that would react with water-soluble P compounds during the acidulation process, the solubility of compacted PR + SSP or PR + TSP can be adjusted to match that of PAPR. For example, compacted Togo PR + SSP with a P ratio of PR:SSP at 1:1.2 has the same water solubility as that of PAPR-50% H₂SO₄. Likewise, Togo PR + TSP at a 1:1 PR:TSP P ratio has the same water and citrate solubility as PAPR-20% H₃PO₄ (Table 1) (Kpombekou, 1989). If the PR contains impurities such as Fe₂O₃ and Al₂O₃ in substantial amounts, the quality of PAPR

produced from this rock will be affected. In a study conducted at IFDC to investigate the effect of Fe₂O₃ + Al₂O₃ content of PR on water and citrate solubility of

Table 1. Solubility of Partially Acidulated Togo PR and Compacted Products of PR and SSP

P Source	Total P	Percent of Total P	
		Water-Soluble P	Citrate-Soluble P
		(%)	
Togo PR	16.4	0	10.4
SSP	8.7	84.0	16.0
TSP	21.0	84.8	14.8
Togo PAPR-50% H ₂ SO ₄	12.0	45.8	8.3
Compacted PR + SSP + KCl ^a	9.6	45.8	9.9
Togo PAPR-20% H ₃ PO ₄	18.4	41.8	7.6
Compacted PR + TSP + urea + KCl ^b	12.6	41.8	7.7

a. P ratio of Togo PR:SSP = 45:55, K = 7.2%.

b. P ratio of Togo PR:TSP = 50:50, N = 6.3%, K = 9.5%.

Source: Kpombekou, 1989.

PAPR produced from eight PRs, it was found that the water-soluble P content of PAPR at 50% acidulation with H₂SO₄ ranged from 43% to 53% if the Fe₂O₃ + Al₂O₃ content of the PR was less than 2.4%, but the solubility was considerably reduced if the Fe₂O₃ + Al₂O₃ content of PR was more than 7% (Hammond et al., 1989). For example, the water-soluble P content of Capinota PR with 8.8% of Fe₂O₃ + Al₂O₃ at 50% acidulation was only 15% of the total P (Table 2).

Table 2. Solubility of PAPR-50% H₂SO₄ Produced From PRs With Different Fe₂O₃ + Al₂O₃ Contents

P Source	Fe ₂ O ₃ + Al ₂ O ₃	Total P	PAPR-50% H ₂ SO ₄	
			Water-Soluble P ^a	Citrate-Soluble P ^a
(%)				
Bayovar (Peru)	1.5	9.9	42.7	17.2
Hahotoe (Togo)	1.9	11.5	46.0	10.2
Huila (Colombia)	2.3	7.5	51.5	9.8
Central Florida (U.S.A.)	2.4	10.2	51.0	16.2
Kodjari (Burkina Faso)	7.1	9.0	29.1	8.7
Tilemsi Valley (Mali)	8.5	10.2	32.3	14.0
Capinota (Bolivia)	8.8	6.8	14.6	31.8
Tahoua (Niger)	12.4	9.2	25.5	24.1

a. As % of total P.

Source: Hammond et al., 1989.

Hammond et al. (1989) hypothesized that the reduction in water-soluble P content was due to the

reaction of H₂SO₄ with Fe₂O₃ and Al₂O₃ during the acidulation process and the release of Fe³⁺ and Al³⁺ ions, which then reacted with water-soluble P to form water-insoluble Fe P and Al P. In the absence of H₂SO₄, Fe₂O₃ and Al₂O₃ in the PR would not fix a significant amount of water-soluble P added to the PR as superphosphate as in the case with the PR + SSP mixtures. This was illustrated in an experiment by Chien (1989, unpublished), the results of which are given in Table 3. When an aqueous solution containing 12.5 mg P as KH₂PO₄ was added to Kodjari PR from Burkina Faso (7.1% Fe₂O₃ + Al₂O₃), Tahoua PR from Niger (12.4% Fe₂O₃ + Al₂O₃), and Sukulu Hills PR from Uganda (37.7% Fe₂O₃ + Al₂O₃), less than 6.5% of the added P was fixed by Kodjari and Tahoua PR, compared with 17.6% fixed by Sukulu Hills PR. When these PRs were treated with 0.1 N H₂SO₄, there was little difference in the amount of water-soluble P released from the three PRs. On the other hand, when the acid-PR suspensions were dried at 100°C and P extracted with water after drying, a significant reduction in water solubility ranging from 27.6% in the case of Tahoua PR to 71% with Sukulu Hills PR occurred (Table 3). This suggests that when PR with high Fe₂O₃ + Al₂O₃ content is partially acidulated with H₂SO₄, reversion of water-soluble P into the water-insoluble form takes place during the drying process. It also suggests that compacted PR + SSP or PR + TSP with PR that has a high Fe₂O₃ + Al₂O₃ content should have a higher water-soluble P content than PAPR produced from the same PR because no acidulation and drying are needed in the compaction process.

Table 3. Water-Soluble P Content of Three PRs as Influenced by Treatment With P Solution and Acidulation

PR Source	Total P ₂ O ₅	Fe ₂ O ₃ + Al ₂ O ₃	Water-Soluble P as Influenced by Treatments				
			12.5 mg P Added in Water		0.1 N H ₂ SO ₄ Added		
			P in Solution	P Fixed	P Before Drying	P After Drying	P Reverted
	(%)	(%)	(mg)	(%)	(mg)	(mg)	(%)
Kodjari	25.3	7.1	11.9	4.8	24.3	12.4	49.0
Tahoua	27.8	12.4	11.7	6.4	21.4	15.5	27.6
Sukulu Hills	12.5	37.7	10.3	17.6	28.8	8.3	71.2

Source: S. H. Chien, 1989 (unpublished data).

IV. Agronomic Evaluation

The agronomic effectiveness of a P source, whether it is PR, PAPR, PR + SSP, or PR + TSP, is influenced by three factors, among others. These factors include the rate of absorption of the phosphate ions needed by the plants to meet nutrient requirements, the rate at which the phosphate ions are released from the fertilizer to the soil solution, and the rate at which the released P is immobilized by the soil. To be agronomically effective, the rate at which phosphate ions are released from the fertilizer should be equal to or in excess of the rate at which P is fixed by the soil and the rate at which P needs to be absorbed by the plants.

Partially Acidulated Phosphate Rocks

Chien and Hammond (1988) have summarized the results of a large number of trials carried out by IFDC scientists in Asia, Africa, and Latin America on the agronomic effectiveness of PAPRs. These studies indicated that partial acidulation can improve the agronomic effectiveness of low quality PRs, which are not reactive enough to be used as direct application fertilizers. Field trials conducted by IFDC scientists in the tropics have shown that PAPR at 50% acidulation with H₂SO₄ or 20% acidulation with H₃PO₄ approaches

the effectiveness of SSP or TSP if the PR does not contain appreciable amounts of iron and aluminum oxides as impurities.

On the other hand, it has been found that the agronomic effectiveness of PAPR will be significantly reduced if the PR used for the production contains large amounts of Fe₂O₃ + Al₂O₃. In trials that compared the effectiveness of various PRs and PAPRs in Niger, it was observed that Tahoua PAPR-50% H₂SO₄ was less effective than directly applied Tahoua PR (Figure 2) although Parc W PAPR was more effective than Parc W PR in the same trial (Figure 3) (IFDC, 1987). Likewise, Tilemsi Valley PAPR-30% H₂SO₄ was less effective than Tilemsi Valley PR for maize in field trials conducted in Gambia (Bationo et al., 1986). The unsatisfactory performance of the Tahoua and Tilemsi Valley PAPR can be attributed to the high Fe₂O₃ + Al₂O₃ content in the PRs—Tahoua has 12.4% and Tilemsi Valley 8.8% Fe₂O₃ + Al₂O₃, compared with 2.9% in the case of Parc W PR.

A greenhouse study subsequently conducted at IFDC Headquarters (Hammond et al., 1989) with a range of PRs having different Fe₂O₃ + Al₂O₃ contents demonstrated clearly that the relative agronomic

effectiveness (RAE) of PAPR-50% H_2SO_4 with respect to SSP decreased with increasing $Fe_2O_3 + Al_2O_3$ content in PR (Figure 4). For example, Togo PAPR-50% H_2SO_4 was 84% as effective as SSP, whereas Capinota PAPR-50% H_2SO_4 was only 44% as effective as SSP. Such PRs, therefore, are not suited for partial acidulation.

Phosphate Rock-Superphosphate Mixture

Mixing PR with soluble P fertilizers to enhance the agronomic effectiveness of low-quality PRs is an alternative to partial acidulation. Adding small amounts of soluble phosphates to act as a starter dose until the nutrients from the PR become available has been shown to increase the effectiveness of these rocks. As with PAPR, when the PR-superphosphate mixture is applied to the soil, the soluble MCP will provide the plants with the nutrient to satisfy the requirement of the first critical stage of plant growth. After the extensive root system has been established, the plants will be able to use the P from PR more effectively (Chien and Hammond, 1988).

Chien et al. (1987) studied the effectiveness of the reactive North Carolina PR mixed with TSP at different ratios and found that the dry-matter yield of and P uptake by maize grown on a limed soil (pH 6.2) increased with increasing proportions of TSP in the TSP-PR mixture. Although PR alone was less effective than TSP, PR mixed with TSP at a P ratio of 1:1 was just as effective as TSP.

Compacted Mixtures of PR and TSP

A disadvantage of mixing finely ground PR with superphosphates is that it creates dust during application. Moreover, during the mixing and application procedures, segregation of particles could take place. Mixtures would be more attractive to store, transport, and apply if they were compacted into granules.

Recent studies at IFDC have shown that compaction of PR with TSP or SSP could significantly improve the effectiveness of PRs with low reactivity,

especially those with high iron and aluminum oxide contents.

In a greenhouse experiment to compare the agronomic effectiveness of Pesca PR, PAPR, and PR compacted with TSP, Chien et al. (1987) found that Pesca PR compacted with TSP and urea was as effective as TSP in increasing the dry-matter weight of maize. Both were more effective than PAPR-20% H_3PO_4 or PR compacted with TSP alone (Figure 5). Urea increased P availability probably because of the chelation of Ca^{++} ions with soil organic matter solubilized as a result of urea hydrolysis in soil that had a high organic matter content (Chien, 1979).

Two greenhouse trials were conducted at IFDC in 1988 with Togo PR, Togo PAPR-50% H_2SO_4 , and Togo PR compacted with SSP and KCl. Togo PR, which has low reactivity, was ineffective as a P source for maize or cowpeas, but when the PR was partially acidulated or compacted with SSP such that the water-soluble P content of the product was 45% of the total P, the agronomic effectiveness of the PR increased substantially, especially with cowpeas. In the maize experiment, compacted materials and PAPR were equally effective in increasing biomass yield and P uptake (Figure 6). For cowpeas, compacted mixtures of PR and TSP were more effective than PAPR (Figure 7) (Kpombekou et al., 1991).

In 1990, PAPR and a compacted product, PR + TSP + urea + KCl, produced from Dorowa PR from Zimbabwe were compared with SSP in agronomic effectiveness using maize and ryegrass as test crops. Dorowa PR was a very poor source of P because of its low reactivity. The compacted product was found to be as effective as SSP + urea + KCl for maize, and both were more effective than PAPR + urea + KCl (Figure 8). For ryegrass, the three P sources were almost equally effective (Figure 9).

Likewise, low reactive Mussoorie PR from India compacted with monoammonium phosphate (MAP) on a 50:50 P_2O_5 basis was as good a P source for maize grown in Hartsells soil (pH 4-8) as MAP (Figure 10).

Compaction with soluble P is an alternative to partial acidulation in enhancing the agronomic

effectiveness of phosphate rocks with low reactivity; however, compaction is a more effective option than partial acidulation if the PR contains large amounts of $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$. In a study to compare the agronomic effectiveness of partially acidulated versus compacted mixtures of PR + TSP of Capinota PR from Bolivia and Huila PR from Colombia, the PRs were acidulated at 50% level with H_2SO_4 . Capinota PR, which has low reactivity and contains 8.8% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$, and Huila PR, which has moderate reactivity and low $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ (2.3%), were also mixed with TSP to provide 50% of the total P in the mixture in soluble form. These materials were then compacted, crushed, and screened to 1.18- to 3.35-mm (minus 6- plus 14-mesh) size granules—the same size as that of the PAPRs. Biomass yield and P uptake by maize grown in Hartsells silt loam (pH 4.8) showed that the effectiveness of Huila PAPR was the same as that of the compacted PR + TSP mixture, and both were not statistically different from that of TSP (Figure 11). On the other hand, Capinota PAPR was only half as effective as TSP though Capinota PR + TSP and TSP had the same effectiveness (Figure 12). Phosphate rock compacted with TSP, urea, and KCl was no more effective than PR compacted with TSP alone (Menon and Chien, 1990).

To investigate the effect of plant species on the agronomic effectiveness of PAPR and PR + TSP, kidney beans and upland rice were grown in Hartsells silt loam fertilized with Capinota PAPR-50% H_2SO_4 , Capinota PR + TSP (50% P as TSP), Huila PAPR-50% H_2SO_4 , and Huila PR + TSP (50% P as TSP). Compared with TSP alone, compaction increased the relative effectiveness of Capinota PR from 43% to 80% in rice grain production and 51% to 92% in bean biomass yield. Likewise, P uptake by rice increased from 47% to 79% and by beans from 51% to 92% of that of TSP by compacting Capinota PR with TSP (Figures 13 and 14). When the moderately reactive Huila PR was compacted with TSP, its effectiveness was increased from 91% for the PR alone to 95% for PAPR and 88% for PR + TSP in promoting bean biomass and from 79% for PR to 88% for PAPR and 84% for PR + TSP in increasing P uptake. For rice,

Huila PAPR was 81% as effective as TSP and PR + TSP and 79% as effective as TSP compared with PR alone, which was 75% as effective as TSP in promoting P uptake (Menon et al., 1991).

Further trials using PRs with different $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ contents clearly showed that the agronomic effectiveness of PRs with low reactivity and high $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ contents can be improved more by compaction with soluble phosphates than by partial acidulation. Phosphate rocks from Togo (Hahotoc, 1.9% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$), Mali (Tilemsi Valley, 8.5% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$), Niger (Tahoua, 9.9% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$), and Burundi (Matongo, 32% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$), which have low reactivities, were partially acidulated at 50% acidulation with sulfuric acid. The PRs were also compacted with TSP such that 50% of the total P came from TSP. The P fertilizers were applied at 0, 50, 100, 200, and 300 mg P kg^{-1} soil to Hartsells silt loam (pH 4.8); maize was grown as the test crop, followed by a second crop of maize and a third crop of upland rice to study the residual effect of the different P sources.

With all the sources tested, there was a significant variation in yield and P uptake by the first maize crop because of the rate and source of the P used. Depending on the rate of P used in soil treated with Hahotoc PAPR, the dry-matter yield of maize ranged from 19 to 46 g/pot, compared with 18 to 48 g in soils fertilized with the compacted product—PR + TSP. With all the other P sources, application of compacted materials resulted in significantly higher biomass yield and P uptake compared with PAPR application (Figures 15 and 16).

The agronomic effectiveness of the PAPR decreased with increase in $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ content of the PRs used. PAPR from Hahotoc PR having 1.9% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ was 86% as effective as TSP in increasing biomass yield and 72% as effective in promoting P uptake; whereas, PAPR from Matongo PR with 32% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ was only 12% as effective as TSP in increasing biomass yield and 16% as effective in increasing P uptake. On the other hand, the relative agronomic effectiveness of compacted products was hardly affected by $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ content. The

compacted Hahotoc product, PR + TSP, was as effective as PAPR. In contrast, Matongo PR + TSP was 74% as effective as TSP in increasing biomass and 91% as effective in increasing P uptake as TSP (Figure 17).

For the second crop of maize, there was no significant difference between the dry-matter yield of maize from soil treated with PAPR or PR + TSP for each individual P source except in the case of Matongo PR + TSP treated soil, which produced significantly higher yields of maize than did the soil treated with PAPR. Rice that was grown following the two maize crops showed an increase in yield when the rate of P applied prior to the planting of the first maize crop was increased up to 100 mg P kg⁻¹. At application rates higher than 100 mg kg⁻¹, there was no increase in grain or straw yield. The compacted PR + TSP performed better than PAPR in all cases although the difference was not statistically significant (Figure 18).

The results of this series of trials clearly demonstrate the superior performance of compacted mixtures of PR and soluble P over PAPR when the PRs contain high levels of Fe₂O₃ + Al₂O₃. The comparative advantage of the compacted mixtures over PAPR can be attributed to the higher amount of soluble P in the mixtures. In PAPR the soluble-P content decreased as the Fe₂O₃ + Al₂O₃ content of the PR source material increased. In compacted mixtures of PR + TSP, soluble-P content was not affected by the oxide content of the PR (Figure 19).

In all of these studies, the compacted products contained 50% of the total P in a soluble form. Decreasing the amount of TSP in the mixture to less than 50% of the total results in a significant reduction in crop yield. This was revealed in a greenhouse study using compacted mixtures of TSP and Togo or Capinota PR with TSP ranging from 10% to 50% of the total P (Menon et al., 1995). Dry-matter yield of maize grown in Hartsells silt loam or Waverly clay loam increased when the application rate of all of the compacted products was

increased (Figure 20). However, the dry-matter yield was significantly decreased when the amount of water-soluble P in the applied fertilizer was decreased (Figure 21). In previous studies, a compacted mixture of TSP and Togo PR with 50% total P in a soluble form performed as well as TSP alone; however, in this experiment the compacted materials did not perform as well. The compacted product in which Togo PR contributed 50% of the total P was 75% as effective as TSP in increasing dry-matter yield of maize in Hartsells soil and 91% as effective in Waverly soil. The relative agronomic effectiveness (RAE) of 50:50 Capinota PR:TSP in Hartsells soil was 68% and in Waverly soil 71%. Reducing the percent of TSP in the compacted product—Togo PR + TSP—to 30%, 20%, and 10% decreased the RAE to 52%, 37%, and 24% in Hartsells soil, and 52%, 37%, and 18% in Waverly soil. Similar results were also found with Capinota PR + TSP.

It is evident that besides TSP, the PR is also contributing to plant-available P in soils when compacted PR + TSP is applied. For example, when 100 mg P kg⁻¹ was applied as Togo PR, dry-matter yield of maize was only 0.8 g/pot. When 100 mg P kg⁻¹ as TSP was used, 13.3 g/pot dry-matter yield was obtained. On the other hand, when the compacted product containing 100 mg P as TSP and 100 mg P as Togo PR was applied, the dry-matter yield obtained was 15.2 g/pot. This would suggest that 1.9 g/pot dry-matter yield resulted because PR was applied mixed and compacted with TSP. Therefore, P availability of PR in the presence of TSP was greater than that of PR alone.

The results of this research show that when low reactive PRs that are not suitable for direct application are compacted with TSP, the product should contain not less than 50% of the total P in soluble form.

Conclusions

The results obtained from IFDC laboratory and greenhouse studies indicate that compaction of PR with soluble P sources is a potentially attractive alternative technology to partial acidulation of those PRs that have low reactivity and are not suitable for use as direct application fertilizers. Compaction is especially appropriate for those PRs that contain high levels of $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ since partial acidulation of these types of

PRs normally produces poor quality products, which contain low water-soluble P. Further work is needed to evaluate the agronomic effectiveness of PR compacted with soluble P sources under field conditions.

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Appendix

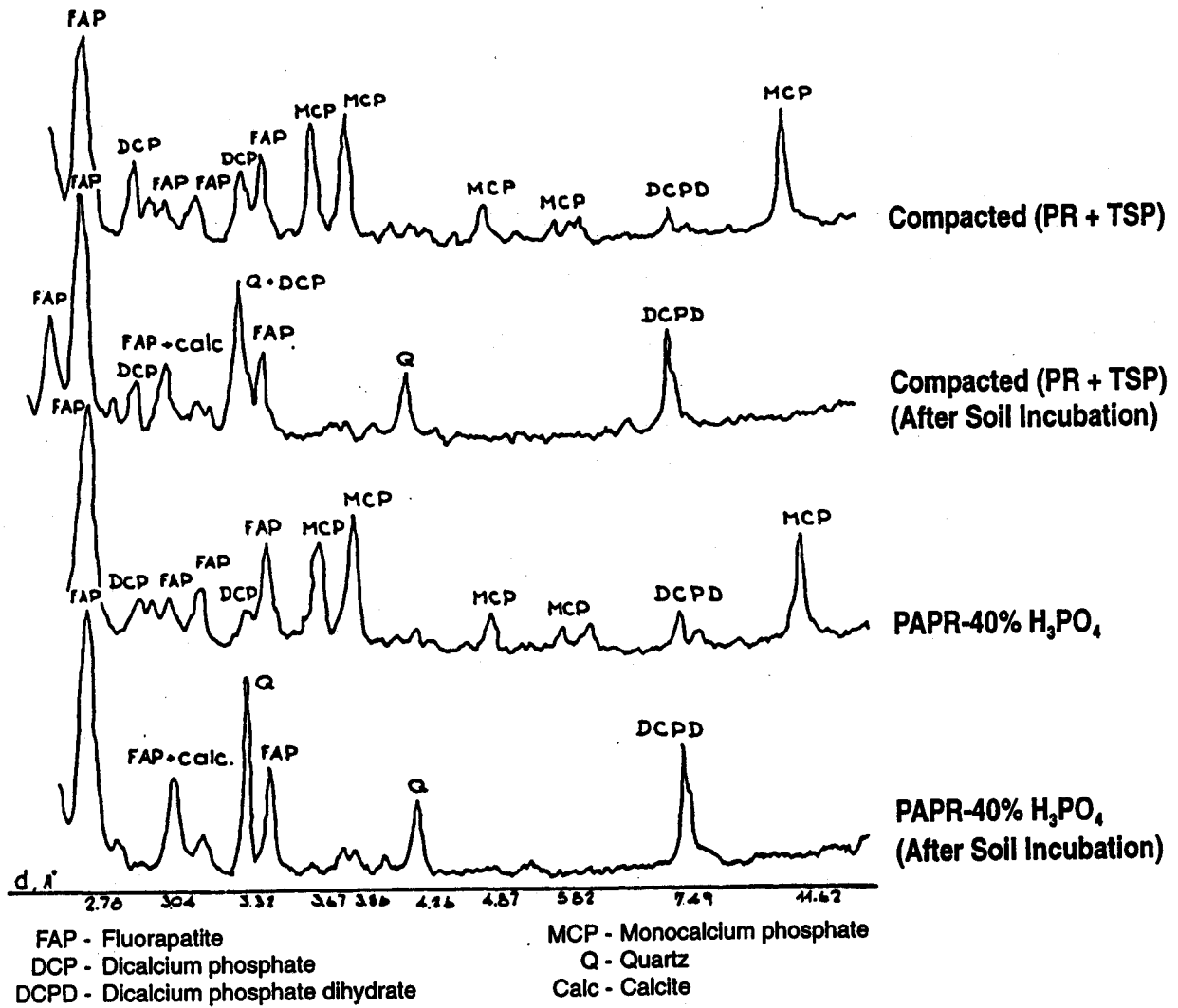


Figure 1. X-ray Diffractions of Two P Fertilizers Before and After Soil Incubation.
 PR Source = Arad, Israel (Hagin and Katz, 1985).

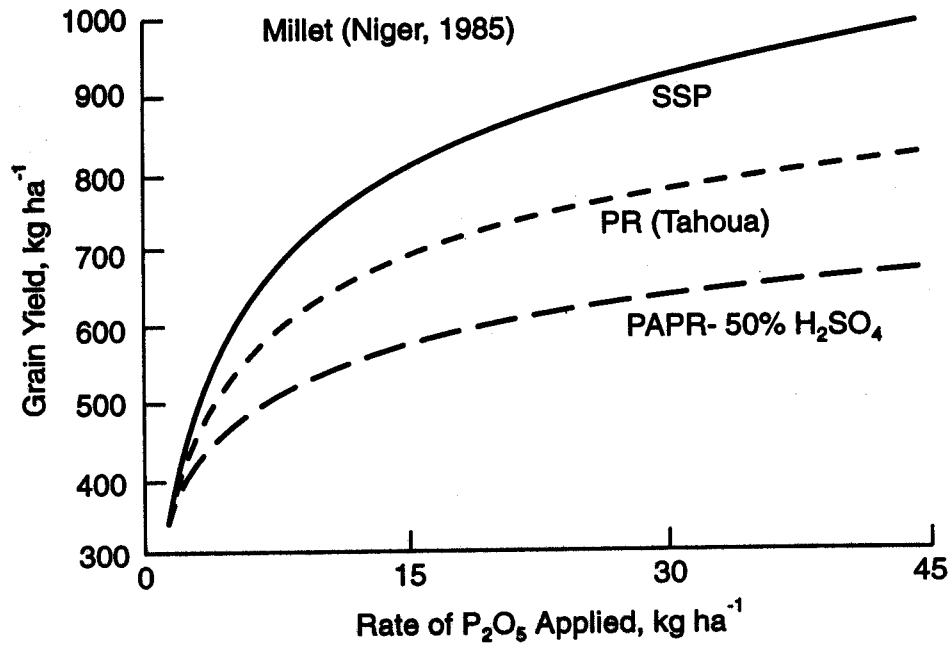


Figure 2. Grain Yield of Millet Obtained With SSP, Finely Ground Tahoua PR, and Granular Tahoua PAPR-50% H₂SO₄ at Gobery, Niger in 1985 (IFDC,1987).

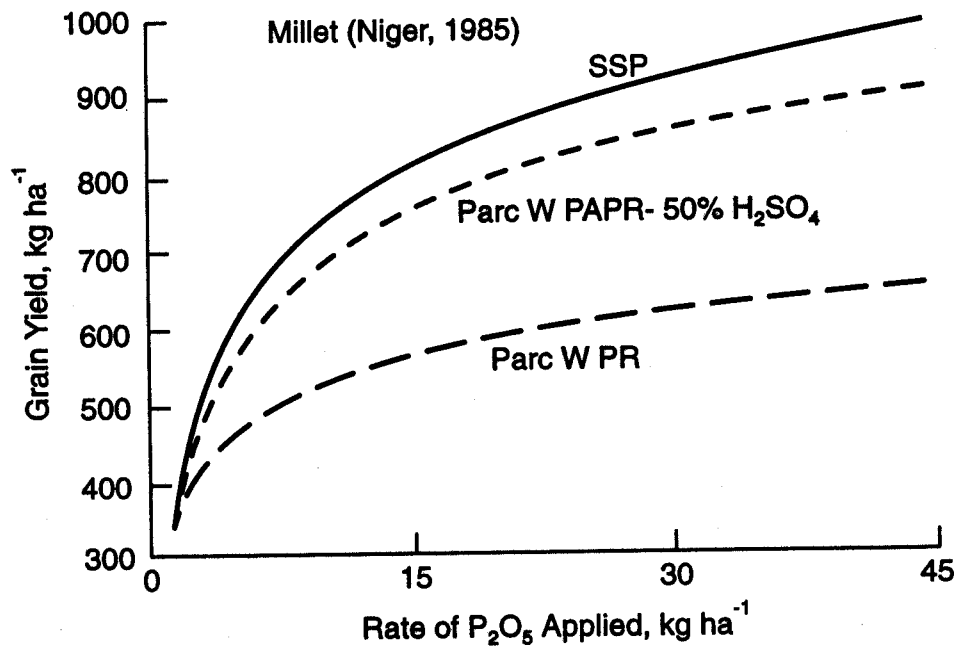


Figure 3. Grain Yield of Millet Obtained With SSP, Finely Ground Parc W PR, and Granular Tahoua PAPR-50% H₂SO₄ at Gobery, Niger in 1985 (IFDC,1987).

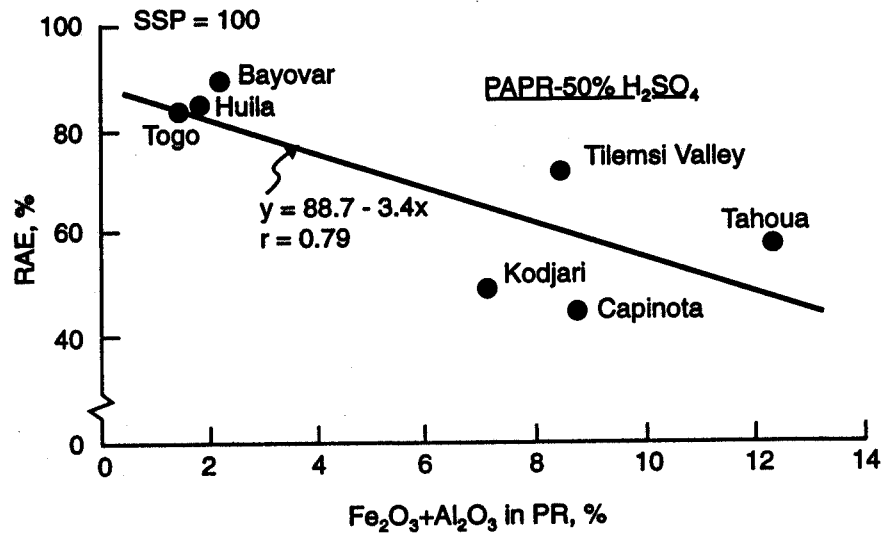


Figure 4. Relative Agronomic Effectiveness (RAE) in Dry-Matter Yield of Maize Obtained With SSP and Various PAPR-50% H₂SO₄ Products as Influenced by Fe₂O₃+Al₂O₃ Content in PRs (Hammond et al., 1989).

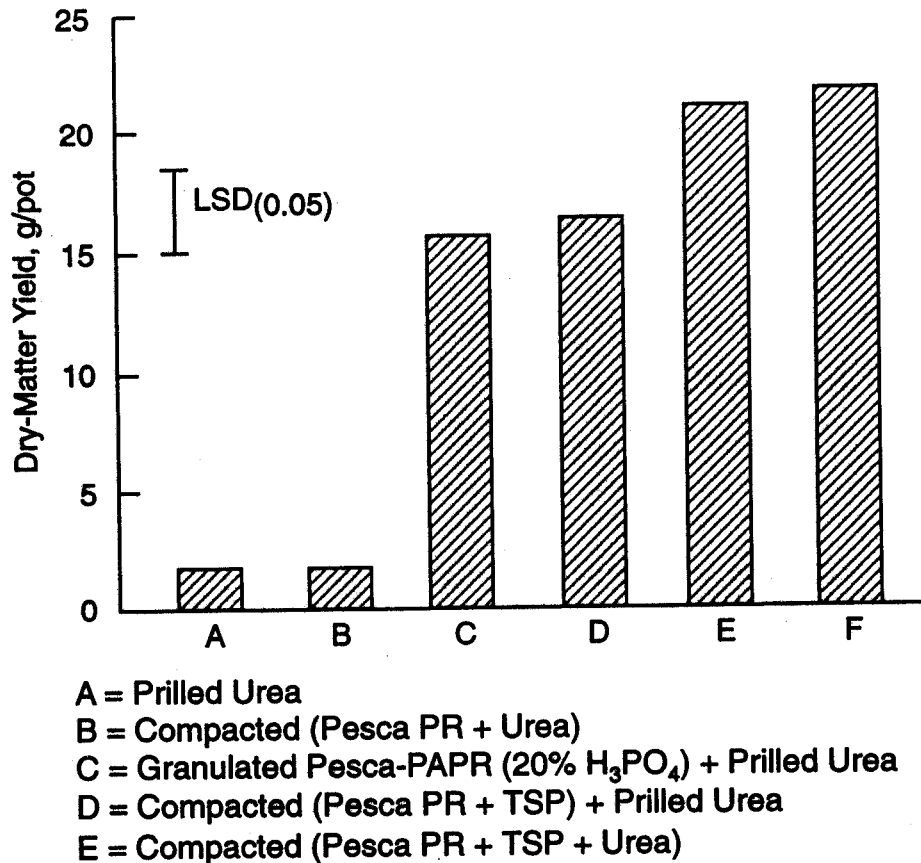


Figure 5. Dry-Matter Yield of Maize Obtained With Various P Fertilizers (Chien et al., 1987).

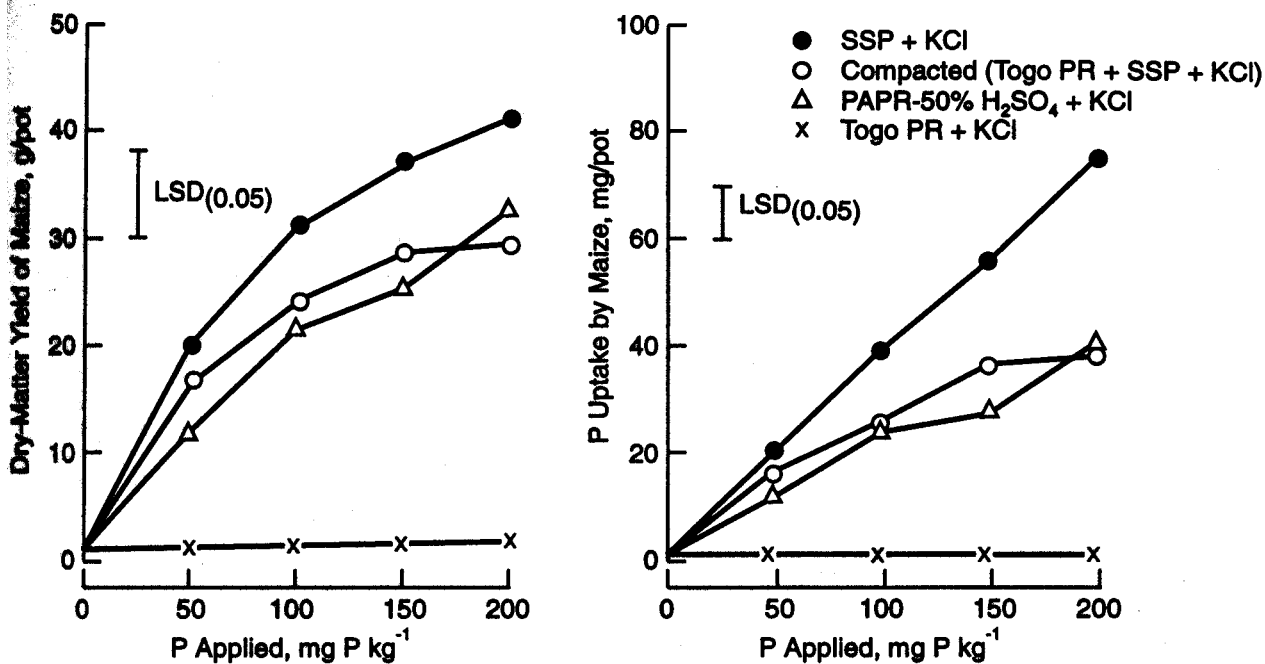


Figure 6. Dry-Matter Yield of Maize and P Uptake Obtained With Various P Fertilizers (Kpombekou et al., 1991).

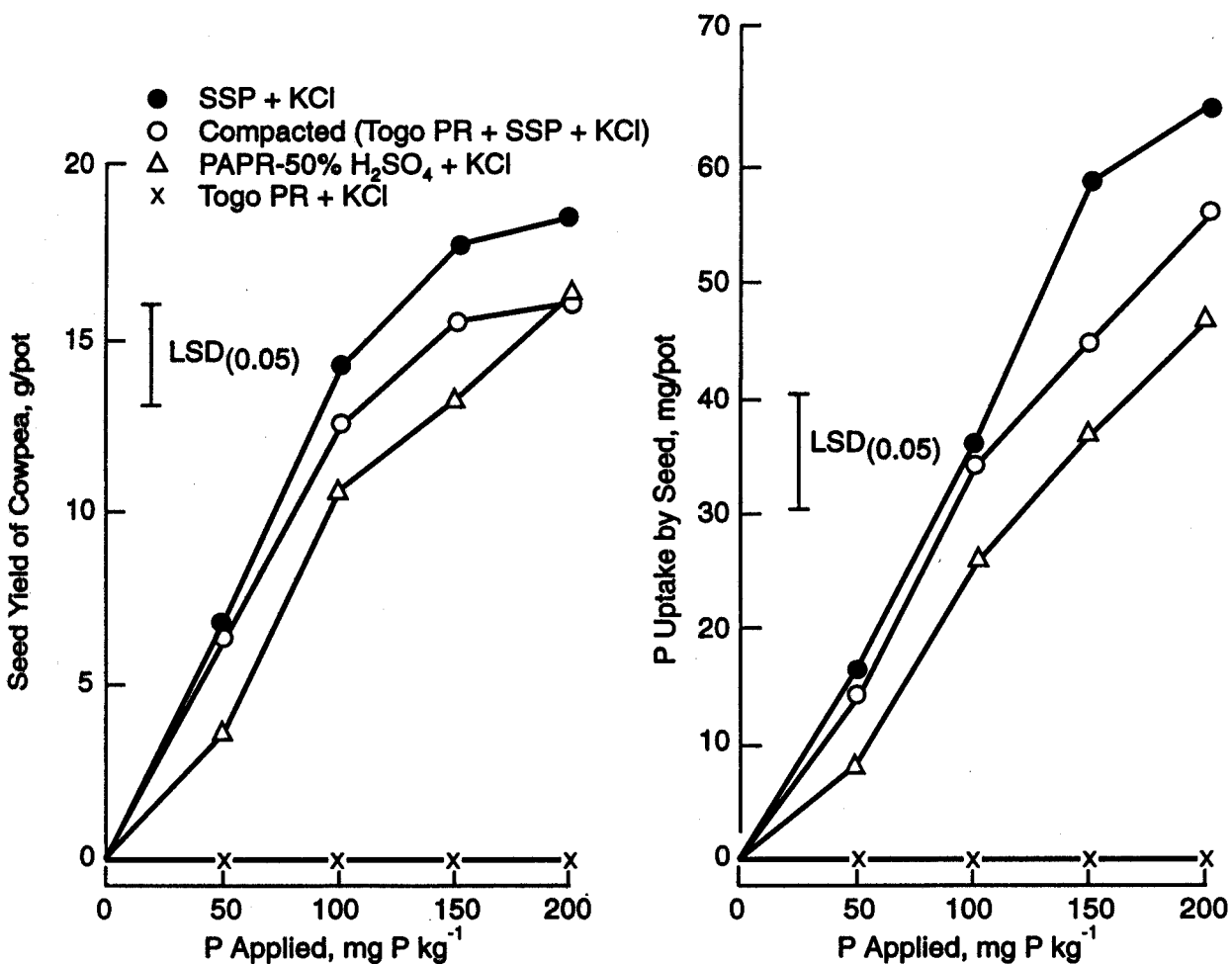


Figure 7. Seed Yield of Cowpea and P Uptake by Seed Obtained With Various P Fertilizers (Kpombekou et al., 1991).

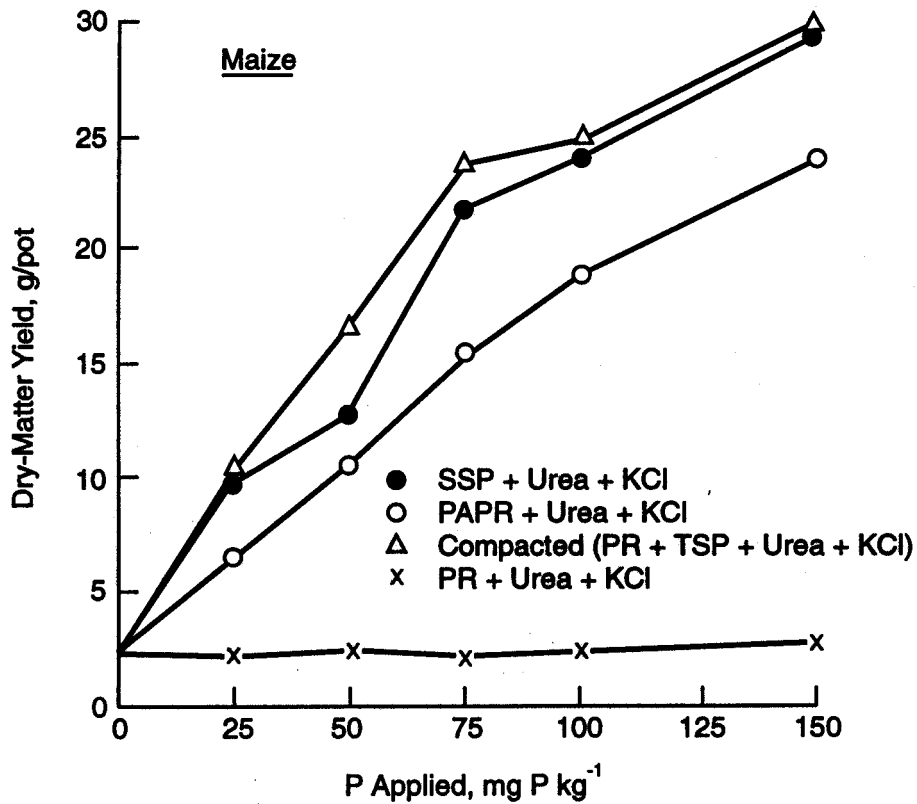


Figure 8. Dry-Matter Yield of Maize Obtained With Various P Fertilizers. The PR Used Was Dorowa PR From Zimbabwe (E. M. Govere, 1990, Unpublished Data).

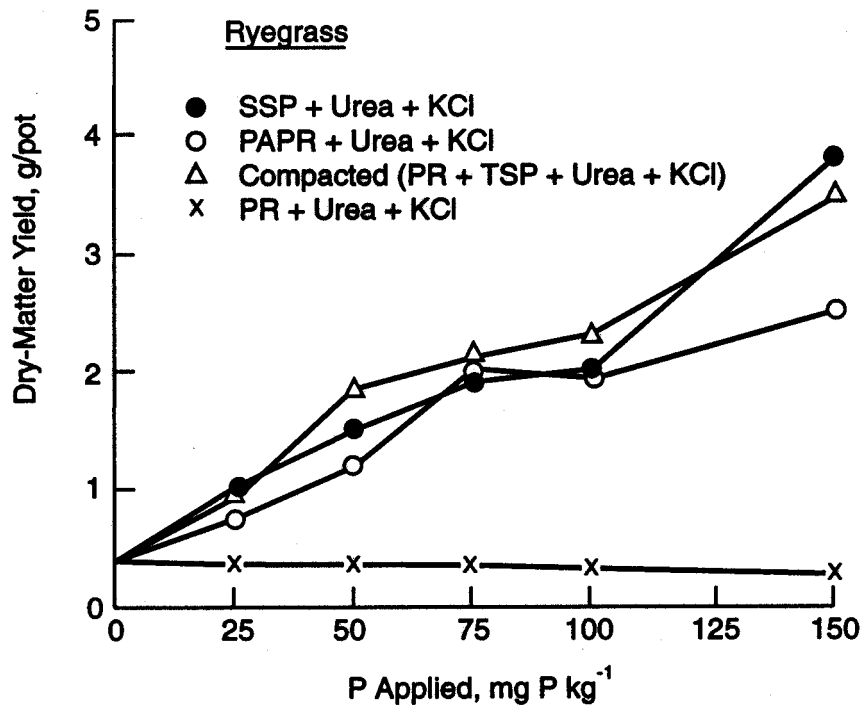


Figure 9. Dry-Matter Yield of Ryegrass Obtained With Various P Fertilizers. The PR Used Was Dorowa PR From Zimbabwe (E. M. Govere, 1990, Unpublished Data).

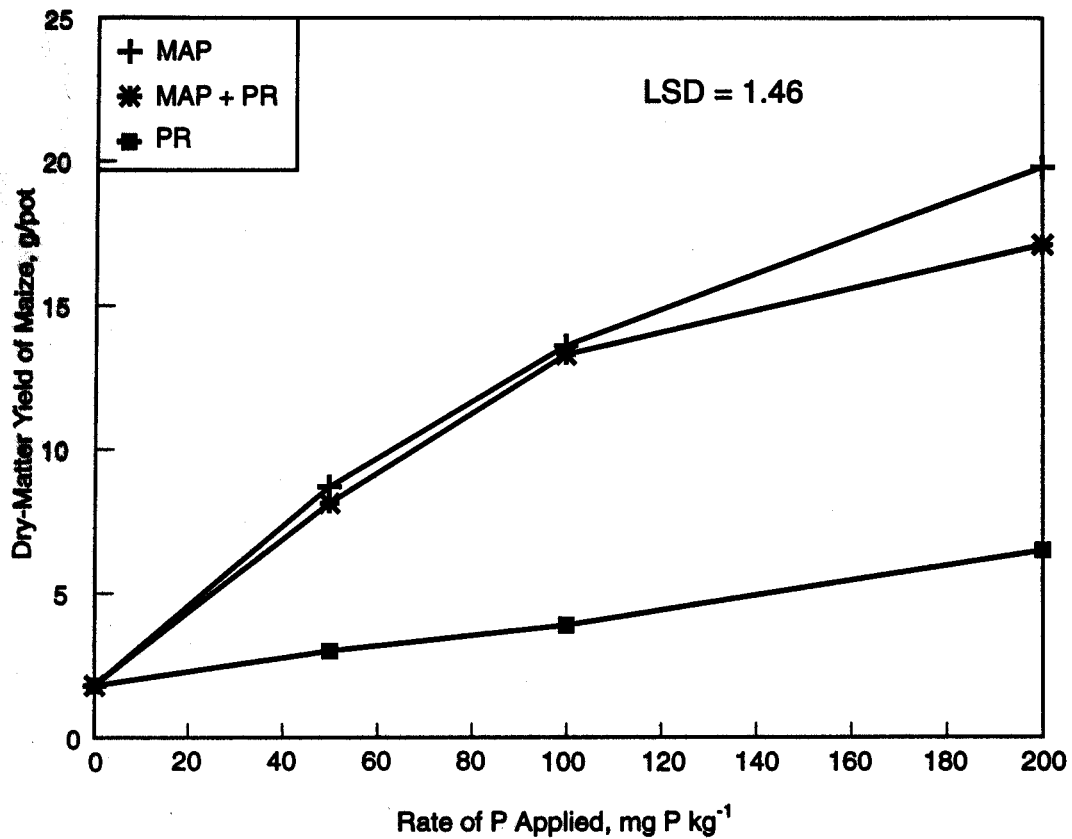


Figure 10. Dry-Matter Yield of Maize Obtained With Various Fertilizers. The PR Used Was Mussoorie PR From India (IFDC Unpublished Data).

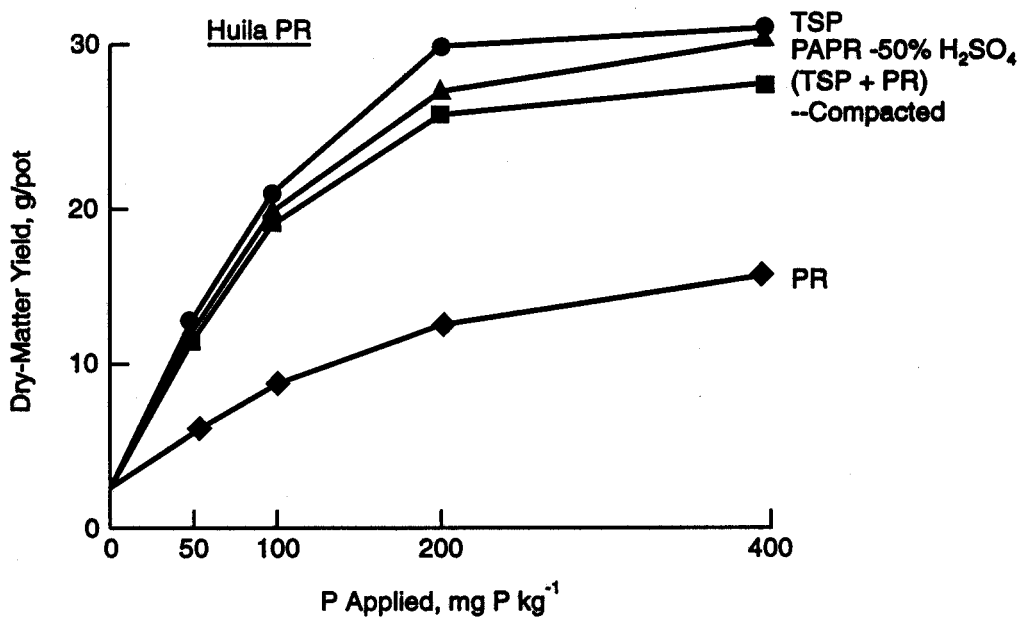


Figure 11. Dry-Matter Yield of Maize as Influenced by P Source and Rates of Application (Huila PR) (Menon and Chien, 1990).

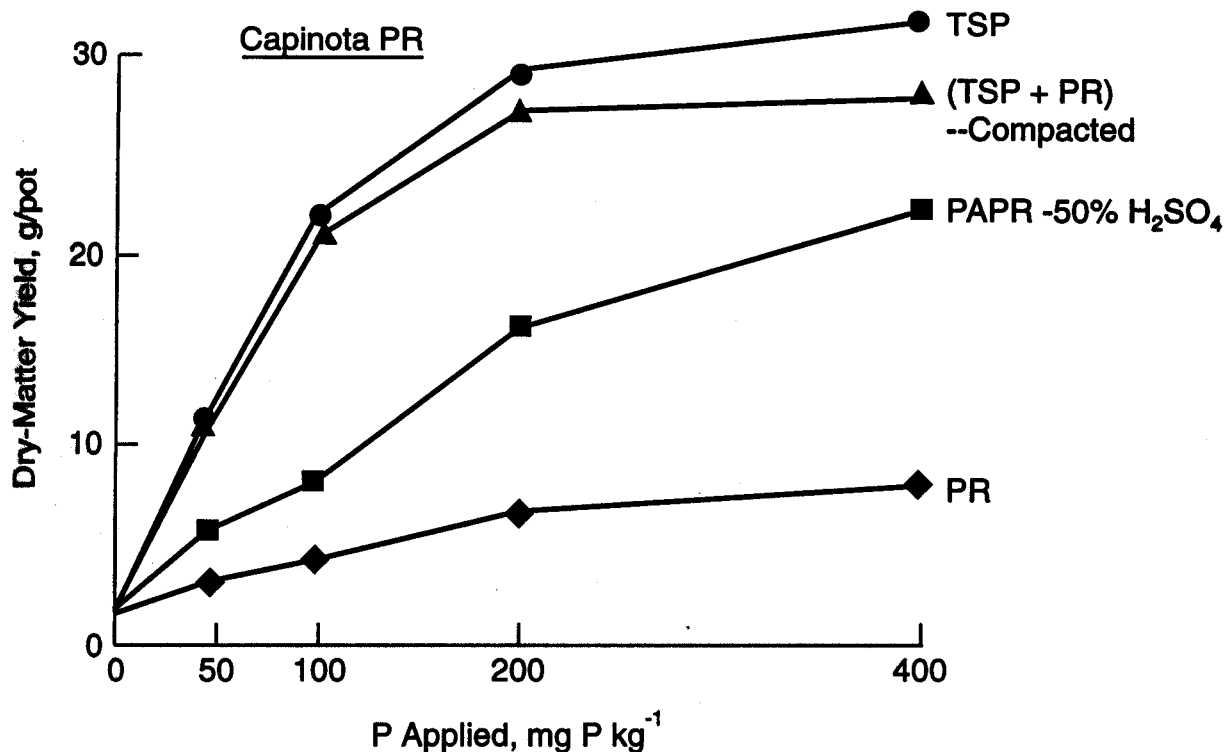


Figure 12. Dry-Matter Yield of Maize as Influenced by P Source and Rates of Application (Capinota PR) (Menon and Chien, 1990).

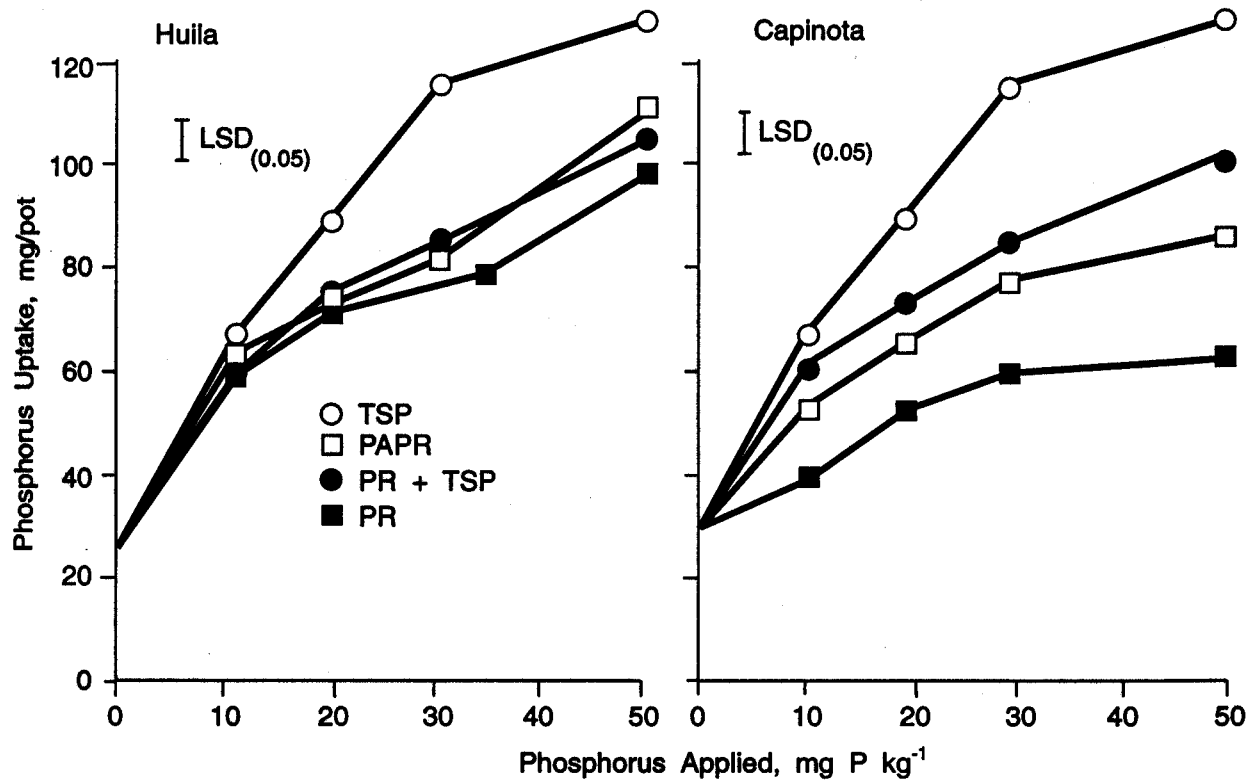


Figure 13. Phosphorus Uptake by Rice From Soil Treated With Triple Superphosphate (TSP) or Phosphate Rock (PR), Partially Acidulated PR (PAPR), or Compacted PR Plus TSP From Huila, Colombia, or Capinota, Bolivia (Menon et al., 1991).

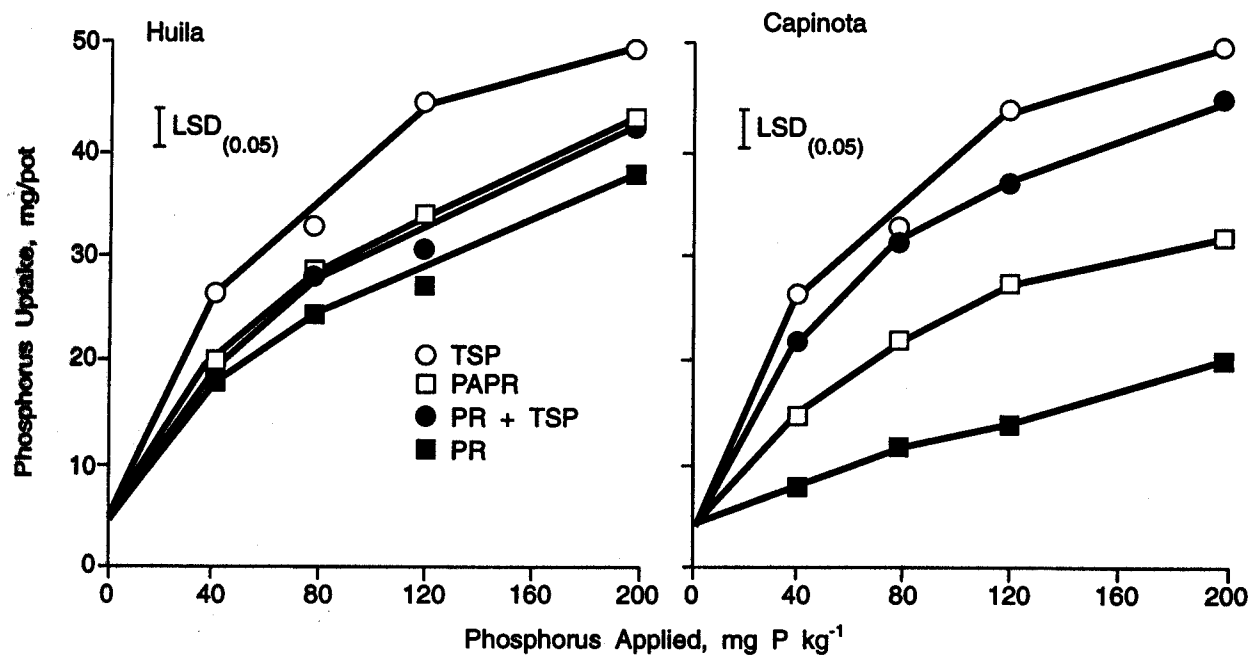


Figure 14. Phosphorus Uptake by Bean From Soil Treated With Triple Superphosphate (TSP) or Phosphate Rock (PR), Partially Acidulated PR (PAPR), or Compacted PR Plus TSP From Huila, Colombia, or Capinota, Bolivia (Menon et al., 1991).

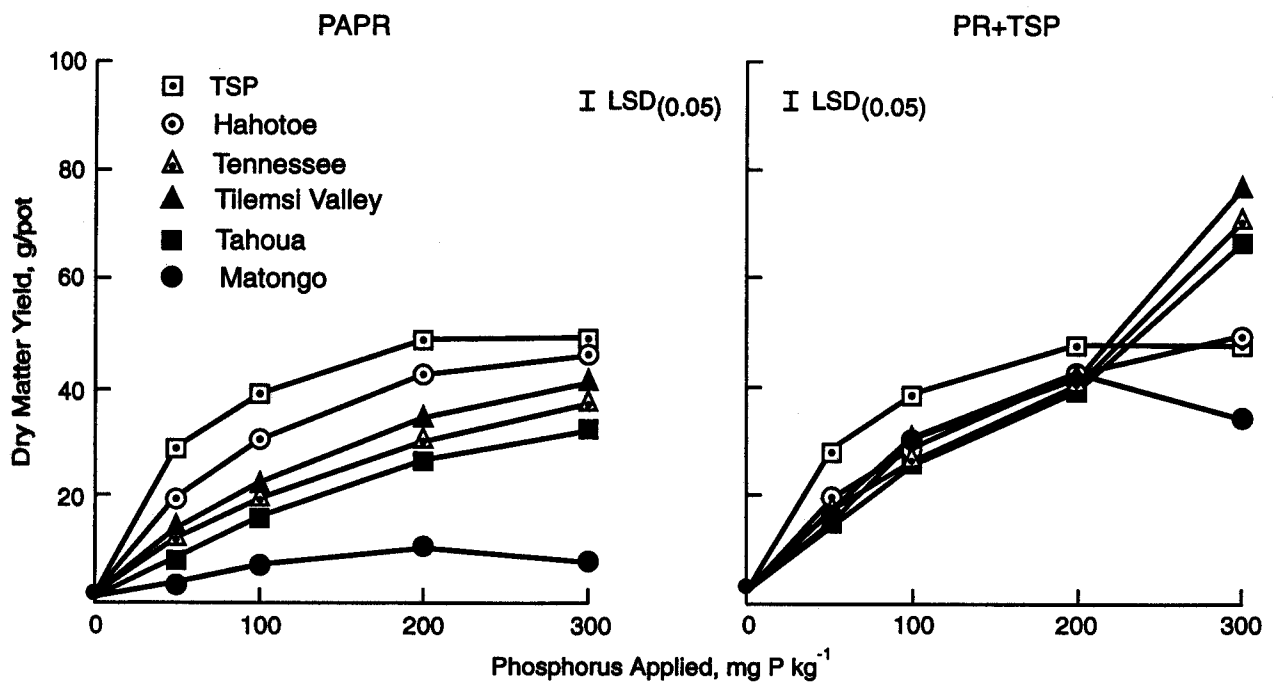


Figure 15. Dry-Matter Yield of Maize From Soil Treated With Different P Fertilizers (First Crop).

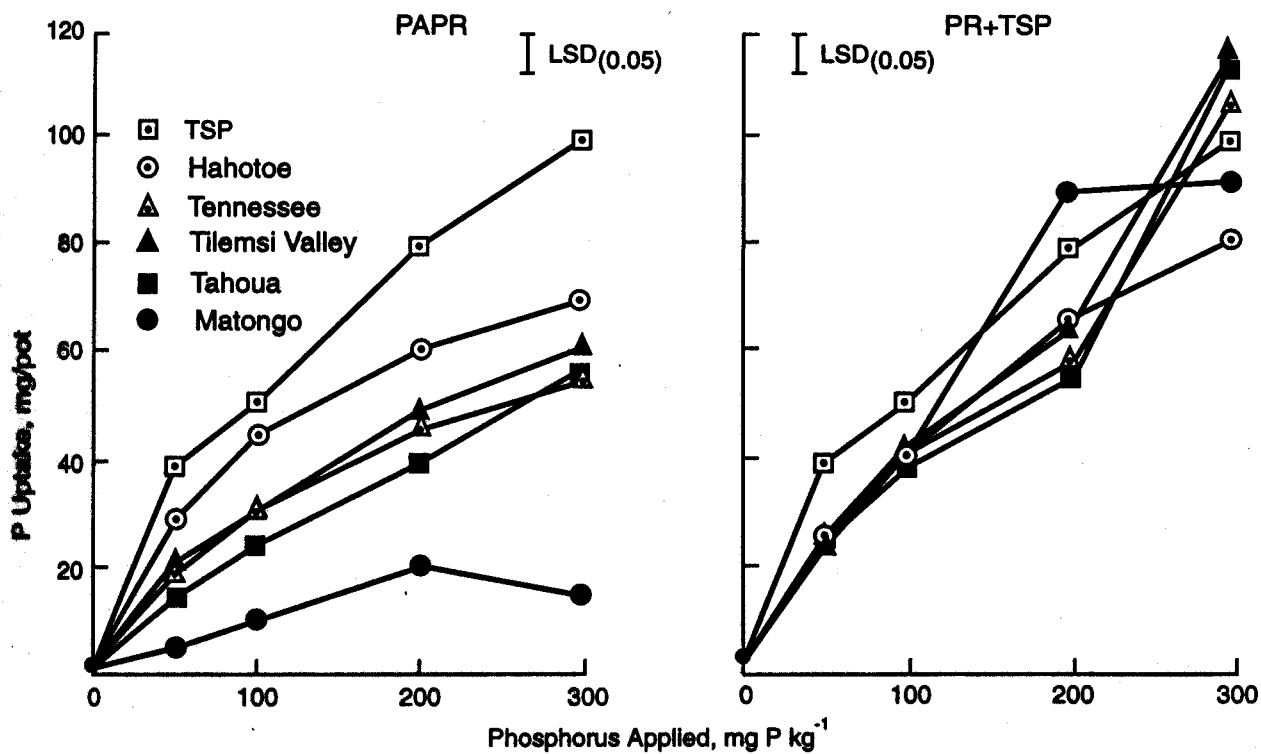


Figure 16. Phosphorus Uptake by Maize From Soil Treated With Different P Fertilizers (First Crop).

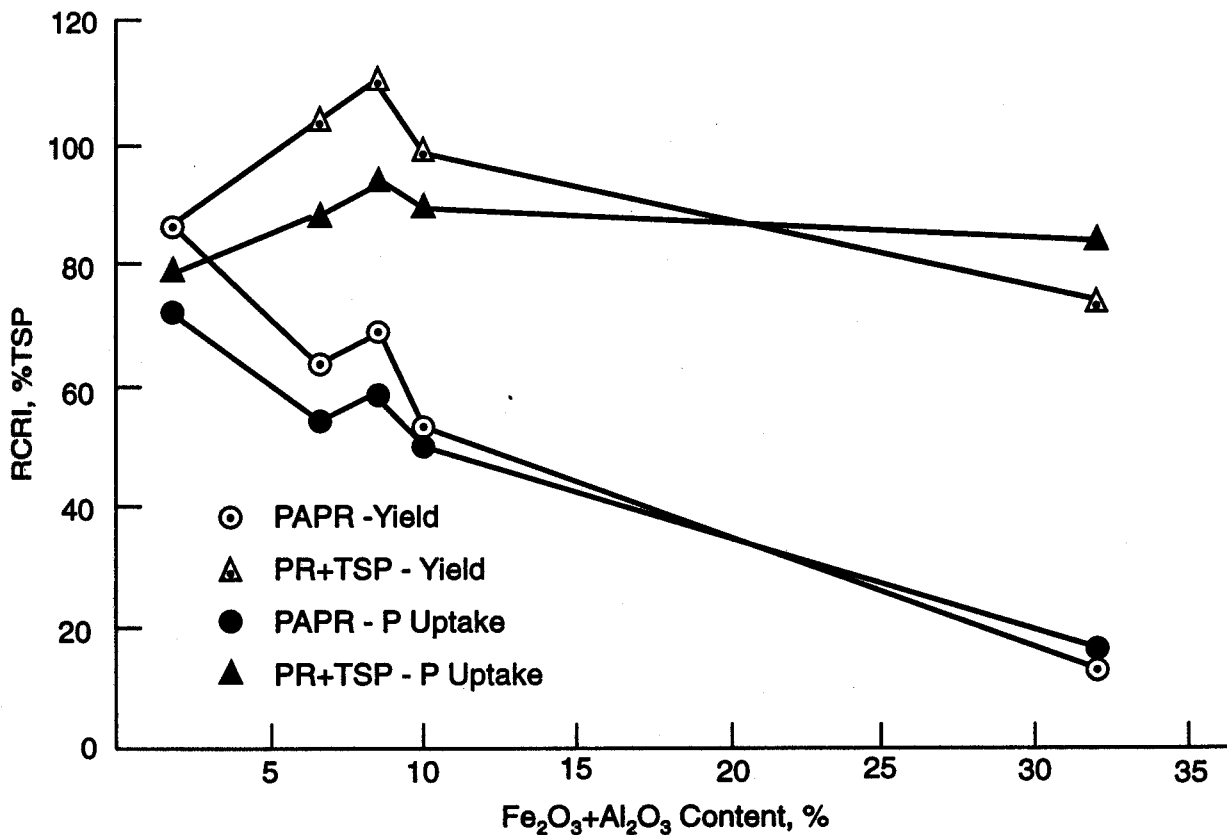


Figure 17. Relative Crop Response Index (RCRI) for Biomass Yield and P Uptake of Maize as Influenced by $Fe_2O_3+Al_2O_3$ Content of PR.

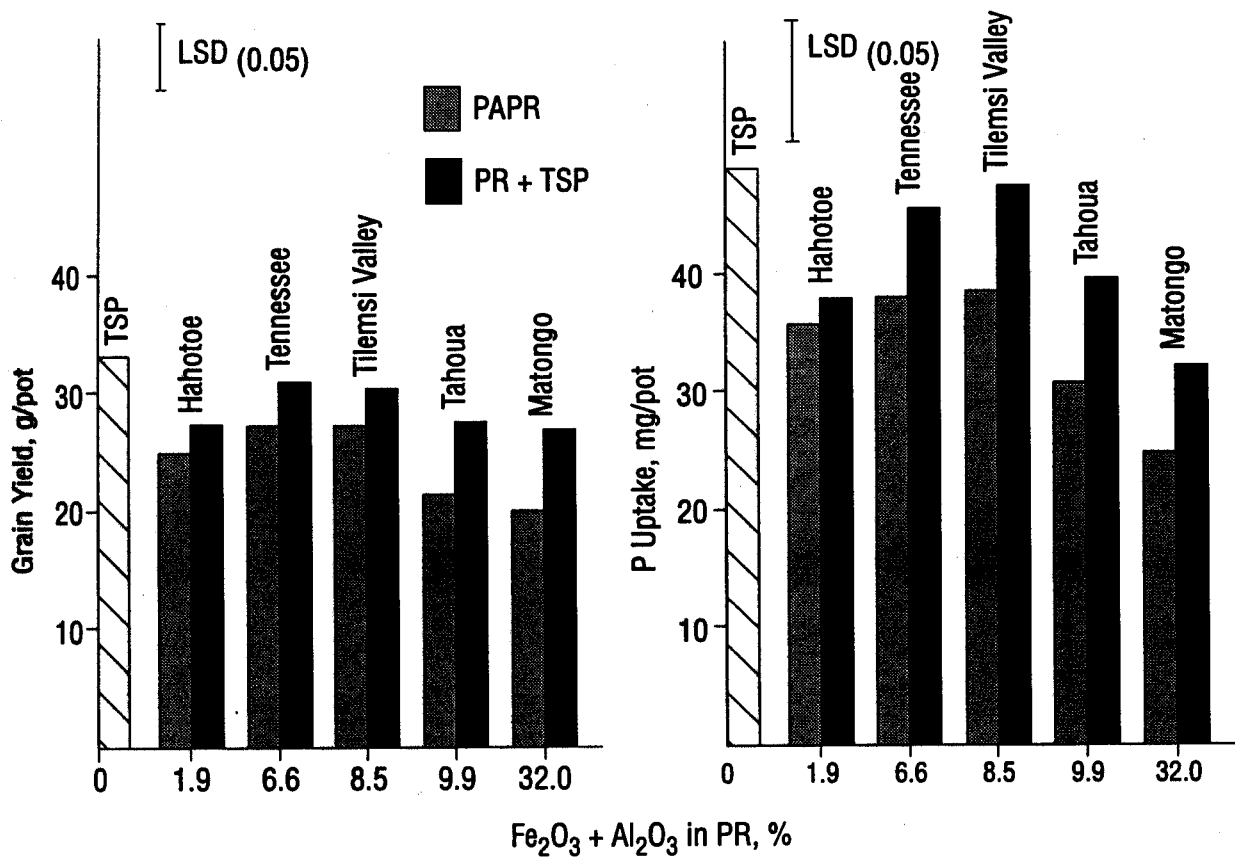


Figure 18. Grain Yield and P Uptake of Rice Obtained Using PAPER and PR + TSP as Influenced by Fe₂O₃ + Al₂O₃ Content of PR.

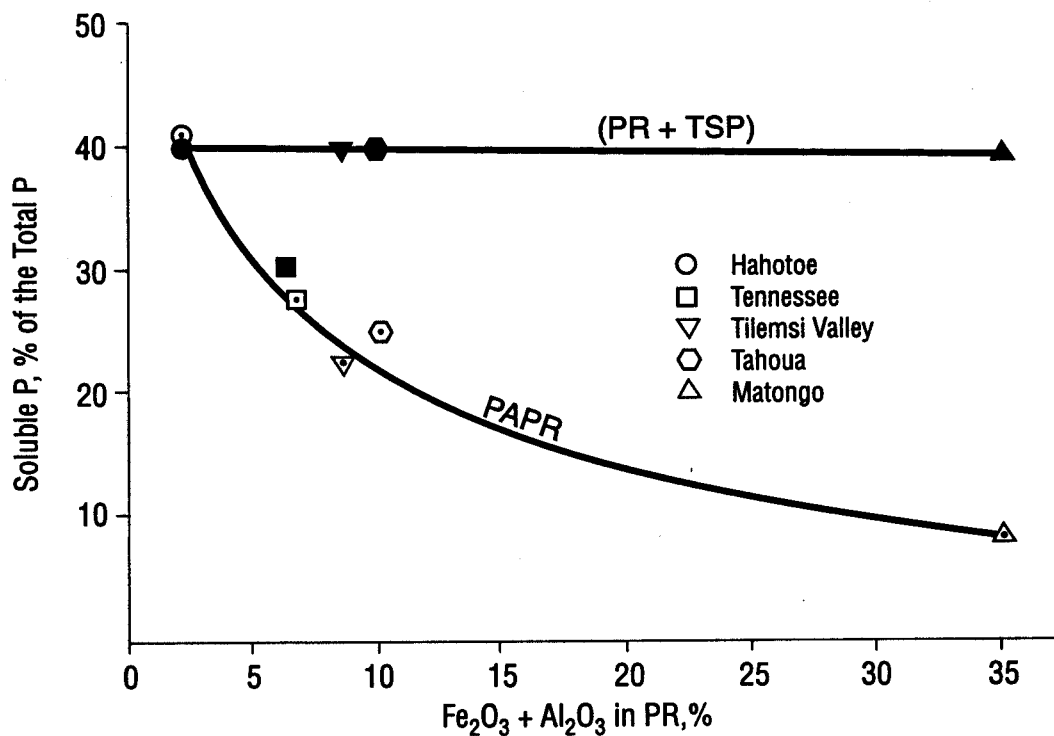


Figure 19. Influence of Fe₂O₃ + Al₂O₃ in the PR on Water-Soluble P Content of PAPER at 50% Acidulation With H₂SO₄, and Compaction With TSP.

Hartsells Soil

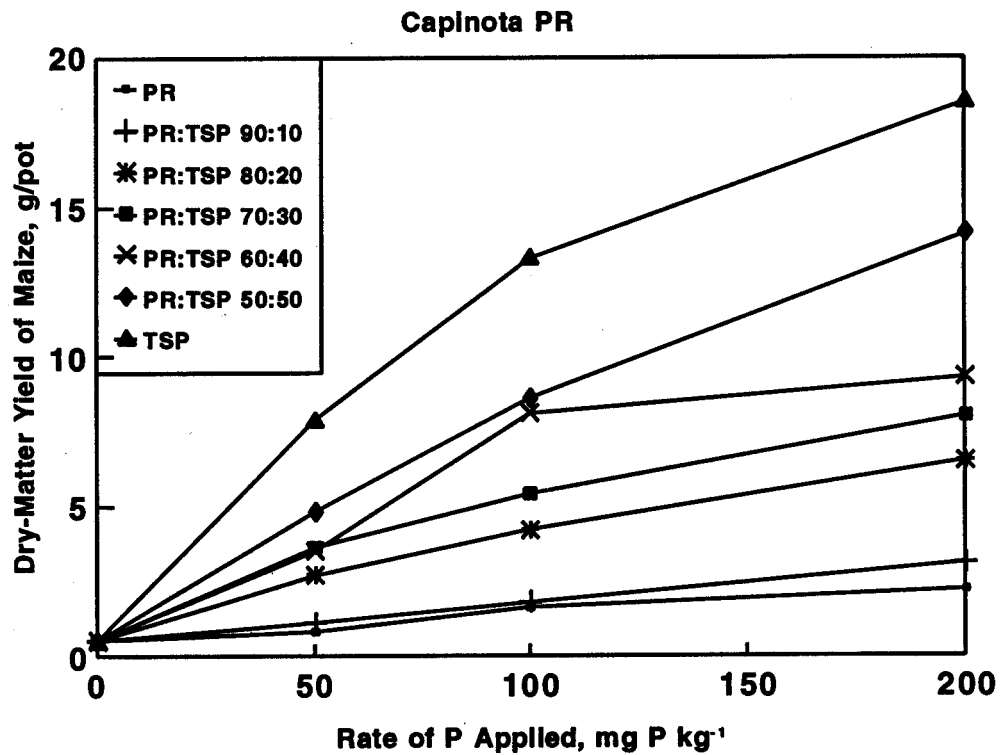
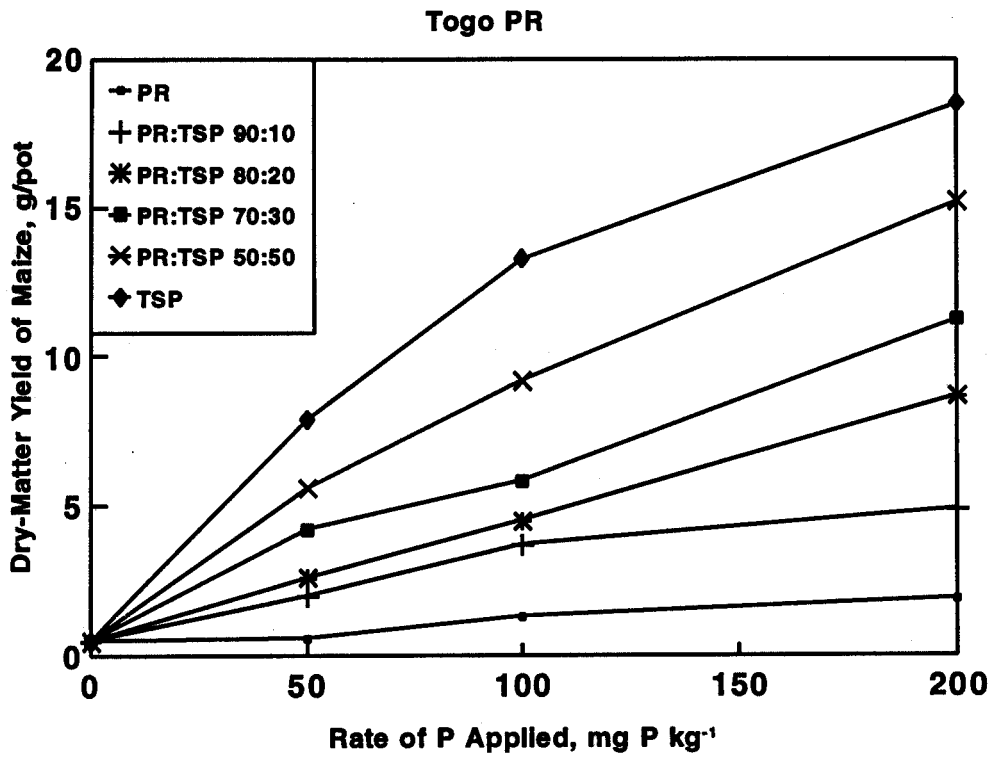


Figure 20. Dry-Matter Yield of Maize as Influenced by Rate of Application of Different P Sources.

Waverly Soil

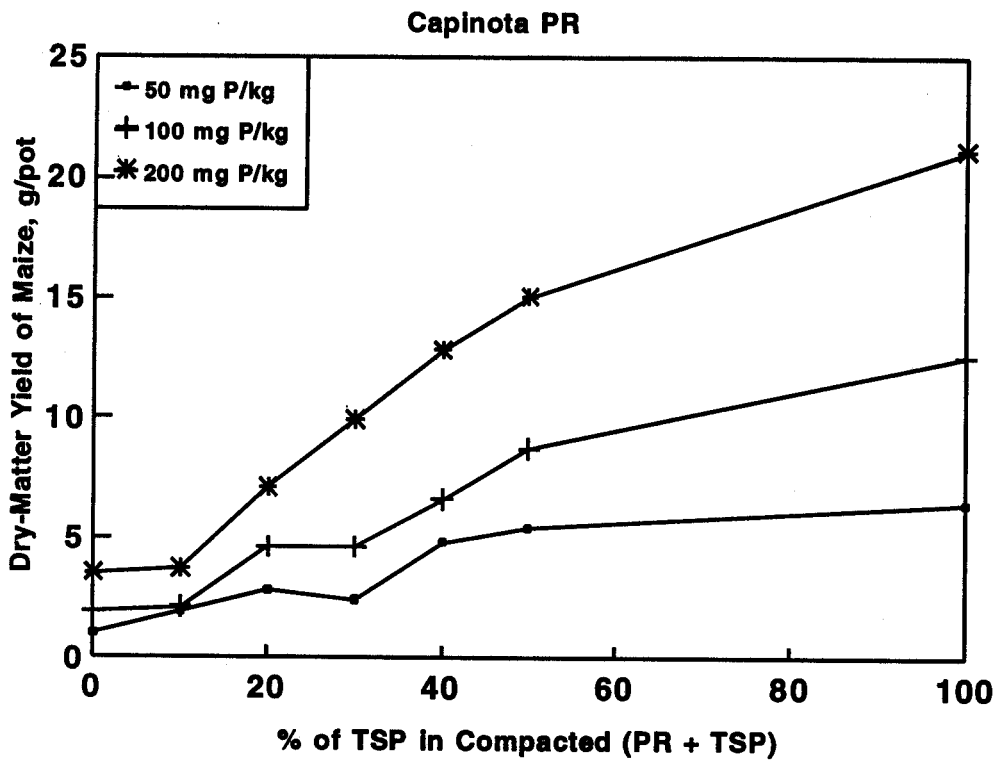
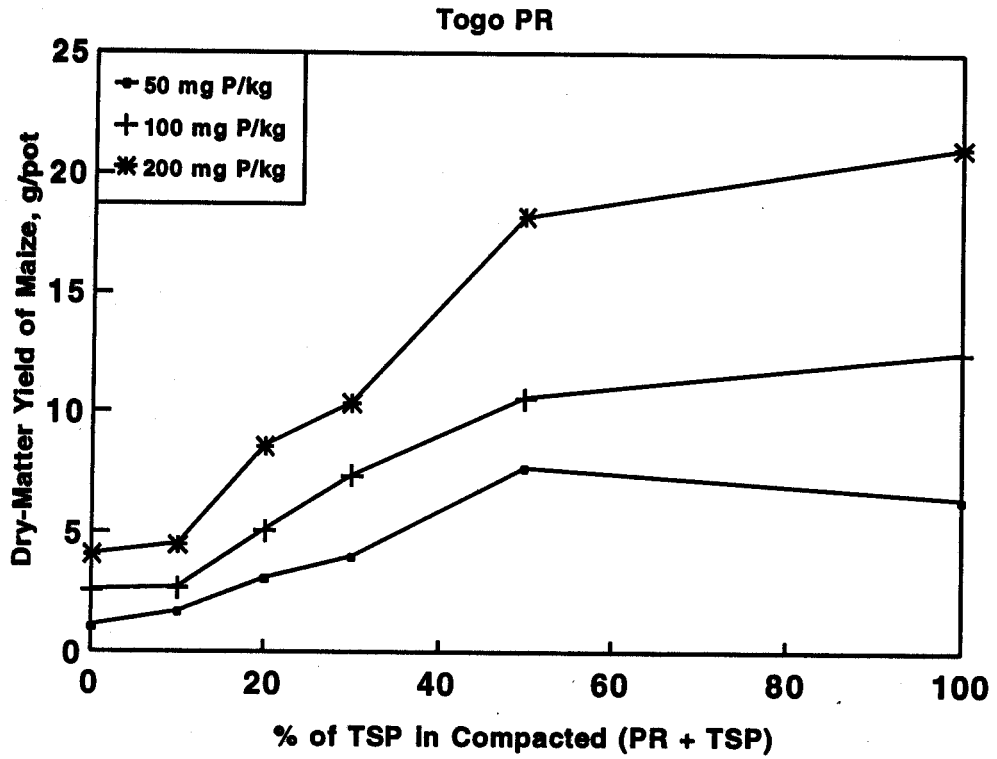


Figure 21. Dry-Matter Yield of Maize as Influenced by the Soluble P Content of Different P Sources.

IFDC

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