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Yield and P uptake by rice and wheat grown in a sequence as influenced by phosphate fertilization with diammonium phosphate and Mussoorie rock phosphate with or without crop residues and phosphate solubilizing bacteria

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SUMMARY

The field experiments were carried out at the Indian Agricultural Research Institute, New Delhi during 1996–97 to 1998–99 to study the effect of phosphate solubilizing bacteria (PSB) and incorporation of wheat and rice residue on the relative efficiency of diammonium phosphate (DAP) and Mussoorie rock phosphate (MRP) in three cycles of rice–wheat cropping system. Application of MRP had no significant effect on grain and straw yield and P uptake by rice and wheat; however, when it was inoculated with PSB, it increased grain and straw yields as well as P uptake of both rice and wheat. Efficiency of MRP + PSB was further increased when rice and wheat residues were incorporated and this practice made MRP on a par with DAP. Available P in soil after three cycles of rice–wheat cropping was more after MRP + PSB and incorporation of rice and wheat residues than after DAP. The results of the present study, therefore, indicate that low grade rock phosphate such as MRP can be advantageously utilized in rice–wheat cropping system when applied with PSB inoculation and incorporation of rice and wheat residues.

INTRODUCTION

Rice–wheat cropping systems cover about 22 million hectares in north India, Pakistan, Nepal, Bangladesh and China (Singh & Paroda 1994). In India it occupies about 12 million hectares and contributes just under one-third of total grain production (Kumar *et al.* 1998). Thus, rice–wheat systems are of considerable significance to India's food self-sufficiency. However, the practice of cereal–cereal cropping on the same piece of land has been detrimental to soil fertility and the sustainability of this system is in question (Yadav *et al.* 2000). There is evidence of stagnation or decline in the productivity of rice–wheat systems even with application of the recommended dose of NPK fertilizers (Yadav 1998). Depletion of soil organic C, lower moisture retention, reduction in water stable aggregates and available Zn status have been identified as reasons for the unsustainability of rice–wheat cropping systems even with adequate NPK application (Nambiar 1995). Hence, the complementary role of organic manures is being increasingly explored for sustainable rice–wheat cropping systems. However, non-availability of sufficient farmyard manure and compost and involvement of extra cost are the biggest hindrances in its use in rice–wheat systems. Recycling of residues of these crops has a great potential in meeting the need for organic matter addition in soils and Prasad *et al.* (1999) have reported that incorporation of rice or wheat residue is beneficial to rice–wheat cropping systems.

Phosphorus is a costly primary plant nutrient since the manufacture of phosphate fertilizers requires phosphorus-rich rock, sulphur and energy. However, there are substantial deposits of low grade rock phosphate in several countries of the world. One such deposit is Mussoorie rock phosphate in India. Although attempts have been made in the past to use finely ground Mussoorie rock phosphate directly in soils of pH 7 and above (Sharma *et al.* 1983;

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Sharma & Prasad 1996), it is still not widely used due to its lower efficiency as compared with ordinary superphosphate or diammonium phosphate, the two most widely used phosphate fertilizers in India.

Some soil microorganisms including bacteria, fungi and actinomycetes have the capability to convert plant unavailable phosphorus compounds such as fluor and hydroxy apatites (the major components of rock phosphate) to plant available mono- and dicalcium phosphate (Cosgrove 1977; Illmer & Schinner 1992) and these have been referred to as phosphate solubilizing organisms (Goldstein 1986). Experiments with phosphate solubilizing bacteria (PSB) such as *Pseudomonas striata*, *Bacillus polymexa* etc. have shown their usefulness on crop growth and yield (Lifshitz *et al*. 1987; Gaur 1990) and inoculation of PSB along with rock phosphate resulted in increased phosphorus availability in rice (Monod *et al*. 1989), wheat (Tiwari *et al*. 1993), sorghum (Jisha & Alagawadi 1996), groundnut (Hebbara & Suseeladevi 1990) and sunflower (Rachewad *et al*. 1992). No reports are available on the effect of inoculation of PSB with rock phosphate in a rice–wheat cropping system and hence the present study was undertaken.

MATERIALS AND METHODS

The field experiments were conducted during the 3 crop years (July–June) of 1996–97, 1997–98 and 1998–99 at New Delhi. The soil was a sandy clay loam in texture with pH of 8·2 (1:2·5 soil to water) and it contained 6·7 g/kg organic C (Walkley & Black 1934), 0·65 g/kg total Kjeldahl N (Jackson 1958), 7 mg/kg available P (Olsen *et al*. 1954) and 146 mg/kg available K (Jackson 1958).

The experiments were laid out in a split plot design with three replications. The four main plot treatments (17·5 m × 3 m) consisted of crop residue management as follows: (i) no residue, (ii) wheat residue incorporation before rice transplanting, (iii) rice residue incorporation before wheat sowing and (iv) wheat residue before rice transplanting and rice residue before wheat sowing. A general wheat crop was grown in the experimental field before the start of this experiment. After harvesting the wheat, the experimental field was divided into three blocks for replications, and each replication block was further divided into four main plots. In the rice crop, the residue of the preceding wheat was brought in for treatments (ii) and (iv) and incorporated with a mould-board plough before the rice was transplanted. Similarly, before sowing wheat, rice residue was incorporated in treatments (iii) and (iv). Thus treatment (i) was the control, treatment (ii) shows the direct effect of wheat residue on rice and residual effect of wheat residue on the next wheat crop, treatment (iii) shows the direct effect of rice residue on wheat and residual effect of rice residue on the next rice crop and treatment (iv) shows the combined effect of residues of both wheat and rice on both the crops. These treatments were repeated in the same plots for 3 years of study. The subplot treatments (4 m × 3 m) were: (i) no phosphorus, (ii) 26 kg P/ha as diammonium phosphate (DAP), (iii) 26 kg P/ha as Mussoorie rock phosphate (MRP) and (iv) 26 kg P/ha MRP + phosphate solubilizing bacteria (PSB). These treatments were applied to both rice and wheat crops grown in sequence for 3 years. The net subplot size was 3·5 m × 2·6 m for rice and 3·5 m × 2·53 m for wheat.

Crop residue

Partly cropped residues of rice and wheat at 6 tonnes/ha (dry weight basis) were spread uniformly on the soil surface as per treatment and incorporated with the help of a disc plough before puddling in the case of rice and before preparatory tillage in the case of wheat.

Phosphorus fertilizers

Commercial grade granulated diammonium phosphate (180 g N and 200 g P/kg fertilizer) and finely ground (to pass 2 mm diameter pore size sieve) Mussoorie rock phosphate (MRP) (80 g P/kg fertilizer) were used. Of the total P in MRP, 0·12 was soluble in neutral ammonium citrate.

Phosphorus solubilizing bacteria (PSB)

The culture of a promising PSB *Pseudomonas striata* was obtained from the Microbiology Division, Indian Agricultural Research Institute, New Delhi. Inoculation in rice was done by dipping the roots of rice seedlings in PSB culture slurry and inoculation in wheat was done by dipping the seeds in culture slurry. The seeds were then dried in shade and sown. Rock phosphate was applied separately.

Field techniques

The field experiment was started with a rice crop (July–October) and was followed by wheat (November–April). The same rotation was practised for the next 2 years of experimentation. The field was flooded and puddling was carried out using a tractor-drawn disc harrow after wheat residue incorporation. Just before final puddling each year, P as per treatment, 33 kg K/ha as muriate of potash and 4·5 kg Zn/ha as Zinc sulphate heptahydrate were applied to each plot. Nitrogen as urea at 120 kg N/ha was applied in two splits, half 10 days after transplanting and the rest at panicle initiation. Rice cultivar Pusa 169 of 140 day duration (developed at the Indian Agricultural Research Institute, New Delhi) was transplanted in the first week of July employing two to three 21–25-day old seedlings/hill at a spacing of 20 cm × 10 cm. Rice was harvested in the last week of October.

The field was irrigated after the harvest of the rice crop and when the soil reached an appropriate condition, the rice residue was incorporated as per treatment with a disc plough followed by double discing and planking. Before final discing 60 kg N/ha as urea, P as per treatment and 33 kg K/ha as muriate of potash were applied to each plot. A second dose of 60 kg N/ha as urea was given 30 days after sowing. Wheat cultivar HD 2329 (developed at the Indian Agricultural Research Institute, New Delhi) was sown in the third week of November and harvested in the second week of April.

Sampling and analysis

Prior to the start of the field experiment a composite soil sample was drawn from 0–25 cm soil layer and analysed for organic C (Walkley & Black 1934), total Kjeldahl N (Jackson 1958), available P (Olsen *et al.* 1954) and available K (Jackson 1958). At rice and wheat maturity, grain and straw samples were analysed for total P after digesting the dried and finely ground samples in nitric-sulphuric-perchloric tri-acid mixture (Prasad 1998). The P uptake was calculated by multiplying P concentration in grain and straw with their respective dry weights. At the harvest of each crop soil samples were drawn from 0–25 cm layer and analysed for available P.

Statistical analysis

Data of each character were statistically analysed using the standard procedure of variance analysis (Gomez & Gomez 1984).

RESULTS

Grain yield

The effects of residue incorporation on individual crops of rice and wheat were not significant but the combined grain yield of the rice–wheat cropping system was significantly increased when residue of both rice and wheat was incorporated in 1996–97 (Table 1). However in 1997–98 and 1998–99, in addition to the incorporation of both rice and wheat residues, incorporation of wheat or rice residues also resulted in a significant increase in total grain yield of the rice–wheat system.

Application of MRP did not increase the grain yield of rice or wheat (Table 1). However, MRP when inoculated with PSB increased the grain yield of both rice and wheat; the increase was significant and was similar to DAP. This was also true for the combined yield of rice and wheat.

The interaction between crop residue and P fertilizer was significant during the first 2 years (Table 1). In the case of rice the effect of MRP + PSB was significant only when the residue of preceding wheat was incorporated before transplanting of rice. Without wheat residue, MRP + PSB increased grain yield by 0·4–0·6 t/ha, whereas with wheat residue, MRP + PSB increased grain yield by 0·8–1·0 t/ha, which was significant and similar to that obtained with DAP.

In the case of wheat the interaction between crop residue and phosphorus was significant during 1996–97 and 1997–98. When no residue or residue of either rice or wheat was incorporated, MRP increased grain yield by 0·0–1·0 t/ha, whereas when residue of both rice and wheat was incorporated, MRP increased grain yield by 1·2–1·4 t/ha, which was significant over no P control. Similarly the efficiency of MRP + PSB was also increased by incorporation of crop residue. Without residue incorporation MRP + PSB increased grain yield over no P control by 0·5–0·9 t/ha, whereas when residue of preceding rice was incorporated before wheat sowing, MRP + PSB increased grain yield by 1·2–1·5 t/ha.

Straw yield

Straw yield of both rice and wheat was not significantly influenced by incorporation of crop residue during all the 3 years of study (Table 2). Application of MRP also had no significant effect on straw yield of both rice and wheat, while MRP + PSB increased straw yield of rice as well as wheat significantly and the increase was similar to that with DAP.

The interaction between crop residue and phosphorus was significant only in the second year in the case of wheat and in all the 3 years in the case of rice + wheat. When no residue or residue of either wheat or rice was incorporated, MRP and MRP + PSB failed to increase straw yield over no P control. On the other hand, when residue of both wheat and rice was incorporated, MRP + PSB increased straw yield significantly over no P control.

Phosphorus uptake

Rice

Incorporation of crop residues had no significant effect on P uptake by rice, while application of P increased it significantly in all 3 years of the study (Table 3). P uptake with MRP was significantly less than that with DAP, while MRP + PSB was as effective as DAP. The interaction 'crop residue × source of P' was significant in the last 2 years of the study. MRP was not able to supply adequate P to rice even in the presence of crop residue, whereas MRP + PSB significantly increased P uptake of rice over no P control and was on a par with DAP when residue of both wheat and rice was incorporated. Without residue incorporation MRP + PSB also failed to increase P uptake of rice. Thus, residue incorporation increased efficiency of MRP + PSB.

Table 1. *Grain yield (t/ha) of rice–wheat cropping system as influenced by crop residue incorporation and phosphate fertilization*

	1996–97					1997–98					1998–99				
Crop residue	Control	DAP	MRP	MRP+ PSB	Mean	Control	DAP	MRP	MRP+ PSB	Mean	Control	DAP	MRP	MRP+ PSB	Mean
Rice															
No residue	3·8	4·5	4·0	4·4	4·2	3·4	4·1	3·4	3·8	3·7	3·6	4·0	3·7	3·9	3·8
Wheat residue	4·0	4·4	4·3	4·8	4·4	3·4	4·5	4·1	4·4	4·1	3·9	4·4	4·0	4·3	4·2
Rice residue	4·2	4·7	4·4	4·7	4·5	3·8	4·4	4·0	4·3	4·1	3·9	4·3	4·2	4·5	4·2
Wheat+rice residue	4·3	4·7	4·7	5·1	4·7	3·3	4·6	4·1	4·6	4·1	3·6	4·2	3·8	4·2	3·9
Mean	4·1	4·6	4·4	4·8	–	3·5	4·4	3·9	4·3	–	3·8	4·2	3·9	4·2	–
S.E.															
Residue (R) (D.F.=6)			0·19					0·27					0·17		
Fertilizer (F) (D.F.=24)			0·09					0·14					0·12		
R × F (D.F.=24)			0·25					0·41					0·34		
Wheat															
No residue	3·8	4·3	4·1	4·3	4·1	3·2	4·2	3·6	4·1	3·8	3·6	4·1	3·8	4·0	3·9
Wheat residue	4·1	4·8	4·1	4·7	4·4	3·9	4·6	3·8	4·8	4·3	4·0	4·4	4·1	4·4	4·2
Rice residue	3·3	4·7	4·3	4·8	4·3	3·6	4·9	4·1	4·8	4·4	4·0	4·5	4·1	4·4	4·3
Wheat+rice residue	3·4	4·5	4·8	5·1	4·4	3·7	4·5	4·9	4·9	4·5	4·1	4·3	4·0	4·2	4·2
Mean	3·6	4·6	4·3	4·7	–	3·6	4·5	4·1	4·6	4·3	3·9	4·3	4·0	4·3	4·2
S.E.															
Residue (R) (D.F.=6)			0·29					0·30					0·11		
Fertilizer (F) (D.F.=24)			0·19					0·15					0·07		
R × F (D.F.=24)			0·53					1·43					0·25		
Rice+wheat															
No residue	7·6	8·8	8·1	8·7	8·3	6·6	8·3	7·0	7·9	7·5	7·2	8·1	7·5	7·9	7·7
Wheat residue	8·1	9·2	8·4	9·5	8·8	7·3	9·1	7·9	9·2	8·4	7·9	8·8	8·1	8·7	8·4
Rice residue	7·5	9·4	8·7	9·5	8·8	7·4	9·3	8·1	9·1	8·5	7·9	8·8	8·3	8·9	8·5
Wheat+rice residue	7·7	9·2	9·5	10·2	9·1	7·0	9·1	9·0	9·5	8·6	7·7	8·5	8·2	8·4	8·2
Mean	7·7	9·2	8·7	9·5	–	7·1	8·9	8·0	8·9	–	7·7	8·5	8·0	8·5	–
S.E.															
Residue (R) (D.F.=6)			0·21					0·29					0·16		
Fertilizer (F) (D.F.=24)			0·18					0·22					0·15		
R × F (D.F.=24)			0·53					0·60					0·43		

Table 2. *Straw yield (t/ha) of rice–wheat cropping system as influenced by crop residue incorporation and phosphate fertilization*

	1996–97					1997–98					1998–99				
Crop residue	Control	DAP	MRP	MRP+PSB	Mean	Control	DAP	MRP	MRP+PSB	Mean	Control	DAP	MRP	MRP+PSB	Mean
Rice															
No residue	5·9	7·4	6·5	6·7	6·6	5·1	6·1	5·6	6·2	5·8	6·9	7·6	6·9	7·2	7·1
Wheat residue	6·8	7·3	7·0	7·4	7·1	6·1	6·4	6·4	6·6	6·4	6·9	7·6	7·4	7·5	7·4
Rice residue	6·8	7·8	6·8	7·7	7·3	5·6	6·4	6·0	6·2	6·1	7·0	8·1	7·5	7·4	7·5
Wheat+rice residue	6·7	7·7	6·9	8·2	7·4	5·7	6·7	6·2	6·6	6·3	7·3	8·4	7·8	8·1	7·6
Mean	6·6	7·6	6·8	7·5	–	5·6	6·4	6·0	6·4	–	7·0	7·9	7·4	7·6	7·5
S.E.															
Residue (R) (D.F.=6)			0·53					0·29					0·18		
Fertilizer (F) (D.F.=24)			0·19					0·15					0·16		
R×F (D.F.=24)			0·54					0·43					0·46		
Wheat															
No residue	5·5	6·8	5·7	6·2	6·0	6·3	7·3	6·2	6·7	6·6	4·4	4·8	4·4	4·5	4·5
Wheat residue	6·2	7·5	6·8	6·9	6·9	6·5	7·4	6·6	7·3	6·9	5·2	5·6	5·1	5·4	5·3
Rice residue	5·7	7·6	6·2	6·7	6·6	6·6	7·3	6·8	7·1	6·9	4·8	5·2	4·9	5·1	5·0
Wheat+rice residue	5·9	7·5	7·0	7·4	6·9	6·2	7·5	6·8	8·5	7·3	4·6	5·2	5·2	5·4	5·1
Mean	5·8	7·3	6·4	6·8	–	6·4	7·4	6·6	7·4	–	4·7	5·2	4·7	5·1	4·9
S.E.															
Residue (R) (D.F.=6)			0·22					0·38					0·18		
Fertilizer (F) (D.F.=24)			0·12					0·22					0·15		
R×F (D.F.=24)			0·33					0·62					0·44		
Rice+wheat															
No residue	11·4	14·2	12·3	12·9	12·7	11·4	13·4	11·8	12·9	12·4	11·3	12·4	11·3	11·7	11·6
Wheat residue	13·0	14·8	13·8	14·3	14·0	12·6	13·8	13·0	13·.9	13·3	12·1	13·2	12·5	12·9	12·7
Rice residue	12·5	15·5	13·0	14·4	13·9	12·2	13·7	12·8	13·3	13·0	12·4	13·3	12·4	12·5	12·7
Wheat+rice residue	12·6	15·2	13·9	15·6	14·3	11·9	14·2	13·0	15·1	13·6	11·9	13·6	13·0	13·5	13·0
Mean	12·4	14·9	13·2	14·3	–	12·0	13·8	12·6	13·8	–	11·9	13·1	12·1	12·7	–
S.E.															
Residue (R) (D.F.=6)			0·37					0·29					0·30		
Fertilizer (F) (D.F.=24)			0·18					0·21					0·19		
R×F (D.F.=24)			0·52					0·59					0·54		

Table 3. *Phosphorus uptake (kg/ha) of rice–wheat cropping system as influenced by crop residue incorporation and phosphate fertilization*

	1996–97					1997–98					1998–99				
Crop residue	Control	DAP	MRP	MRP+ PSB	Mean	Control	DAP	MRP	MRP+ PSB	Mean	Control	DAP	MRP	MRP+ PSB	Mean
Rice															
No residue	9·4	12·1	10·6	12·0	11·0	8·0	10·1	8·5	10·4	9·3	9·2	11·2	9·9	10·4	10·2
Wheat residue	9·9	12·1	11·3	12·7	11·5	9·1	11·9	11·4	12·2	11·2	10·5	12·3	11·2	12·2	11·6
Rice residue	10·3	12·9	11·6	12·5	11·8	9·5	11·5	10·5	11·7	10·8	10·3	12·1	11·4	12·3	11·5
Wheat + rice residue	10·8	12·4	12·3	13·6	12·3	9·0	12·1	11·0	12·2	11·1	9·7	12·0	10·7	12·2	11·2
Mean	10·1	12·4	11·4	12·7	–	8·9	11·4	10·3	11·6	–	9·9	11·9	10·8	11·8	–
S.E.															
Residue (R) (D.F. = 6)			0·60					0·64					0·53		
Fertilizer (F) (D.F. = 24)			0·26					0·35					0·28		
R × F (D.F. = 24)			0·75					0·99					0·80		
Wheat															
No residue	11·7	13·8	13·4	14·6	13·4	11·0	15·1	12·6	14·4	13·3	12·0	14·5	12·7	13·6	13·2
Wheat residue	12·4	15·9	13·9	15·8	14·5	13·4	14·6	13·4	16·5	14·5	13·6	15·8	14·1	15·7	14·8
Rice residue	11·0	15·9	14·7	16·5	14·6	12·6	17·4	14·5	17·0	15·4	13·7	15·7	14·3	15·1	14·7
Wheat + rice residue	11·4	15·5	16·3	17·3	15·2	12·9	16·7	17·0	17·7	16·0	13·4	15·7	14·2	14·7	14·6
Mean	11·7	15·3	14·6	16·1	–	12·5	16·0	14·4	16·4	–	13·2	15·3	13·9	14·8	–
S.E.															
Residue (R) (D.F. = 6)			0·89					1·02					0·45		
Fertilizer (F) (D.F. = 24)			0·58					0·51					0·31		
R × F (D.F. = 24)			1·64					1·44					0·89		
Rice + wheat															
No residue	21·1	25·9	24·0	26·6	24·4	19·0	25·2	21·1	24·8	22·6	21·2	25·7	22·6	24·0	23·4
Wheat residue	22·3	28·0	25·2	28·5	26·0	22·5	26·5	24·8	28·7	25·7	24·1	28·1	25·3	25·9	26·4
Rice residue	21·3	28·8	26·3	29·0	26·4	22·1	28·9	25·0	28·7	26·2	24·0	27·8	25·7	27·4	26·2
Wheat + rice residue	21·8	27·9	28·6	30·9	27·5	21·9	28·8	28·0	29·9	27·1	23·1	27·7	24·9	26·9	25·8
Mean	21·8	27·7	26·0	28·8	26·2	21·4	27·4	24·7	28·0	25·4	23·1	27·2	24·7	26·6	25·5
S.E.															
Residue (R) (D.F. = 6)			0·94					0·96					0·68		
Fertilizer (F) (D.F. = 24)			0·54					0·50					0·39		
R × F (D.F. = 24)			1·53					1·43					1·11		

Table 4. *Balance sheet (kg/ha) of phosphorus after 3 years of rice–wheat cropping system*

Treatment	Added: Residue	Added: Fertilizer	Removed	Balance	Depletion or addition/year
No residue					
Control	0	0	61·0	−61·0	−20·3
DAP	0	156	76·8	+79·2	+26·4
MRP	0	156	67·7	+88·3	+29·4
MRP+PSB	0	156	75·4	+80·6	+26·9
Wheat residue					
Control	5·6	0	68·9	−63·3	−21·1
DAP	6·4	156	82·6	+79·8	+26·6
MRP	5·7	156	75·3	+86·4	+28·8
MRP+PSB	6·1	156	85·1	+77·0	+25·6
Rice residue					
Control	6·1	0	67·4	−61·3	−20·4
DAP	6·9	156	85·5	+77·4	+25·8
MRP	6·5	156	77·0	+85·5	+28·5
MRP+PSB	6·9	156	85·1	+77·8	+25·9
Rice+wheat					
Control	11·2	0	67·2	−56·0	−18·7
DAP	13·5	156	84·4	+85·1	+28·4
MRP	13·0	156	81·5	+87·5	+29·2
MRP+PSB	14·2	156	87·7	+82·5	+27·5

Wheat

The benefit of application of crop residues was seen from the second year onward. In the second year incorporation of residue of both rice and wheat resulted in significantly more P uptake than no residue incorporation, whereas in the third year incorporation of rice or wheat residue also increased P uptake over no residue incorporation. P fertilization also increased P uptake by wheat. DAP and MRP+PSB were equally effective and increased P uptake of wheat significantly over no P control in all 3 years of the study, whereas MRP increased P uptake of wheat only in the first and second years.

The crop residue × P sources interaction was significant in the first 2 years of the study. Application of wheat residue (to preceding rice) had no significant effect on the efficiency of different sources of P, whereas application of rice residue (before wheat sowing) significantly increased the efficiency of MRP+PSB and resulted in significantly more P uptake than no P control in the first and second year of the study. Application of both rice and wheat residues to the rice–wheat cropping system led to a significant increase in the efficiency of both MRP and MRP+PSB in the first and the second year of the study.

Balance sheet of phosphorus

There was a negative balance of phosphorus ranging from 18·7 to 21·1 kg P/ha per year when fertilizer P was not applied, whereas application of P either through DAP or MRP resulted in a positive balance of P ranging from 25·6–29·4 kg P/ha per year (Table 4).

Available P content of soil

During the first year, incorporation of residue of either wheat, rice or both did not significantly affect the available P content of soil (Table 5). During the second year, the available P content of the soil increased significantly when residue of both wheat and rice was incorporated over no residue incorporation, whereas during the third year the available P content of the soil increased significantly when residue of either wheat or rice was incorporated. Available P content was further increased when residue of both wheat and rice was incorporated.

Effects of P application on the available P content of the soil were seen in the second and third years of the study. Available P in the soil was highest with MRP+PSB, significantly more than MRP in both the second and third years of the study. MRP, in turn, had significantly more available P than DAP.

The interaction between crop residues and P fertilizer was significant in the second and third years of the study and showed that application of DAP significantly increased the available P content of soil over no P control when no residue was incorporated, whereas it did not increase available P content of soil when residue of either rice, or wheat or both crops was incorporated. Available P in soil was highest when residues of both rice and wheat were incorporated along with MRP+PSB.

Table 5. *Available (0·5 M $NaHCO_3$ extractable) P in soil after wheat harvest as influenced by crop residue incorporation and phosphate fertilization*

Crop residue	1996–97					1997–98					1998–99				
	Control	DAP	MRP	MRP+PSB	Mean	Control	DAP	MRP	MRP+PSB	Mean	Control	DAP	MRP	MRP+PSB	Mean
No residue	15·0	20·0	17·0	18·0	17·0	12·9	18·8	20·0	26·8	21·1	6·0	13·2	22·9	26·8	17·1
Wheat residue	15·5	20·5	18·5	21·5	19·0	20·1	25·0	23·1	31·4	24·9	23·7	25·3	26·6	32·8	27·1
Rice residue	16·5	20·5	18·5	20·0	18·9	18·6	22·0	29·8	31·4	25·4	20·9	24·0	33·8	34·8	28·4
Wheat+rice residue	14·0	19·0	16·0	18·0	17·0	28·5	29·6	36·0	38·7	33·2	30·0	30·0	47·7	47·5	38·8
Mean	15·3	20·0	17·5	19·4	18·0	20·1	23·9	27·3	32·1	26·2	20·2	23·2	32·8	35·5	41·4
S.E.															
Residue (R) (D.F. = 6)			0·03					1·58					1·25		
Fertilizer (F) (D.F. = 24)			0·02					0·72					0·69		
R × F (D.F. = 24)			0·06					2·04					1·95		

DISCUSSION

Much of the crop residue, especially that for rice in the rice–wheat cropping system, is burned due to the short carry-over period (2–3 weeks) between rice harvest and wheat sowing. In addition to the loss of plant nutrients, crop residue burning creates health and environmental problems (Staniforth 1979). *In situ* incorporation of rice and wheat residues is, therefore, considered desirable. However, the farmers are reluctant to adopt this practice because of the additional farm resources required for the incorporation of crop residues; also some harmful effects have been observed during the early growing period of the crop due to temporary immobilization of soil and applied fertilizer nitrogen (Prasad *et al.* 2001) and this may affect the grain yield (Sharma & Prasad 2001). In the present study, incorporation of rice and/or wheat residues had no adverse effect on the grain and straw yield of the rice or wheat crop. On the contrary, grain and straw yield of the rice–wheat cropping system was significantly increased by residue incorporation. Prasad *et al.* (1999) also observed that rice and wheat residues can be safely incorporated in soil without any detrimental effects on the rice or wheat crop grown immediately after incorporation. Leaving crop residues on the surface as in no tillage practices increases soil organic matter, total N, P, K, Fe, Mn, Zn and Cu; it improves soil physical properties such as soil aggregates, bulk density and hydraulic conductivity and also considerably increases soil microbial activity as reviewed by Prasad & Power (1991). Incorporation of crop residues will have similar advantages. Increased soil organic C due to incorporation of rice–wheat residues has been reported by Prasad & Mishra (2001) and Sharma & Prasad (2001). Prasad *et al.* (1999) reported increased organic C, available P and available K due to residue incorporation. Improvement in bulk density, hydraulic conductivity and mean aggregates diameter has been reported by Tripathi (1992). Incorporation of crop residue also results in increased microbial activity as judged by increased microbial count and biomass, CO_2 evolution and dehydrogenase activity in soil (IARI 1996). These improvements in physical, chemical and biological properties of soils lead to increased grain and straw yield of rice.

Rock phosphate is not an efficient source of phosphorus for field crops grown on neutral and alkaline soils (Govil & Prasad 1972, 1974; Prasad & Dixit 1976). In the present study MRP did not significantly increase grain or straw yield of rice or wheat, although phosphorus uptake by these crops was significantly increased over no P control, indicating some release of P from MRP during the crop growth period. However, when MRP was applied along with PSB it was as efficient as diammonium phosphate (DAP) in respect of grain and straw yield as well as P uptake by rice and wheat. The efficiency of MRP+PSB was further increased when rice and/or wheat residue was incorporated. Among the phosphate solubilizing organisms *Pseudomonas striata* (the culture used in the present study) has been reported as the most efficient solubilizer of the insoluble mineral phosphates (Tiwari *et al*. 1993). The mechanisms responsible for P solubilization by PSB include the presence of organic acids (Sperber 1958; Katznelson & Bose 1959), glucose (Goldstein & Liu 1987), H^+ excretion originating from NH_4^+ assimilation (Parks *et al*. 1990) and respiratory H_2CO_3 production (Jurinak *et al*. 1986). Incorporation of crop residues will accelerate all these processes due to the release of organic acids, glucose and CO_2 on its decomposition. This explains our finding of increased efficiency of MRP+PSB in the presence of crop residues. Paul Raj & Velayudham (1996) also reported that in rice the efficiency of MRP was increased when farmyard manure (FYM) was applied along with MRP+PSB. Increased P uptake by rice and wheat and rice–wheat cropping systems due to application of P as DAP or MRP or MRP+PSB is in accord with the findings of Gangaiah & Prasad (1999) and Aipe & Prasad (2001). There was a negative P balance when P was not applied. These results are in accord with those of Dobermann *et al*. (1996) who, on the basis of results from a large number of long-term experiments on rice, reported a negative balance of 4·4–17·1 kg P/ha in plots receiving adequate NK but no P. Since the rice–wheat cropping system in the present study received 52 kg P/ha/y as MRP or DAP and only 24·0–29·9 kg P/ha/y was removed by both the crops, a positive P balance was obtained as expected.

The effects of treatments on available P in soil were observed in the second and third years of study. Thus it takes some time before a build-up in soil P takes place. Incorporation of rice or wheat residue resulted in a significant increase in available P over control and incorporation of residues of both rice and wheat gave significantly more available P in soil than the incorporation of a single crop residue. These results are expected since residue for each crop of rice or wheat recycled about 6–7 kg P/ha. A number of studies in the USA involving no tillage practices when crop residues are left *in situ* have shown accumulation of P in surface soil (Hargrove 1985; Follett & Peterson 1988; Weil *et al*. 1988). Plots receiving MRP+PSB had more available P in soil than MRP in the seond and third years of the present study, however, the difference between these two sources was not significant when both rice and wheat crop residues were incorporated. Thus the presence of decaying organic residues had a pronounced effect on the release of P from MRP in the presence or absence of PSB as judged by residual available P in soil. Rokima & Prasad (1991) reported that application of farmyard manure enhanced the build up of all forms of inorganic P, especially Ca-P. This will result in higher values for Olsen available P, since 0·5 M $NaHCO_3$ is a good extracter for Ca-P (Prasad 1998) and this is why it is the recommended soil P test for calcareous, neutral and alkaline soil (Prasad & Power 1997). Available P in soil was the least with DAP, indicating rapid fixation of applied water soluble P and relatively less availability of this fixed P as compared with P in MRP. Again, application of crop residues along with DAP also maintained higher available P in soil.

The present study thus clearly brings out that low grade rock phosphates such as MRP can be advantageously utilized in rice–wheat cropping when applied with PSB inoculation and incorporation of rice and wheat residues; this practice gives good yields as obtained with DAP but enriches the soil more with available P.

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