RELATIVE EFFICIENCY OF DIAMMONIUM PHOSPHATE AND MUSSOORIE ROCK PHOSPHATE PLUS PHOSPHATE SOLUBILIZING BACTERIA ON PRODUCTIVITY AND PHOSPHORUS BALANCE IN RICE-POTATO-MUNGBEAN CROPPING SYSTEM

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□ *Field experiments were conducted at the Indian Agricultural Research Institute, New Delhi, India for three years from 2001–2002 to 2003–2004 to study the relative efficiency of diammonium phosphate (DAP) and mussoorie rock phosphate (MRP) in a rice-potato-mungbean cropping system. Phosphorus application significantly increased productivity, protein yield and energy output of rice-potato-mungbean cropping system and resulted in an increase in 0.5 M sodium bicarbonate ($NaHCO_3$) extractable phosphorus (P) content in soil. The MRP at 35 kg P ha^{-1} was at par with 17.5 kg P ha^{-1} as DAP in terms of productivity, protein yield, and energy output but significantly superior in terms of PSB population in soil. Phosphorus balance (application – crop removal) was generally more positive for MRP than DAP and the highest with an application of 52.5 kg P ha^{-1} as MRP. Present study indicates that P requirement of a rice-potato-mungbean cropping system can be met with 76–79% higher dose of MRP as compared to DAP.*

Keywords: available P, CO_2 evolution, diammonium phosphate, energy output, mussoorie rock phosphate, PSB, productivity, protein yield

INTRODUCTION

The rice (*Oryza sativa*)—wheat (*Triticum aestivum*) cropping systems (RWCS) occupy about 28.8 million hectares (m ha) in Asia's five countries, namely, India, Pakistan, Nepal, Bangladesh and China (Prasad, 2005). These countries are just five of the more than 200 countries of the world, but they represent 43% of the world population on 20% of the world's arable land (Singh and Paroda, 1994). Taking these five countries together, RWCS cover 28% of the total rice area and 35% of the total wheat area. In India RWCS occupy 12 m ha and contributes about 31% of the total food grain

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production (Kumar et al., 1998). Similarly, in China RWCS occupy about 13 m ha (Jiaguo, 2000) and contribute about 25% of the total cereal production in the country (Lianzheng and Yixian, 1994). Thus, RWCS are of considerable significance in meeting Asia's food requirements. However, the practice of following a cereal-cereal cropping system on the same piece of land over years has led to soil fertility deterioration and questions are being raised on its sustainability (Duxbury et al., 2000; Ladha et al., 2000; Prasad, 2005). Efforts were therefore made to find alternative cropping systems, especially those involving legumes, which have soil recuperative properties (Singh and Dwivedi, 2006). Rice-potato-mungbean was found to be the most remunerative and soil recuperative cropping system for north-western India (Sharma and Sharma, 2004).

Phosphorus (P) is a limiting plant nutrient in Indian agriculture and 60% soils are low to medium in available P (Motsara, 2002). Additions of inorganic P as water-soluble phosphate fertilizers undergo complex exchanges between various soil P pools (Stevenson, 1986). This is especially true in the tropics where many soils have extremely high P fixation capacity (Sanchez and Uehara, 1980). Consequently, large amounts of fertilizer P are needed to attain reasonable crop yields. In India the price of fertilizer P is the highest; the cost of 1 kg P_2O_5 varies from US $ 0.34 through DAP to US $ 0.38–0.57 through single super phosphate as against US $ 0.22 for 1 kg N through urea and US $ 0.16 for 1 kg K_2O through muriate of potash. Because of high cost, small and marginal farmers in India generally skip P fertilization. The nitrogen (N):P consumption ratio in India is 2.6:1 (FAI, 2006) as against the desirable ratio of 2:1 for sustainable crop production (Tiwari, 2002). The high cost of phosphorus in India is because bulk of the phosphate rock for making phosphate fertilizers is imported. However, there are substantial deposits of low-grade rock phosphate in India, which can partly meet the crop demands for P. One such deposit is mussoorie rock phosphate (MRP). Attempts have been made in the past to use finely ground MRP directly in soil of pH 7 and above with the help of phosphate solubilizing micro-organisms (PSB/PSM), which have the capability to convert plant unavailable P apatites to plant available phosphate forms (Cosgrove, 1977; Illmer and Schinner, 1992; Sharma et al., 1983; Sharma and Prasad 1996, 2003).

The present investigation was undertaken to study the relative efficiency of diammonium phosphate (DAP) and MRP + PSB on production and P balance in a rice-potato-mungbean cropping system. This information is currently not available in the literature.

MATERIALS AND METHODS

Site and Soil

The field experiments were conducted during the three crop years (June–July) from 2001–2002 to 2003–2004 at the Indian Agricultural

Research Institute, New Delhi, India (28° 38′ N latitude, 77° 11′ E longitude and 228.6 m above mean sea level). The soil of the experimental field was sandy clay loam, having 52.5% sand, 21.0% silt, and 26.5% clay. It contained 12.0 Mg ha^{-1} organic carbon (C), 1.3 Mg ha^{-1} Kjeldahl N, 16.0 kg ha^{-1} 0.5 M sodium bicarbonate ($NaHCO_3$) extractable P, and 500 kg ha^{-1} 1 N ammonium acetate (NH_4OAC) extractable K, and had a pH of 8.3 at the start of experiment.

Experimental Design and Treatments

The experiments were laid out in a randomized block design with four replications. The treatments consisted of control, 17.5 kg P ha^{-1} as DAP, 17.5 kg P ha^{-1} as MRP, 35.0 kg P ha^{-1} as DAP, 35 kg P ha^{-1} as MRP, and 52.5 kg P ha^{-1} as MRP. These treatments were applied to each crop of the system each year. The treatments were continued throughout the study (three years) in the same plots. The plot size was 7.5 m × 7 m.

Phosphorus Fertilizers

Commercial grade granulated diammonium phosphate (DAP) containing 18% N and 20% P and mussoorie rock phosphate (MRP) containing 8.3% P were used. Of the total P in MRP 12% was soluble in neutral ammonium citrate. The MRP plots were inoculated with phosphates solubilizing bacteria (PSB) *Pseudomonas striata*. For inoculation with PSB, a slurry was prepared by dissolving 200 g brown sugar in 250 ml water and then warming it for 15 minutes at 40°C. The slurry thus prepared was diluted 10 times with water and a packet of PSB culture, obtained from the Microbiology Division, Indian Agricultural Research Institute, New Delhi, India, was added to diluted slurry. Inoculation in rice crop was done by dipping the roots of the seedlings in PSB culture slurry, while inoculation in potato and mungbean was done by dipping the tubers/seeds in culture slurry. The tubers/seeds were then dried in shade for 24 hours and then sown.

Field Techniques

During summer, the plots were irrigated and tilled at optimum moisture level. Mungbean variety 'PS 16' was seeded at a uniform row spacing of 30 cm in the last week of March each year. The crop received a basal dose of 20 kg N ha^{-1} as urea and P as per treatment. No K was applied to this crop. The crop was harvested in the last week of June.

During the rainy season the field was flooded with water and puddled with a tractor-drawn off-set disc harrow. A basal dose of 33 kg K ha^{-1} as muriate of potash, 4.5 kg ha^{-1} zinc (Zn) as zinc sulfate heptahydrate and P as per treatments was applied at final puddling. Nitrogen at 120 kg N ha^{-1} as urea was applied in two splits, half dose at 10 days after transplanting (DAT) and the rest at 30 DAT. The rice variety 'Pusa Basmati 1' was transplanted in mid-July with two to three seedlings of 21–25 days of age hill^{-1} at a spacing of 20 cm × 10 cm. Rice was harvested in the first week of November each year of the experimentation.

During winter season the field was irrigated after the rice harvest and when the soil came to condition, the land was prepared by disking and planking. Potato variety 'Kufri Badshah' was sown during the second week of November. The potato crop received 60 kg N ha^{-1} as urea, P as per treatment and 67 kg K ha^{-1} as muriate of potash at sowing and 60 kg N ha as urea at 40 days after sowing (DAS). The potato was harvested in the second week of March.

Soil Sampling and Chemical Analysis

At harvest grain/tuber and straw samples were drawn from each plot and analyzed for total P as per procedure described by Prasad et al. (2006). After completion of each one-year cycle of rice-potato-mungbean cropping system, soil samples (0–20 cm depth) for each plot were collected and analysed for 0.5 M $NaHCO_3$ extractable P. Further at the end of 3 cycles of the system the soil samples (0–20 cm) were also analyzed for the population of phosphorus solubilizing bacteria (PSB) and carbon dioxide (CO_2) evolution from soil as per procedure described by Subba Rao (1977).

Rice Equivalents, Protein Yield, and Energy Output

The productivity of a cropping system cannot be compared on the basis of grain/tuber yields *per se* because the crops differ in the value of their economic produce. Therefore rice equivalents of different crops were calculated using following expression:

$$\text{Rice equivalents (Mg ha}^{-1}) = \text{Yca} \times \text{Pca/Pcr}$$

where, Yca is the economic yield of a crop a (other than rice) in Mg ha^{-1}, Pca is the unit price of the economic produce of that crop a and Pcr is the unit price of rice grain.

Since the data on rice equivalents are subject to variation in commodity prices in India, protein yield ha^{-1} and energy output ha^{-1} were also computed for the human nutrition viewpoint. Protein content was determined by using a Infratec 1255 Food and Feed Analyzer (Foss Tecator AB, Höganäs, Sweden) and energy output was calculated as per procedure given by Singh et al. (1996).

RESULTS

Productivity

Phosphorus application increased rice yield in all the three years of study (Table 1). In the first and the second years a significant increase in rice yield was obtained with 35 kg P ha^{-1} as DAP or 52.5 kg P ha^{-1} as MRP. In the third year application of DAP at 17.5 kg P ha^{-1} also significantly increased the rice yield; there was no further significant increase in rice grain yield when the level of P was raised.

During winter season, potato responded to P application (Table 1). MRP and DAP were at par at 17.5 kg ha^{-1} and significantly increased potato yield over control in the first and the third year of study. Further, increase in the rate of P application from 17.5 to 35 kg ha^{-1} as DAP or to 35 or 52.5 kg P ha^{-1} as MRP also resulted in a significant additional increase in potato yield in the first and the third years. In the second year of the study a significant increase in potato yield was obtained only with DAP at 17.5 or 35 kg P ha^{-1}, the difference between two levels of DAP was not significant.

In the case of summer mungbean, DAP at 35 kg ha^{-1} was at par with MRP at 52.5 kg ha^{-1} and significantly increased mungbean yield over control in the first two years, whereas in the third year both DAP and MRP at 17.5 kg P ha^{-1} also increased seed yield of mungbean over control. Further, increase in rate of MRP from 17.5 to 52.5 kg P ha^{-1} also resulted in an additional increase in seed yield of mungbean.

As regards to total productivity DAP at 17.5 kg P ha^{-1} and MRP at 35 kg P ha^{-1} were at par and resulted in significantly more rice equivalents than control in all the three years of study. The value of rice equivalents was further increased when the rate of DAP and MRP was increased from 17.5 to 35 and from 35 to 52.5 kg P ha^{-1}, respectively.

The relationship between amount of P applied in a year to rice-potato-mungbean cropping system and mean productivity over the three years followed a linear pattern; the 'r' value being 0.999 for DAP and 0.998 for MRP (Figure 1). With the help of linear equation, $y = a + bx$, the P dose for targeted yield of 15, 16, 17, 18, 19 and 20 Mg ha^{-1} of rice-potato-mungbean cropping system was calculated separately for DAP and MRP and values are given in Table 2. Data indicate that required quantity of MRP for a targeted yield was 76–79% higher than that of DAP.

Protein Yield

Application of DAP at 17.5 kg P ha^{-1} increased protein yield of rice over control in the last two years of study, whereas MRP at 17.5 kg P ha^{-1} had no significant effect on protein yield of rice in any one of the three years of study (Table 1). MRP increased protein yield of rice significantly in all the

TABLE 1 Effects of rates and sources of phosphorus on productivity, protein yield and energy output of rice-potato-mungbean cropping system

Rates and sources of P	Productivity (Mg ha^{-1})				Protein yield (Mg ha^{-1})				Energy output (K cal ha^{-1} × 10^{-6})			
	Rice	Potato	Mungbean	Total rice equivalents	Rice	Potato	Mungbean	Total rice equivalents	Rice	Potato	Mungbean	Total rice equivalents
2001–2002												
Control	5.8	22.7	0.5	13.8	0.34	0.47	0.11	0.92	20.4	19.5	1.8	41.7
17.5 kg P ha^{-1} as DAP	6.1	26.4	0.7	15.7	0.36	0.56	0.16	1.08	21.4	22.7	2.5	46.6
17.5 kg P ha^{-1} as MRP	6.0	26.1	0.5	15.1	0.36	0.54	0.12	1.02	21.1	22.5	1.8	45.4
35.0 kg P ha^{-1} as DAP	6.5	28.6	0.7	16.7	0.39	0.60	0.16	1.15	22.8	24.6	2.3	49.9
35.0 kg P ha^{-1} as MRP	6.2	26.8	0.6	15.7	0.37	0.57	0.14	1.08	21.8	23.1	2.1	47.0
52.5 kg P ha^{-1} as MRP	6.7	28.6	0.8	16.8	0.40	0.60	0.19	1.19	23.5	24.6	2.8	50.9
LSD ($P = 0.05$)	0.55	0.93	0.20	0.7	0.03	0.03	0.02	0.04	1.90	1.80	NS	2.70
2002–2003												
Control	5.0	26.7	0.7	14.6	0.35	0.52	0.15	1.02	17.6	23.0	2.5	43.1
17.5 kg P ha^{-1} as DAP	5.4	28.0	0.9	15.9	0.38	0.56	0.20	1.14	19.0	24.1	3.2	46.3
17.5 kg P ha^{-1} as MRP	5.2	27.2	0.8	15.2	0.36	0.54	0.17	1.07	18.3	23.4	2.8	44.5
35.0 kg P ha^{-1} as DAP	5.6	28.8	1.1	16.7	0.40	0.57	0.24	1.21	19.6	24.8	3.9	48.3
35.0 kg P ha^{-1} as MRP	5.5	27.2	0.9	15.7	0.38	0.54	0.20	1.12	19.3	23.4	3.2	45.9
52.5 kg P ha^{-1} as MRP	5.7	27.5	1.1	16.4	0.40	0.55	0.23	1.18	20.0	23.7	3.9	47.6
LSD ($P = 0.05$)	0.58	1.20	0.30	0.60	0.03	0.02	0.03	0.05	2.00	1.50	1.10	2.80
2003–2004												
Control	5.4	22.6	0.6	13.6	0.35	0.49	0.14	0.98	19.0	19.4	2.1	40.5
17.5 kg P ha^{-1} as DAP	5.9	24.2	0.8	15.0	0.39	0.53	0.19	1.11	20.7	20.8	2.8	44.3
17.5 kg P ha^{-1} as MRP	5.6	23.8	0.8	14.5	0.37	0.51	0.18	1.06	19.7	20.5	2.8	43.0
35.0 kg P ha^{-1} as DAP	6.0	26.2	0.9	15.9	0.40	0.57	0.21	1.18	21.1	22.5	3.2	46.8
35.0 kg P ha^{-1} as MRP	5.9	25.6	0.9	15.6	0.39	0.55	0.21	1.15	20.7	22.0	3.2	45.9
52.5 kg P ha^{-1} as MRP	5.9	26.6	1.0	16.1	0.39	0.58	0.24	1.21	20.7	22.9	3.5	47.1
LSD ($P = 0.05$)	0.47	1.20	0.12	0.80	0.03	0.03	0.03	0.04	1.60	1.50	0.40	3.00

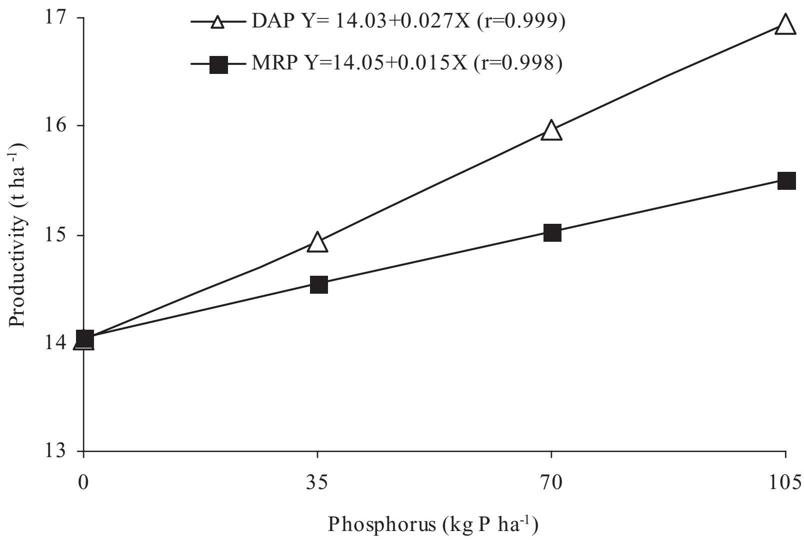

FIGURE 1 Relationship between P application in a year and mean productivity of 3 years under rice-potato-mungbean cropping system.

three years when it was applied at 35 kg P ha^{-1}. Further, increase in the rate of DAP from 17.5 to 35 kg P ha^{-1} and of MRP from 35 to 52.5 kg P ha^{-1} did not result in an additional increase in protein yield of rice except in the second year when 52.5 kg P ha^{-1} as MRP gave significantly higher protein yield than 17.5 kg P ha^{-1} as MRP.

During winter season, application of DAP and MRP at 17.5 kg P ha^{-1} gave similar but significantly more protein yield than control in the first year of study, whereas in the second year MRP at 17.5 and 35 kg P ha^{-1} had no significant effect on protein yield of potato. The MRP at 52.5 kg P ha^{-1} and DAP at 17.5 kg P ha^{-1} resulted in similar but significantly higher protein yield than control. In the third year MRP at 35 kg P ha^{-1} was similar to DAP at 17.5 kg P ha^{-1} and significantly increased protein yield of potato. The

TABLE 2 Quantity of P as DAP and MRP required for targeted yield of rice-potato-mungbean cropping system (based on mean yield over 3 years)

Targeted yield (Mg ha^{-1})	DAP	MRP
15	35.9	63.3 (176)*
16	73.0	130.0 (178)
17	110.0	196.7 (179)
18	147.0	263.3 (179)
19	184.1	330.0 (179)
20	221.1	396.7 (179)

*Values in parentheses are percentage of P required as DAP.

protein yield of potato further increased significantly when the rate of DAP was increased from 17.5 to 35 kg P ha^{-1} and of MRP from 35 to 52.5 kg P ha^{1}.

During summer MRP at 17.5 kg P ha^{-1} had no significant effect on protein yield of mungbean in the first two years, whereas DAP at 17.5 kg P ha^{-1} significantly increased protein yield of mungbean over control in all the three years of study (Table 1). The increase in the rate of DAP from 17.5 to 35 kg P ha^{-1} also increased protein yield of mungbean significantly in all three years of study. Protein yield of mungbean also increased significantly with increasing rate of MRP; however difference between 17.5 and 35 kg P ha^{-1} was not significant in the third year of study.

As regards to total protein yield of the system, application of 17.5 kg P ha^{-1} as MRP increased total protein yield of the system over control and 17.5 kg P ha^{-1} as DAP increased total protein yield over 17.5 kg P ha^{-1} as MRP in all the three years. At 35 kg P ha^{-1} DAP was significantly superior to MRP in the first and the second years of study. MRP at 52.5 kg P ha^{-1} was at par with 35 kg P ha^{1} as DAP in all the three years.

Energy Output

Phosphorus application significantly enhanced energy output of rice in all the three years of study (Table 1). During the first two years energy output of rice increased significantly when the rate of P application was increased from 0 to 35 kg P ha^{-1} as DAP and 0 to 52.5 kg P ha^{-1} as MRP, whereas during the third year DAP at 17.5 kg P ha^{-1} and MRP at 35 kg P ha^{-1} also significantly increased energy output of rice over control. Further, an increase in P application either through DAP or MRP gave no additional advantage in energy output of the rice.

During winter season DAP and MRP, at 17.5 kg P ha^{-1} being at par, significantly increased energy output over the control only in the first year of study. Furthermore, increase in the rate of DAP from 17.5 to 35 kg P ha^{-1} and of MRP from 17.5 to 52.5 kg P ha^{-1} also resulted in an additional increase in energy output in this year. In the second year MRP even at 52.5 kg P ha^{-1} had no significant effect on energy output of potato, whereas DAP at 35 kg P ha^{-1} significantly increased energy output of potato over control. In the third year, energy output of potato increased significantly when rate of DAP and MRP was increased from 0 to 35 kg P ha^{-1}. Further, increase in rate of MRP from 35 to 52.5 kg P ha^{-1} did not increase energy output.

During summer P application significantly increased energy output of mungbean in last two years of study. In the second year energy output increased significantly when rate of P application was raised from 0 to 35 kg P ha^{-1} as DAP and from 0 to 52.5 kg P ha^{-1} as MRP, whereas in the third year energy output of mungbean increased significantly with increasing rate of both DAP and MRP up to 35 kg P ha^{-1}, sources being at par.

Regarding total energy output of rice-potato-mungbean cropping system, application of 17.5 kg P ha^{-1} as DAP significantly increased energy output over control in all three years, whereas MRP at 17.5 kg P ha^{-1} increased energy output over control in the first year only. Further increase in rate of DAP from 17.5 to 35 kg P ha^{-1} in the first two years and of MRP from 17.5 to 35 kg P ha^{-1} and from 35 to 52.5 kg P ha^{-1} resulted in an additional increase in energy output of the system in first year of study.

Phosphorus Uptake

Application of 17.5 kg P ha^{-1} as DAP significantly increased P uptake by rice in all the three years of study, whereas MRP at 17.5 kg P ha^{-1} increased P uptake of rice only in the first year of study (Figure 2). During the second year P uptake of rice increased significantly when the rate of MRP application was increased from 0 to 35 kg P ha^{-1}. Further, increase in the rate of application from 35 to 52.5 kg P ha^{-1} as MRP or 17.5 to 35 kg P ha^{-1} as DAP did not result in an additional increase in the amount of P uptake by rice.

During the winter season DAP at 17.5 P ha^{-1} in all the three years and MRP at 17.5 kg P ha^{-1} in the first two years significantly increased P uptake over control. Further, increase in the level of DAP from 17.5 to 35 kg P ha^{-1} and of MRP from 17.5 to 52.5 kg ha^{-1} also resulted in an additional increase in P uptake in all the three years of study.

During summer, MRP at 17.5 kg P ha^{-1} had no significant effect on P uptake of mungbean over control in all the three years of study, whereas DAP at 17.5 kg P ha^{-1} and MRP at 35 kg P ha^{-1} being at par, significantly increased P uptake of mungbean over control in the first and the second years of study. DAP at 35 kg P ha^{-1} was significantly superior to MRP at 35 kg P ha^{-1} and significantly increased P uptake by mungbean over 17.5 kg P ha^{-1} of their respective source in last two years. Similarly, 52.5 kg P ha^{-1} of MRP was significantly superior to 35 kg P ha^{-1} of MRP in all the three years of study.

As regards to total P uptake of the system, DAP and MRP at 17.5 kg P ha^{-1} being at par, significantly increased P uptake of the system over control in all the three years of study (Figure 2). Further, increase in the level of DAP from 17.5 to 35 kg P ha^{-1} resulted in an additional increase in P removal by the system in all the three years, whereas in case of MRP, P removal by the system increased when rate of P application was increased from 17.5 to 52.5 kg P ha^{-1} in the first year and to 35 kg P ha^{-1} in the second and the third years of study.

Phosphorus Balance of Three Years

Rice resulted in a negative balance of 52 kg P ha^{-1} without P application and 4–6 kg P ha^{-1} with the application of 52.5 kg P ha^{-1} in three years,

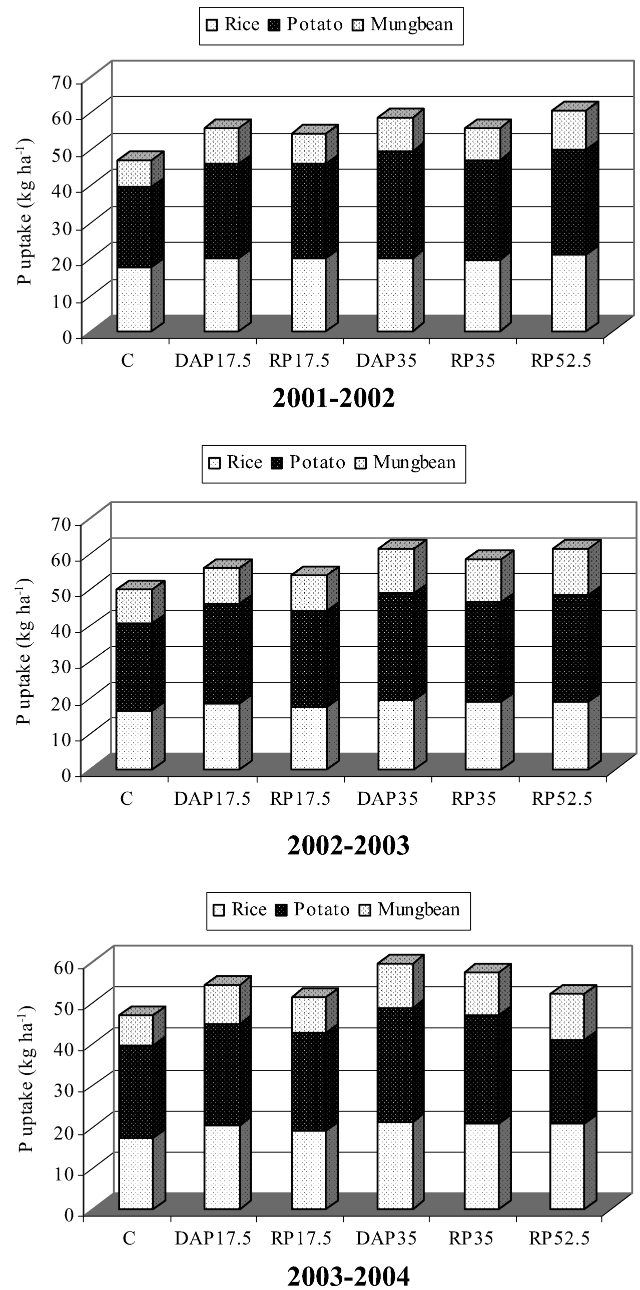

FIGURE 2 Effect of rates and sources of phosphorus on P uptake in rice-potato-mungbean cropping system.

whereas application of 105 and 157.5 kg P ha^{-1} in three years resulted in a positive (+) balance of 45.5 and 96.4 kg P ha^{-1}, respectively (Table 3). Similarly, during the winter season, application of 0 and 52.5 kg P ha^{-1} in three years resulted in a negative (−) balance of 68.1 and 23.6–25.4 kg P

TABLE 3 Balance sheet of P of 3 years in rice-potato-mungbean cropping system as influenced by rates and sources of phosphorus

		Rice		Potato		Mungbean		Total	
Treatment	P applied ($kg ha^{-1}$) to each crop A	P removed B	P balanced A-B	P removed C	P balanced A-C	P removed D	P balanced A-D	P removed (E = B + C + D)	P balanced (A × No of crops –E)
Control	0	51.8	–51.8	68.1	–68.1	24.3	–24.3	144.2	–144.2
17.5 kg P ha^{-1} as DAP	52.5	58.8	–6.3	77.9	–25.4	28.4	+24.1	165.1	–7.6
17.5 kg P ha^{-1} as MRP	52.5	56.8	–4.3	76.1	–23.6	27.3	+25.2	160.2	–2.7
35.0 kg P ha^{-1} as DAP	105.0	60.3	+44.7	86.5	+18.5	33.2	+71.8	180.0	+135.0
35.0 kg P ha^{-1} as MRP	105.0	59.5	+45.5	81.6	+23.4	30.5	74.5	171.6	+143.4
52.5 kg P ha^{-1} as MRP	157.5	61.1	96.4	86.3	+71.2	34.7	+122.8	182.1	+290.4

ha^{-1}, respectively. Application of 105 and 157.5 kg P ha^{-1} in three years, on the other hand, resulted in a positive (+) balance of 18.5–23.4 and 71.2 kg P ha^{-1}, respectively. During summer, the P removal by mungbean was less than P applied to this crop and it mitigated negative P balance of the system.

As regards P balance of the system, application of 0 and 157.5 kg P ha^{-1} to the three crops of the system in three years resulted in a negative (−) P balance of 144.2 and 2.7–7.6 kg ha^{-1}, respectively, whereas application of 315 and 472.5 kg P ha^{-1} to three crops in three years resulted in positive (+) balance of 135–143.4 and 290.4 kg P ha^{-1}, respectively.

0.5. M $NaHCO_3$ Extractable P Content in Soil

The 0.5 M $NaHCO_3$ extractable P content in soil increased significantly with each successive increase in the level of MRP up to 52.5 kg ha^{-1} and of DAP up to 35 kg ha^{-1} after completion of all the three cycles of the system (Table 4). MRP was at par with DAP at 17.5 kg P ha^{-1} but significantly inferior at 35 kg P ha^{-1}. MRP at 52.5 kg P ha^{-1} was at par with DAP at 35 kg P ha^{-1} and recorded significantly more 0.5 M $NaHCO_3$ extractable P content in soil than MRP at 35 kg P ha^{-1} and DAP at 17.5 kg P ha^{-1}.

Net Change in Available P Content in Soil

Application of 0–17.5 kg P ha^{-1} to each crop of the system resulted in negative (−) change in 0.5 M $NaHCO_3$ extractable P content in soil after completion of all the three cycles of the cropping system, whereas application of 35 kg P ha^{-1} $crop^{-1}$ resulted in a negative (−) change in 0.5 M $NaHCO_3$ extractable P content in soil after the first cycle but positive (+) change after the second and the third cycles; positive (+) change being higher after

TABLE 4 Effect of rates and sources of phosphorus on 0.5 M $NaHCO_3$ extractable P in soil and net change in 0.5 M $NaHCO_3$ extractable P over initial* value after completing a cycle of rice-potato-mungbean cropping system

	0.5 M $NaHCO_3$ extractable P (kg ha^{-1})			Net change in 0.5 M $NaHCO_3$ extractable P over initial* value (kg ha^{-1})		
Rates and sources of P	2001–02	2002–03	2003–04	2001–02	2002–03	2003–04
Control	12.6	12.5	12.2	−3.4	−3.6	−3.8
17.5 kg P ha^{-1} as DAP	13.6	16.2	15.9	−2.4	+0.2	−0.1
17.5 kg P ha^{-1} as MRP	13.3	15.4	15.7	−2.7	−0.6	−0.3
35.0 kg P ha^{-1} as DAP	14.2	19.4	20.2	−1.8	+3.4	+4.2
35.0 kg P ha^{-1} as MRP	15.4	17.1	18.1	−0.6	+2.1	+2.1
52.5 kg P ha^{-1} as MRP	17.2	18.8	19.6	+1.2	+2.8	+3.6
LSD ($P = 0.05$)	0.63	0.99	1.12	—	—	—

*Initial value: 16 kg P ha^{-1}.

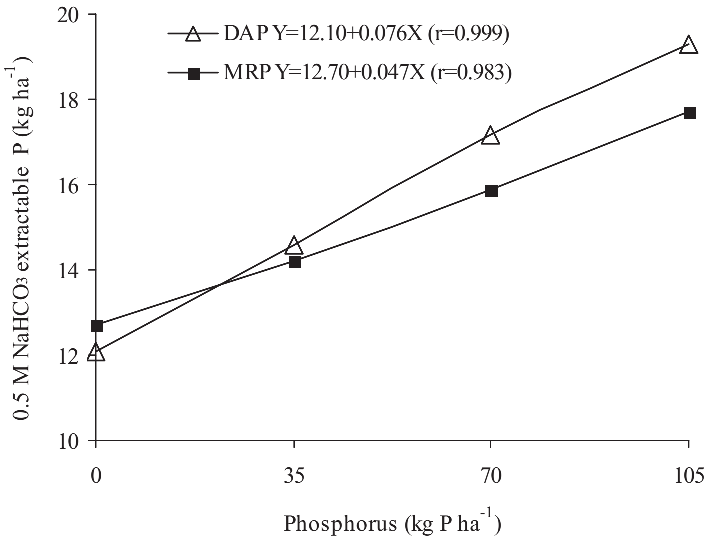

FIGURE 3 Relationship between P application in a year and 0.5 M $NaHCO_3$ extractable P in soil after completion of three cycles of rice-potato-mungbean cropping system.

the third cycle (Table 4). Application of 52.5 kg P ha^{-1} $crop^{-1}$ resulted in a positive (+) change in 0.5 M $NaHCO_3$ extractable P content after completion of all the three cycles and this positive (+) change increased with the time. There was no significant difference between sources of P after completion of all the three cycles of the system.

A linear pattern was observed between amount of P applied in a year and 0.5 M $NaHCO_3$ extractable P content in soil after completion of three cycles of the system (Figure 3). Using the linear equation, $y = a + bx$, the quantity of P to be applied per year to maintain a particular level of 0.5 M

TABLE 5 Quantity of P as DAP and MRP required to apply per year to maintain a desired level of 0.5 M $NaHCO_3$ extractable P in soil after completion of three cycles of rice-potato-mungbean cropping system

Level of 0.5 M $NaHCO_3$ extractable P (kg ha^{-1})*	DAP	MRP
16	51.3	70.2 (137)**
17	64.5	91.5 (142)
18	77.6	112.8 (145)
19	90.8	134.0 (148)
20	103.9	155.3 (149)
30	235.5	368.1 (156)
50	498.7	793.6 (159)

*The critical values of 20 and 50 kg P per ha of 0.5 M $NaHCO_3$ extractable P for rice and potato, respectively have been reported by Tondon (1987).

**Values in parentheses are percentage over P required as DAP.

TABLE 6 Effect of rate and source of phosphorus on phosphorus solubilizing bacteria (PSB) and CO_2 evolution from soil after completion of three cycles of rice-potato-mungbean cropping system

Rates and sources of P	PSB (cells × 10^3 g^{-1} soil)	CO_2 evolution (mg g^{-1} soil 24^{-1} hrs)
Control	7.9	0.104
17.5 kg P ha^{-1} as DAP	10.4	0.254
17.5 kg P ha^{-1} as MRP	15.9	0.282
35.0 kg P ha^{-1} as DAP	12.2	0.269
35.0 kg P ha^{-1} as MRP	16.8	0.291
52.5 kg P ha^{-1} as MRP	18.4	0.371
LSD ($P = 0.05$)	0.8	0.018

$NaHCO_3$ extractable P in soil after completion of third cycle of the system was calculated separately for DAP and MRP (Table 5). To maintain 0.5 M $NaHCO_3$ extractable P content in soil at initial level (16 kg P ha^{-1}), 51.3 kg P ha^{-1} as DAP and 70.2 kg P ha^{-1} as MRP was expected to apply per year. To increase the level of 0.5 M $NaHCO_3$ extractable P by 1 kg P ha^{-1}, the P dose was expected to increase by 13.2 kg P ha^{-1} yr^{-1} as DAP and 21.3 kg P ha^{-1} yr^{-1} as MRP.

Phosphate Solubilizing Bacteria (PSB) in Soil

The number of PSB increased significantly with increasing rate of MRP up to 52.5 kg P ha^{-1} and of DAP up to 35 kg P ha^{-1} (Table 6). However, MRP resulted in more number of PSB in soil than DAP. MRP even at 17.5 kg P ha^{-1} resulted in significantly more number of PSB in soil than DAP at 35 kg P ha^{-1}.

CO_2 Evolution from Soil

Application of 17.5 kg P ha^1 as DAP or MRP significantly increased CO_2 evolution from soil over control (Table 6). Further, increase in the rate of DAP or MRP from 17.5 to 35 kg P ha^{-1} did not result in an additional increase in CO_2 evolution from soil. Further, MRP resulted in more CO_2 evolution than DAP at 17.5 as well as at 35 kg P ha^{-1} and MRP at 52.5 kg P ha^{-1} resulted in the highest amount of CO_2 evolution in soil, which was significantly more to that resulted with lower levels of MRP.

DISCUSSION

Productivity of rice-potato-mungbean cropping system increased as the level of P was increased both with DAP and MRP and linear response equations fitted well for both the sources (Figure 1). The increase in productivity due to P application was more with DAP than with MRP. Phosphorus uptake by different crops as well as the total P uptake of the cropping system was also more with DAP than with MRP (Figure 2). Govil and Prasad (1974) also reported that P uptake increased as the water soluble P fraction in TSP—RP mixtures increased. Response of all the crops in rice-potato-mungbean cropping system was expected since the available Olsen's P was below the critical level in the soil of the experimental field.

Of late there has been considerable interest in direct application of rock phosphate (Babare et al., 1997; Bolan et al., 1990; Casnova, 1995; Dahanayake et al., 1995; Rajan et al., 1996). In most of these studies ground phosphate rock was compared with single or triple super phosphate (SSP or TSP) and the doses of rock phosphate required for equivalent effects were two or three times of that for SSP or TSP. For example Mathur et al. (1979) reported that for soybean (*Glycine max*)-wheat (*Triticum aestivum*) and maize (*Zea mays*)-chickpea (*Cicer arietinum*) system 150 kg P_2O_5 ha^{-1} as MRP was comparable to 50 kg P_2O_5 ha^{-1} as SSP. Similarly Maloth and Prasad (1976) reported that for cowpea (*Vigna sinensis*) 200 kg P_2O_5 ha^{-1} as MRP was equal to 100 kg P_2O_5 ha^{-1} as SSP.

Since MRP is indigenously produced and has only 18% P_2O_5, it cannot be used for phosphate fertilizer production. Therefore a number of trials have been conducted in India to compare it with SSP (PPCL, 1983). While in some studies MRP was less effective than SSP, in others it was found to be as good as SSP (Mathur et al., 1979; Rangaswamy and Arunachalam, 1983).

Taking cognizance of the fact that phosphate solubilizing bacteria (PSB) can make native and less soluble P as in MRP more readily available to the crops (Gaur, 1990; Bojinova et al., 1997; He et al., 2002). The present study was made with the combined application of PSB and MRP and the results show that only about 176–179% more P was needed as MRP than DAP. These values are much less than these reported by Mathur et al. (1979) and Maloth and Prasad (1976) and show a definite advantage of using PSB with MRP.

As regards build up of 0.5 M $NaHCO_3$ extractable P in soil application of 52.5 kg P ha^{-1} as MRP with PSB was at par with 35 kg P ha^{-1} as DAP after the second cycle of rice-potato-mungbean system. A higher builds up 0.5 M $NaHCO_3$ extractable P with rock phosphate (RP) is found when very high rates of RP are applied as compared to soluble phosphate fertilizer (Ruaysoongnern and Keerti-Kasikorn, 1998).

As would be expected after three cycles of cropping system the PBS count was much more in plots that received PSB treatment and also this resulted in increased CO_2 evolution. Increased CO_2 evolution due to PSB may partly explain their capacity to solubilize MRP due to maintenance of higher carbonic acid concentration in soil solution as suggested by Sharma and Aggarwal (2006).

Results obtained in the present study thus show that a combined application of MRP and PSB is a good practice and permits better utilization of MRP in rice-potato-mungbean-cropping system.

CONCLUSIONS

The present study shows that MRP along with PSB inoculation can be efficiently used for P fertilization in rice–potato-mungbean cropping system. The dosage of P required as MRP could be 176–179% of DAP for increased productivity and maintenance of available soil P for long term sustainability of in rice–potato-mungbean cropping system.

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