Phosphorus Management for Sustained Crop Production in Rice-Wheat Cropping System in Northwest India

Bijay Singh, Yadvinder Singh, C S Khind, and O P Meelu[1]

Abstract

In a long-term experiment on rice-wheat cropping system progressing at Ludhiana, India since 1990/91, feasibility of different phosphorus (P) management practices was studied in terms of sustainable high yield levels and maintenance of soil productivity. Besides a control (no P), 6 treatments (26, 39, or 52 kg P ha^{-1} yr^{-1}) were applied to rice and wheat in different proportions. Results showed that general recommendation for northwest India of application of 26 kg P ha^{-1} to wheat and no P to rice gave the highest grain yields of rice and wheat. Reducing P dose to wheat to less than 26 kg P ha^{-1} adversely affected the yield of wheat and application of any P to rice did not help increase its yield. Phosphorus balance in the soil obtained by subtracting total P removed by rice and wheat from total P applied, however, changed to negative when 26 kg P ha^{-1} was applied to wheat only. The study indicates that this practice may not be able to produce sustainable high yields in the decades to come. The P balance in the soil further indicated that it may be better to apply more P to wheat rather than applying any P to rice. Application of more than 26 kg P ha^{-1} will ensure build-up of available P in the soil. During the initial 5 years application of 26 kg P ha^{-1} to wheat and no P to rice maintained the Olsen's P in the soil at levels recorded at the initiation of the experiment. Continuation of this trend, however can be tested only by extending the long-term experiment for a decade or so.

Introduction

The soils in northwest India were generally low to medium for available phosphorus (P) a few decades ago. Due to application of P fertilizers year after year, the number of soils testing low and medium have decreased and those testing high have substantially increased (Brar and Singh 1986). Crop recovery of applied P ranges from 15% to 30% and depending on temperature and moisture regimes considerable residual effect may be observed on the succeeding crop (Kamath and Sarkar 1990).

In irrigated soils of northwest India, rice (*Oryza sativa* L.) followed by wheat (*Triticum aestivum* L.) constitutes one of the most important cropping sequences. Based on a large number of field experiments on wheat carried out in the region, a general recommendation of applying 26 kg P ha^{-1} is followed. Being a winter crop, wheat responds to P application more than rice does. Kanwar (1972) found that P deficiency for rice was not prevalent in north India. Due to high temperatures and flooded soil conditions, availability of soil P is substantially enhanced (Gill and Meelu 1983; Singh et al. 1988). Hence, application of 13 kg P ha^{-1} to rice is recommended in soils testing low in available P (<5 mg kg^{-1} 0.5 M $NaHCO_3$ extractable P). Thus many farmers have been applying fertilizer

1. Punjab Agricultural University, Ludhiana 141 004, Punjab, India.

Singh, Bijay, Singh, Yadvinder, Khind, C.S. and **Meelu, O.P.** 2000. Phosphorus Management for Sustained Crop Production in Rice-Wheat Cropping System in Northwest India. Page 22–30 *in* Long-term Soil Fertility Experiments in Rice-Wheat Cropping Systems (Abrol, I.P., Bronson, K. F., Duxbury, J. M. and Gupta, R. K. eds.). Rice-Wheat Consortium Paper Series 6. New Delhi, India: Rice-Wheat Consortium for the Indo-Gangetic Plains.

P to both rice and wheat whether grown in a sequence or otherwise.

In rice-wheat rotation rice does not respond to P when the recommended dose of 26 kg P ha^{-1} is applied to wheat (Gill and Meelu 1983; Saggar et al. 1985). Though this recommendation is now being widely followed its sustainability aspects are not very clear. In China, total P removal by rice and wheat was doubled when P was applied to wheat rather than to rice (Run-Kun et al. 1982).

A long-term field experiment was initiated to investigate sustainability of different P management practices in terms of yield and P balance in the soil. Total removal of P by rice and wheat in comparison to the amount of P applied through fertilizers was assessed to determine the viability of various P management practices.

Materials and Methods

A long-term field experiment with rice-wheat rotation is in progress since winter 1990/91 at Ludhiana (30°56' N, 75°52' E), Punjab, India. The soil was well-drained Fatehpur loamy sand (Typic Ustochrept) with 66% sand, 19% silt, and 15% clay in the surface horizon. The 0–15 cm soil depth had 0.42% organic carbon (Walkley and Black wet digestion method), 0.23 dS m^{-1} electrical conductivity, 0.06% total nitrogen (N), 4.0 mg kg^{-1} 0.5 M $NaHCO_3$ extractable P (Olsen P) and 40 mg kg^{-1} 1M neutral ammonium acetate-extractable potassium (K).

The experiment with 19.8 m^2 (9 m × 2.2 m) plots was laid out in randomized complete block design with 3 replications. The levels of P (kg ha^{-1}) applied to rice and wheat in different treatments were: T1 – $rice_0$, $wheat_0$; T2 – $rice_0$, $wheat_{26}$; T3 – $rice_0$, $wheat_{39}$; T4 – $rice_{26}$, $wheat_0$; T5 – $rice_{13}$, $wheat_{13}$; T6 – $rice_{13}$, $wheat_{26}$; and T7 – $rice_{26}$, $wheat_{26}$.

The wheat cultivar HD 2329 (PBW 343 in 1995/96) was sown in the first week of November at seeding rate of 100 kg ha^{-1} and row spacing of 20 cm. A uniform dose of 120 kg N ha^{-1} through urea and 25 kg K ha^{-1} through muriate of potash was applied to wheat. All of the P (as single superphosphate) and K were drilled below the seed at sowing of wheat. Half of the N was incorporated into the soil at the last preparatory tillage and the second half was top dressed after 3 to 4 weeks just before first irrigation. Wheat was irrigated by applying about 7.5 cm depth of tubewell water at a time and a total of 3–4 irrigations were applied to raise the crop. Wheat was harvested in the first week of April.

After the harvest of wheat, the field was kept fallow till June 7–15, when 5- to 6-week-old seedlings of rice (PR 106 during 1991–94 and PR 111 in 1995–96) were transplanted. Rice seedlings were transplanted with a spacing of 20 cm × 15 cm. A uniform dose of 150 kg N ha^{-1} and 25 kg K ha^{-1} was applied to rice. All P and K were incorporated into the soil with the last puddling operation. One-third of the N was broadcast on soil at rice transplanting. One-third N was top dressed at 3 weeks after transplanting and the remaining one-third at 6 weeks after transplanting. A basal dose of 50 kg zinc sulfate ha^{-1} was applied to rice in alternate years. Both tubewell and canal waters were used to irrigate rice. The water was kept standing continuously in the field for 3 weeks after transplanting rice. Thereafter, irrigations were applied 2 days after the ponded water infiltrated into the soil. Straw of both rice and wheat were removed from the plots after harvest of the crops.

Grain and straw yields of rice were recorded at 14% moisture content and oven-dry basis respectively. Grain and straw samples of both rice and wheat were analyzed for P content by digesting the samples in a mixture of HNO_3, $HClO_4$, and H_2SO_4 (9:3:1) and using the vanadomolybdate yellow color method (Jackson 1967). Available P in 0–15 cm soil samples collected from all the plots 10–15 days after the harvest of rice was determined by extracting the samples with 0.5 N $NaHCO_3$ as described by Olsen et al. (1954).

Results and Discussion

Wheat yield

During winter in all years from 1990/91 to 1995/96, wheat significantly responded to application of P (Table 1). Mean grain yield of wheat was the lowest when no P was applied. In all the years, significant increase in grain yield of wheat were observed up to 26 kg P ha^{-1}. This confirms the results of Meelu and Rana (1978), Gill and Meelu (1983), and Saggar et al. (1985). Azad et al. (1993) reported that on soils low in available P, wheat responded significantly up to 39 kg P ha^{-1} at different locations in Gurdaspur district of Punjab. Application of 13 kg P ha^{-1} each to wheat and rice gave significantly lower grain yield than 26 kg P ha^{-1} applied to wheat in all the 6 years thereby suggesting that direct application of 26 kg P ha^{-1} to wheat is a must for achieving its yield potential. In the present investigation, wheat grain yield did not significantly increase by increasing the P dose beyond 26 kg P ha^{-1}. A response of wheat to applied P was observed in soils possessing Olsen P up to 14 mg kg^{-1} and P application to wheat is made even in soils testing high (>9 mg kg^{-1}) for available P (Gill 1992). It seems that for soils under wheat definition of 'high P' should be readjusted.

Little residual effect of P applied to rice was observed on grain yield of wheat. When no P was applied to wheat, 26 kg P ha^{-1} applied to rice gave about 0.76 t ha^{-1} more wheat grain than the control (no P) (Table 1). Possibly, due to alternating oxidized and reduced conditions, P applied to rice was converted to forms (such as ferric phosphate) which were not as easily available to wheat as directly applied water soluble forms of P.

Irrespective of P treatment to rice or wheat, the grain yield of wheat did not show a declining trend over the years (Table 1). It seems

Table 1. Effect of phosphorus (P) fertilization on grain yields of wheat in rice-wheat cropping system at Ludhiana, Punjab, India.

Treatment (kg P ha^{-1})		Grain yield of wheat (t ha^{-1})						
Rice	Wheat	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	Mean[1]
0	0	2.47	1.82	2.37	2.39	2.26	2.41	2.29±0.08
0	26	4.68	4.19	4.06	4.69	4.56	4.77	4.49±0.08
0	39	4.79	4.52	4.19	4.69	4.75	5.11	4.68±0.09
26	0	2.15	2.77	3.24	2.92	3.83	3.41	3.05±0.15
13	13	4.00	3.67	3.57	3.96	4.03	4.38	3.94±0.09
13	26	5.02	4.09	4.09	4.39	4.89	4.88	4.56±0.11
26	26	4.80	4.16	4.34	4.72	5.08	5.14	4.71±0.11
LSD(P = 0.05)		0.37	0.51	0.43	0.51	0.39	0.42	

1. SEm based on data from 18 plots.

that management of P did not influence sustainability of wheat yields at least during 5–6 years.

Rice yields

Rice did not respond to applied P in 5 out of 6 years (Table 2). In 1995, 26 kg P ha^{-1} gave significantly more grain yield than the control (no P). Lack of response of rice to P is attributed to flooding of soil during growth of rice and high temperatures prevailing during summer in northwest India. Interestingly, the rice crop did not respond even when no application of P was made to both rice and wheat continuously for 5 years. Flooding the soil increases the availability of native and added P (Patrick and Mahapatra 1968; Ponnamperuma 1985) and as a consequence yield responses of lowland rice to fertilizer P are generally small (De Datta and Gomez 1982). Phosphorus availability in soil increases under submerged conditions due to reduction of ferric compounds; increased solubility of Ca-P compounds as a result of pH depression due to CO_2 accumulation by organic matter decomposition and through organic acids released during anaerobic decomposition of organic matter; release of phosphate ions from the exchange between organic anions and phosphate ions in Fe-P and Al-P compounds; and increased P diffusion (Sanyal and De Datta 1991). Gill and Meelu (1983) have demonstrated the positive effects of flooding and high temperature in enhancing the availability of P to rice and consequent lack of response of rice to applied P in the study area. In a 5-year study, Saggar et al. (1985) showed that rice did not respond to P application when the recommended dose of 26 kg P ha^{-1} was applied to wheat. The results of the present long-term experiment, however, indicate that while application of 26 kg P ha^{-1} to wheat is essential to obtain its full yield potential, it has no effect on the yield of following crop of rice which can meet its P

Table 2. Effect of phosphorus (P) fertilization on grain yields of rice in rice-wheat cropping system at Ludhiana, Punjab, India.

Treatment kg P ha^{-1}		Grain yield of rice (t ha^{-1})						
Rice	Wheat	1991	1992	1993	1994	1995	1996	Mean[1]
0	0	6.26	5.23	6.34	4.65	4.01	4.19	5.11±0.24
0	26	5.92	5.42	6.29	4.73	4.10	4.24	5.12±0.21
0	39	5.71	5.75	6.17	4.70	3.87	4.27	5.08±0.22
26	0	5.97	5.60	6.86	4.58	5.02	4.68	5.45±0.20
13	13	6.23	5.87	6.38	4.72	4.45	4.40	5.34±0.21
13	26	5.79	5.46	6.34	4.58	4.10	4.47	5.12±0.20
26	26	6.00	5.48	6.29	5.04	4.90	4.38	5.35±0.17
Mean[2]		5.99 ±0.08	5.55 ±0.08	6.38 ±0.07	4.71 ±0.07	4.35 ±0.10	4.38 ±0.06	
LSD (P=0.05)		NS[3]	NS	NS	NS	0.70	NS	

1. SEm based on data from 18 plots.

2. SEm based on data from 21 plots.

3. NS=not significant.

requirement fully from the enhanced availability of soil P due to high temperatures and flooding of soil.

Contrary to wheat, grain yield of rice showed a declining trend over the years. Slope and intercept of linear regressions of rice grain yield over time reveal the effect of P management on sustainability of rice yields (Table 3). It is interesting to note that when 26 kg P ha^{-1} was applied to rice, the rate of decline of rice yields (slope) was minimum irrespective of whether P was applied to wheat or not. In 0 or 13 kg P ha^{-1} treatments, the slopes were less than those observed for 26 kg P ha^{-1} treatments. Therefore, data of rice grain yield from the 7 treatments were segregated into 2 groups — the treatments receiving 26 kg P ha^{-1} to rice and the treatments receiving 0 or 13 kg P ha^{-1}. Plots of the rice grain yield data in the two groups against years demonstrate the role of applying P to rice in retarding yield decline with time (Fig. 1).

Recently, Nand Ram (1995) compiled data for 20 years (1972–92) from a long-term experiment on rice-wheat-cowpea (*Vigna unguiculata* (L.) Walp.) rotation progressing at Pantnagar in Uttar Pradesh, India. Phosphorus

Table 3. Slope and intercept of linear regressions of rice grain yield over the years for different levels of phosphorus (P) in rice-wheat cropping system at Ludhiana, Punjab, India.

Treatment (kg P ha^{-1})		Intercept	Slope	r^2	SE
Rice	Wheat			(n=18)	
0	0	6.68	–0.45	0.61	0.61
0	26	6.51	–0.40	0.61	0.55
0	39	6.51	–0.41	0.61	0.55
26	0	6.50	–0.30	0.37	0.65
13	13	6.85	–0.43	0.77	0.40
13	26	6.37	–0.36	0.54	0.56
26	26	6.46	–0.31	0.62	0.42

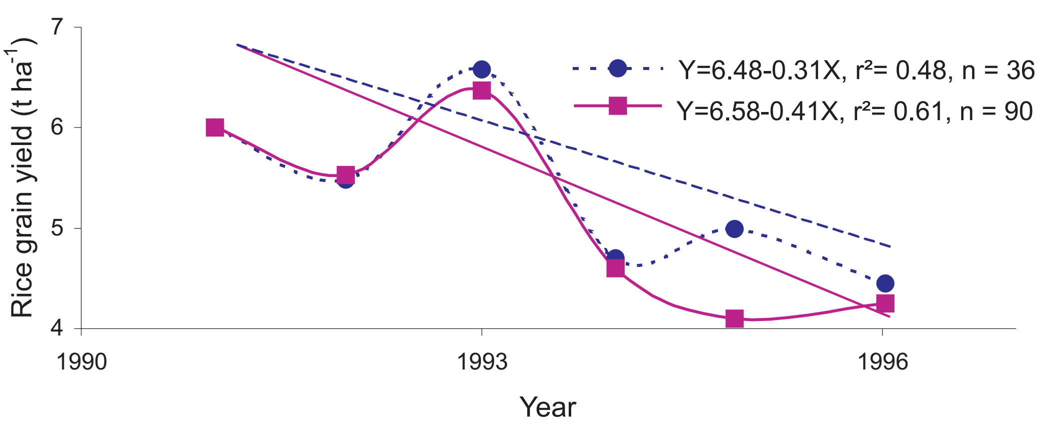

Figure 1. Regression of grain yield of rice at 26 kg P ha^{-1} and at 0 to 13 kg P ha^{-1} during 1990–96 in rice-wheat cropping system at Ludhiana, Punjab, India.

was applied to both rice and wheat. It was observed that both rice and wheat did not exhibit response to P in the early years of the experiment. Mean grain yield response to P application during the last 5 years was 126 kg ha^{-1} for rice and 213 kg ha^{-1} for wheat; mean response during the 20-year period was only 16 kg ha^{-1} for rice and 47 kg ha^{-1} for wheat. Thus, a different pattern of response of rice and wheat to P could be found if the present experiment continues for a long period. The data on P balance in the soil as discussed in the next section provides a better indication in this direction.

P uptake by rice and wheat and P balance in soil

The highest P removal by rice and wheat was recorded when both rice and wheat received 26 kg P ha^{-1} each (Table 4). The amount of total P uptake by rice and wheat depends on production level, amount of applied P and soil type. Rice-wheat cropping system can remove as much as 45 kg P ha^{-1} (Khera et al. 1990). Interestingly, despite effects on wheat yields total P removal by rice and wheat for a given P input level was similar irrespective of the fertilizer dose split between rice and wheat. For example, total grain yield of rice and wheat in the treatment in which 26 kg P ha^{-1} was applied to rice alone, was significantly less than the yield from the treatment in which 26 kg P ha^{-1} was applied only to wheat (Tables 1 and 2), yet total P removal in both treatments was similar.

All treatments to which a total of 26 kg P ha^{-1} is being applied whether to rice, or to wheat or to both the crops, showed a negative balance year after year (Table 5). In the treatment receiving a recommended dose of 26 kg P ha^{-1} to wheat and no P to rice, the P balance is very low. It raises a question as to how long this recommendation will be able to sustain the yields of rice and wheat grown in a sequence. Undoubtedly, continuation of this long-term experiment will provide some answers.

Looking at the P balance in soil, it seems that to ensure high productivity in the years to come and to produce sustainable high yields in the rice-wheat system, around 35 kg P ha^{-1} should be applied in a year. The P balance in the treatments in which 39 kg P ha^{-1} was applied to wheat alone compared with the treatment in

Table 4. Total phosphorus (P) removal in the above ground biomass of rice and wheat as affected by different levels of P applied to the two crops grown in a fixed rotation at Ludhiana, Punjab, India.[1]

Treatment (kg P ha^{-1})		P removal by rice and wheat (kg P ha^{-1})						
Rice	Wheat	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	Total
0	0	24.8	24.4	24.9	24.9	20.8	23.0	142.8
0	26	31.9	32.7	33.1	33.5	29.3	29.9	190.4
0	39	32.3	34.8	33.0	34.8	31.4	32.7	199.0
26	0	32.0	33.0	32.7	30.9	29.2	28.2	186.0
13	13	31.8	30.0	31.7	36.1	29.7	29.1	188.4
13	26	33.1	34.1	35.6	35.8	31.4	33.2	203.2
26	26	37.7	37.5	37.3	37.4	34.3	33.7	217.9

1. Rice and wheat straw not returned back to the soil.

which 26 and 13 kg P ha^{-1} were applied to wheat and rice respectively, indicates that applying more P to wheat may prove more beneficial in the long run (Table 5).

Available P in soil

When no P was applied either to rice or to wheat, a significant decrease in available P was recorded from 1992 onwards. Since measurements were made after the harvest of rice, levels of P applied to rice exerted a profound influence on available P status of the soil. A significant build-up in available P in the soil was observed when 26 kg P ha^{-1} was applied to rice (Table 6). Similar build-up was also observed when along with 13 kg P ha^{-1} to rice, 26 kg P ha^{-1} was applied to wheat. Sharma et al. (1987) observed an increase in available P status from 6.7 kg P ha^{-1} to 12.2 kg P ha^{-1} with similar P levels in rice-wheat system at Ludhiana.

Table 5. Effect of phosphorus (P) fertilization on the P balance in the rice-wheat cropping system at Ludhiana, Punjab, India.

Treatment (kg P ha^{-1})		P balance[1] (kg P ha^{-1})						
Rice	Wheat	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	Total
0	0	–24.8	–24.4	–24.9	–24.9	–20.8	–23.0	–142.8
0	26	–5.9	–6.7	–7.1	–7.5	–3.3	–3.9	–34.4
0	39	6.7	4.2	6.0	4.2	7.6	6.3	35.0
26	0	–6.0	–7.0	–6.7	–4.9	–3.2	–2.2	–30.0
13	13	–5.8	–4.0	–5.7	–10.1	–3.7	–3.1	–32.4
13	26	5.9	4.9	3.4	3.2	7.6	5.8	30.8
26	26	14.3	14.5	14.7	14.6	17.7	18.3	94.1

1. P balance=P applied – P removed by the crops.

Table 6. Effect of different levels of phosphorus (P) applied to rice and wheat on Olsen P in soil after harvest of rice in rice-wheat cropping system at Ludhiana, Punjab, India during 1992–96.

Treatment (kg P ha^{-1})		Available P in soil after rice[1] (kg ha^{-1})				
Rice	Wheat	1992	1993	1994	1995	1996
0	0	8.1	10.3	8.4	7.8	7.5
0	26	10.2	12.8	11.3	10.1	9.8
0	39	10.2	12.7	10.4	11.2	11.0
26	0	11.3	13.3	11.3	12.3	13.0
13	13	10.2	9.9	9.8	10.1	9.9
13	26	13.0	12.6	14.1	12.3	13.0
26	26	13.5	15.8	16.9	17.1	17.0
LSD (P = 0.05)		1.1	1.1	0.9	1.0	1.0

1. Soil available P at initiation of the experiment=10 kg ha^{-1}.

An important observation from the treatment in which recommended dose of 26 kg P ha^{-1} and no P is being applied to wheat and rice, respectively, is that available P status of the soil is maintained equal to the initial status of the soil during 1990/91 (Table 6). Application of 39 kg P ha^{-1} to wheat alone, in general, does not help in increasing the available P status of the soil over that observed with 26 kg P ha^{-1}. Perhaps, during the 30 to 60-day period when after removing from the field plots, the soil samples were dried, processed, and stored before analysis, P might have fixed due to reoxidation. It may explain both the lack of increase in available P by applying 39 kg P ha^{-1} over that observed at 26 kg P ha^{-1} and the negligible change in available P from the initial values in treatments receiving up to 39 kg P ha^{-1}.

Conclusion

The long-term experiment conducted during 1990–96 provides convincing evidence that the general recommendation of applying 26 kg P ha^{-1} to wheat and no P to rice gives high sustainable yields in the rice-wheat system in northwest India. Phosphorus balance in the soil indicates that this recommendation may not be feasible on a long-term basis because of a negative P balance observed year after year. To work out P management practices which can ensure both maintenance of soil productivity (in terms of available P status of the soil) and sustainable high yields in the cropping system, the experiment will have to be continued for 10 to 15 years. Experience from the long-term experiments on P progressing under different soil and climatic conditions provides an indication that yield trends with a particular P management practice may change with time. Keeping in view that even in northwest India, rice responds to P application at a few locations, it is suggested that long-term experiments on the management of P be initiated at more locations where soils are different than at Ludhiana.

References

Azad, A.S., Singh, Bijay, and **Singh, Yadvinder.** 1993. Response of wheat to graded doses of N, P and K in soils testing low, medium and high with respect to P and K in Gurdaspur district of Punjab. Journal of Potassium Research 9:266–270.

Brar, S.P.S., and **Singh, Bhajan.** 1986. Changes in soil fertility under intensive cultivation. Indian Journal of Ecology 13:152–157.

De Datta, S.K., and **Gomez, K.A.** 1982. Changes in phosphorus and potassium responses in wetland rice soils in South and Southeast Asia. Pages 127–146 *in* Phosphorus and potassium in tropics (Pushparajah, E., and Sharifuddin, H.A.H., eds.). Kuala Lumpur, Malaysia: The Malaysian Society of Soil Science.

Gill, H.S., and **Meelu, O.P.** 1983. Studies on the utilization of P and causes for its differential response to rice-wheat rotation. Plant and Soil 74:211–222.

Gill, K.S. 1992. Research on rice-wheat cropping system in the Punjab. Ludhiana, India: Punjab Agricultural University. 43 pp.

Jackson, M.L. 1967. Soil chemical analysis. New Delhi, India: Prentice Hall of India Pvt. Ltd. 498 pp.

Kamath, M.B., and **Sarkar, M.C.** 1990. Fertilizer management practices for increasing fertilizer use efficiency. Pages 53–67 *in* Soil fertility and fertilizer use (Kumar, V., Shrotriya, G.C., and Kaore, S.V., eds.). Vol. IV. New Delhi, India: Indian Farmers Fertiliser Cooperative Limited.

Kanwar, J.S. 1972. Fertiliser use research in India: Retrospect and prospects. Fertiliser News 17(12):27–36.

Khera, M.S., Deshmukh, V.N., Talukdar, M.C., and **Adinarayana, V.** 1990. Strategy for use of potassium in Indian agriculture. Pages 69–93 *in* Soil fertility and fertilizer use (Kumar, V., Shrotriya, G.C., and Kaore, S.V., eds.). Vol. IV. New Delhi, India: Indian Farmers Fertiliser Cooperative Limited.

Meelu, O.P., and **Rana, D.S.** 1978. Crop responses to fertilizer application in Punjab. Pages 492–495 *in* Proceedings of National Symposium on Land and Water Management in Indus Basin 1.

Nand Ram. 1995. Long-term effects of fertilizers on crop production and soil properties in a Mollisol. Technical Research Bulletin 124. Pantnagar, India: Govind Ballabh Pant University of Agriculture and Technology. 36 pp.

Olsen, S.R., Cole, C.V., Watanabe, F.S., and **Dean, L.A.** 1954. Estimation of available phosphorus by extraction with sodium bicarbonate. USDA Circular No. 939. Washington D.C., USA: United States Department of Agriculture.

Patrick, W.H., Jr., and **Mahapatra, I.C.** 1968. Transformations and availability to rice of nitrogen and phosphorus in waterlogged soils. Advances in Agronomy 20:323–359.

Ponnamperuma, F.N. 1985. Chemical kinetics of wetland rice soils relative to soil fertility. Pages 71–89 *in* Wetland soils: Characterization, classification and utilization. Los Bãnos, Philippines: International Rice Research Institute.

Run-Kun, L., Bai-Fan, J., and **Ching-Kwei, L.** 1982. P management for submerged soils. Pages 182–191 *in* Proceedings of the 12th International Congress of Soil Science, Symposia Paper II.

Saggar, S., Meelu, O.P., and **Dev, G.** 1985. Effect of P levels applied in different phases in rice-wheat rotations. Indian Journal of Agronomy 30:199–206.

Sanyal, S.K., and **De Datta, S.K.** 1991. Chemistry of phosphorus transformations in soil. Advances in Soil Science 16:1–120.

Sharma, K.N., Rana, D.S., and **Bhandari, A.L.** 1987. Influence of growing various crops in five fixed cropping sequences on the changes in phosphorus and potassium content of soil. Journal of Agricultural Science, Cambridge 109:281–284.

Singh, Yadvinder, Singh, Bijay, Maskina, M.S., and **Meelu, O.P.** 1988. Effect of organic manures, crop residues and green manure (*Sesbania aculeata*) on N and P transformations in a sandy loam soil at field capacity and under waterlogged conditions. Biology and Fertility of Soils 6:183–187.