Long-term Study on Phosphorus Fertilization for Rice-Wheat Cropping System in an Alkali Soils in the Indo-Gangetic Plains

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Abstract

In a 20-year-old long-term experiment, progressing on a gypsum-amended alkali soil, phosphorus (P) was applied @ 0, 11, and 22 kg ha^{-1} to rice or wheat or to both crops grown in an annual sequence. Except the absolute control plots, all others received 120 kg nitrogen (N) ha^{-1}, through urea, 50 kg potassium (K) ha^{-1} through muriate of potash, and 5 kg zinc (Zn) ha^{-1} through zinc sulfate. Rice and wheat were grown throughout the study. Due to high amount of extractable P in alkali soils, both the crops did not respond to fertilizer P application in the initial 3 years of reclamation.

Rice showed response to P when as a result of leaching, immobilization (caused by added gypsum), higher sorption [due to decrease in soil exchangeable sodium percentage (ESP)], and plant removal, Olsen's extractable P decreased to 7.5 kg ha^{-1} in 0–15 cm soil and 9.5 kg ha^{-1} in 15–30 cm soil. Due to its long duration of growth and capacity to mine soil P from the lower layers, wheat did not respond to P application till the Olsen's P level dropped to 4.5 kg ha^{-1} in 0–15 cm soil and 3.4 kg ha^{-1} in 15–30 cm soil. There was a continuous decrease in extractable P in control plots (no P treatment) while in treatments receiving 22 kg P ha^{-1} to both the crops, there was a significant build-up of extractable P. Sustainable yields of rice and wheat were obtained by fertilizing both the crops with 120 kg N ha^{-1}, 22 kg P ha^{-1}, 50 kg K ha^{-1}, and 5 kg Zn ha^{-1}. After the initial decrease of surface soil pH from 10.3 to 8.5 there was no further change; however, there was a continuous improvement in the pH or ESP of the lower soil layers as a result of rice-wheat cropping.

Introduction

Alkali soils, formed under the influence of sodium carbonate, occur extensively in the Indo-Gangetic plains of India and other parts of the world. Out of 8.4 million ha of salt-affected soils in India, 2.5 million ha are affected due to alkali problem (Singh 1992). Though these soils occur extensively throughout the country, sizeable areas are found in the states of Punjab, Haryana, and Uttar Pradesh.

In the past two decades, efforts were made to reclaim these lands by application of amendments such as gypsum and by adopting suitable agronomic practices. In addition to application of amendments and the choice of crops, management of nutrients is an important aspect of crop production and to sustain the productivity of these problem soils. Alkali soils contain high amounts, up to 136 kg ha^{-1} of $NaHCO_3$ extractable phosphorus (P) formed as a result of reaction of Na_2CO_3 and $NaHCO_3$ with native insoluble calcium phosphates (apatite) to form soluble sodium phosphate. Results of a survey conducted in different states of India showed that the uncultivated alkali soils contained high amount of extractable P not only

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in the surface but throughout the profile (Chhabra et al. 1981). However, it is generally believed that in spite of the soluble nature of sodium phosphate it may not be physiologically available to the crop plants.

The paper deals with the results of a long-term field experiment initiated in 1976 to study the P needs of sequentially grown rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) for obtaining high and sustainable yields on gypsum amended alkali soils.

Materials and Methods

The field experiment was initiated in the rainy season (kharif) 1976 at Karnal, India (75°57' E, 29°43' N). The climate at the site is subtropical, hot and humid rainy season, hot dry summer, warm autumn, and cool winter. The maximum temperature during summer rises to about 46°C and minimum temperature during winter falls to 2°C. Average annual rainfall of the area was 600–700 mm, major portion of which is received during July–September, the rice-growing period. The potential evaporation was highest (12 mm day^{-1}) in summer and lowest in winter (1.1 mm day^{-1}).

The soil was classified as Aquic Natrustalf, Kachwa Series and represents the alluvial alkali soils of the Indo-Gangetic plains. It was calcareous, with a hard *kankar pan* ($CaCO_3$ layer) located at a depth of 60–150 cm. At the beginning of the experiment, soil had high pH and exchangeable sodium percentage (ESP) throughout the profile (Table 1). The experimental field was poorly permeable with an average water infiltration rate of 12 mm day^{-1}. The water table at the site remains below 3 m during crop growth.

Gypsum @ 14 t ha^{-1}, representing 50% of the laboratory-determined gypsum requirement was incorporated in the surface 5 cm of soil in 1974 and two crops of rice were taken before initiating the experiment in 1976. The fertilizer treatments imposed were 0, 11, and 22 kg P ha^{-1} as single superphosphate applied either to wheat (W_0, W_{11}, and W_{22}), to rice (R_0, R_{11}, and R_{22}), or to both rice and wheat grown in a sequence. In addition, there was a control treatment where no nitrogen (N), P, and potassium (K) were applied ($N_0P_0K_0$). In all other plots, a general dose of 120 kg N ha^{-1}, through urea, 50 kg K ha^{-1} through muriate of potash, and 5 kg zinc (Zn) ha^{-1} through zinc sulfate was given. All the K and Zn along with 50% of N was applied basal at the time of transplanting of rice or sowing of wheat. The remaining N was top dressed in two equal parts at 21 days after transplanting or 45 days after sowing. The experiment was conducted in 11.5 m × 4.5 m plots laid out in randomized block design with 4 replications.

Rice (cv Jaya) was transplanted in the first week of July and harvested in first week of October while wheat (cv HD 2009) was sown in the first week of November and harvested in first week of April. The rice crop was irrigated on alternate days, with good quality tube well water having electrical conductivity (EC) of 0.3 to 0.4 dS m^{-1}, to keep 5 cm of water ponded throughout the cropping season. For wheat, the first irrigation was given 21 days after sowing and then when 5 cm cumulative pan evaporation had occurred. Generally, the wheat crop received 4–5 irrigations of 7.5 cm each. At maturity, after removal of borders, whole plots were harvested for computing grain yield which was expressed on a 14% moisture basis as unhusked rice and on a field dry weight basis for wheat.

Plant analysis

Phosphorus concentration in the straw and grain was determined in 5 plants $plot^{-1}$ collected

Table 1. **Physico-chemical characteristics of soil in the experimental field at Karnal, India.**

Characteristics[1]	Depth (cm)	
	0–15	15–30
pH[2]	10.3	10.5
EC[2] (dS m^{-1})	4.6	2.9
$CaCO_3$ (%)	2.6	3.3
ESP	93.0	95.0
CEC [mmol(+) kg^{-1}]	98.0	128.0
$NaHCO_3$-extractable P (kg ha^{-1})	46.0	42.0
Composition of saturation paste extract (mg L^{-1})		
Ca^{2+}	0.8	1.2
Mg^{2+}	0.8	2.1
Na^+	440.8	50.6
K^+	0.3	0.2
CO_3^{2-}	280.0	15.6
HCO_3^-	89.2	26.4
Cl^-	56.0	7.2
SO_4^{2-}	18.8	6.9
Sand (%)	47.4	44.2
Silt (%)	29.6	27.8
Clay (%)	23.0	28.0

1. EC=electrical conductivity; ESP=exchangeable sodium percentage; CEC=cation exchange capacity.
2. Measured on 1:2 soil:water suspension.

randomly at harvest. The plant material was separated into grain and straw, washed with deionized water, oven-dried at 67°C, ground, and passed through a 2 mm screen. The ground plant material was digested in HNO_3:$HClO_4$ (3:1) mixture and analyzed for P by vanadomolybdo-phosphoric yellow color method (Koenig and Johnson 1942).

Soil analysis

Composite soil samples from 0–15 cm and 15–30 cm depth were taken from all plots before transplanting or sowing and after harvest of each crop. Soil samples were air-dried, ground, and passed through a 2 mm sieve. For all the samples, P was extracted at 25°C using 0.5 M $NaHCO_3$, at pH 8.5, and analyzed by the ascorbic acid reductase method (John 1970). The soil pH was measured on 1:2 soil-water suspension using glass electrode pH meter and electrical conductivity (EC) with a conductivity meter.

Results and Discussion

Grain yield

The yield of rice and wheat grown in freshly reclaimed alkali soils was not affected by application of phosphatic fertilizers in the initial 3 years (Table 2) (Chhabra 1985). After 3 years

Table 2. Grain yield of rice and wheat (t ha^{-1}) as affected by phosphorus (P) fertilization of a gypsum-amended alkali soil in Karnal, India during 1976–96.

Treatment[1]	Years of cropping				
	1	5	10	15	20
Rice					
R_0W_0	6.58	5.90	3.88	3.87	3.27
$R_{11}W_0$	7.29	6.31	5.47	5.07	5.49
$R_{22}W_0$	6.78	7.30	6.05	5.22	5.92
R_0W_{11}	6.87	6.92	4.76	4.51	4.12
R_0W_{22}	6.11	6.74	5.34	4.91	4.77
$R_{11}W_{11}$	6.91	6.93	5.86	5.27	5.87
$R_{22}W_{22}$	6.69	6.75	5.90	6.63	6.10
Control (no P)	3.94	2.69	2.59	2.04	2.38
LSD at P = 0.05	NS[2]	0.55	0.94	0.21	0.36
Wheat					
R_0W_0	4.35	4.74	4.32	3.59	3.34
$R_{11}W_0$	4.62	4.70	4.44	3.67	4.37
$R_{22}W_0$	4.38	4.86	4.57	3.74	4.77
R_0W_{11}	4.25	4.75	4.44	3.67	3.97
R_0W_{22}	4.34	4.79	4.74	3.80	4.11
$R_{11}W_{11}$	4.49	4.87	4.69	3.60	4.52
$R_{22}W_{22}$	4.45	4.59	4.83	3.78	4.73
Control (no P)	0.83	0.92	0.95	1.05	0.91
LSD at P = 0.05	NS	NS	NS	NS	0.22

1. Application of P (kg ha^{-1}) to rice (R) and wheat (W).
2. NS=not significant.

of continuous cropping, rice crop started responding to P application but the response was limited to only 11 kg P ha^{-1}. It was after another 7 years that yield of rice was significantly affected by 22 kg P ha^{-1}. In the initial stages of plant growth, i.e., up to 21 days, both rice and wheat showed deficiency symptoms of P in the form of stunted growth, decrease in number of tillers, dirty green leaves, and decrease in biomass production. Grain yield of only rice, however, was significantly affected by P application.

Reduction in rice yield in no P plots (R_0W_0), when compared to the yield obtained in the P fertilized plots ($R_{22}W_{22}$), was 15% in the third year, 20% in the fourth year, 30% in the fifth year, and 40% in the sixth year. It stabilized at 42% even up to 20 years of cropping while in wheat yield, reduction stabilized at lower level, i.e., 30% and that too was recorded after 14 years of continuous cropping (Fig. 1). As in the rice crop, the level of reduction in wheat yield also remained static even after 20 years of cultivation.

In treatment receiving complete fertilizer ($N_{120}P_{22}K_{50}Zn_5$), the yield of both rice and wheat

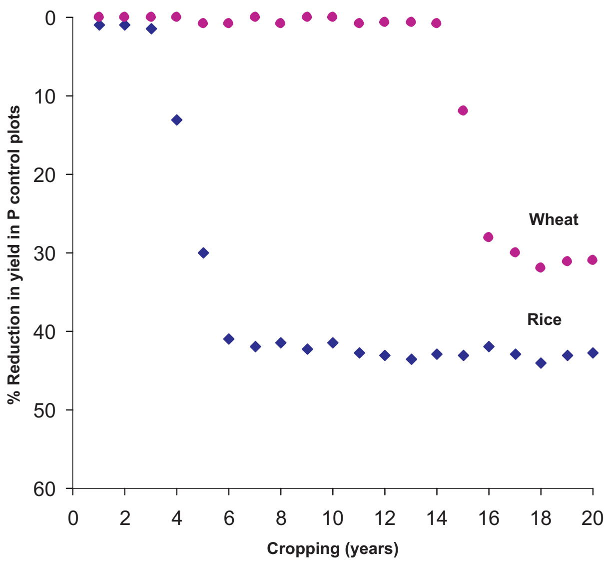

Figure 1. Reduction in grain yield of rice and wheat in control plots without phosphorus (P) as compared to those receiving 22 kg P ha^{-1} to each crop.

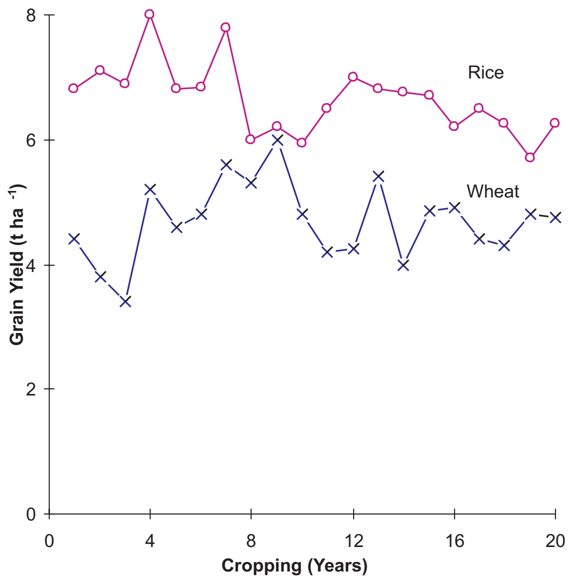

Figure 2. Fluctuations in grain yield of rice and wheat in fertilized plots ($N_{120}P_{22}K_{50}Zn_5$) in a gypsum-amended alkali soil over a period of 20 years from 1976 to 1995.

crop fluctuated every year (Fig. 2). There was no correlation between the yield and the average rainfall, maximum and minimum temperature, and relative humidity. Thus the fluctuation in the data cannot be simply explained on the basis of variations in the climatic factors. Further, use of 3 or 5 years rolling averages also did not help in smoothening the data. However, in general the overall yield of rice had somewhat a declining trend which was not so for wheat.

Lack of response to applied P for both rice and wheat crops in the initial years of reclamation was due to high available P status. A positive correlation between soil ESP and Olsen's extractable P was thus observed in gypsum amended cultivated fields. Pratt and Thorne (1948) observed increase in P solubility with increase in the pH in a sodium-dominated clay system while it decreased in calcium-dominated system.

Rice being shallow rooted and thus dependent mainly on the fertility status of the surface 30 cm layer, started showing response to applied fertilizer P much earlier than wheat crop. When Olsen's P of the surface layer fell below 7.5 kg ha^{-1}, the yield of rice crop started showing a significant decline. Further, during initial years of reclamation, though the extractable P in the surface layer decreased, the lower layers still continued to have moderate to high amounts of extractable P (Chhabra et al. 1981). Consequently, wheat plants, which have relatively deeper rooting system could utilize P from the lower layers to meet their requirement, and responded to P application only after 14 years of cropping when Olsen's P dropped to 4.5 kg ha^{-1} in the 0–15 cm soil and to 3.4 kg ha^{-1} in the 15–30 cm soil. However, the response was limited to only 11 kg P ha^{-1} applied to rice or to wheat crop. In addition to deeper rooting system, wheat being a longer duration crop than rice, gets 30–50 days more to mine soil P and thus to meet its P requirement. These results showed that while assessing the P fertility status of alkali soils, not only the surface but also the subsurface P status should be considered.

The direct effect of P fertilization was more beneficial than its residual effect. It shows that in calcareous alkali soils it is better to apply phosphatic fertilizers to both the crops in a rice-wheat sequence.

Plant composition

In the initial years of cropping no significant effect was observed on P concentration of the grain and straw of both the crops. But with time, the P content of rice crop was significantly affected by differential application of P. Though the biomass production and P content of both the crops were significantly affected initially, grain yield of rice was only affected at maturity.

After 20 years of cropping, the P content in grain and straw of rice and wheat in no P plots was significantly lower than those fertilized with P (Table 3). The P content of both grain and straw were affected by P. The critical concentration of P in the grain, straw, and in 21-day-old plants was 200, 20, and 200 mg $100g^{-1}$ for rice and 250, 15, and 150 mg $100g^{-1}$ for wheat, respectively.

The P content of the plants receiving no fertilizer at all ($N_0P_0K_0$) was more than that of plants receiving only N (R_0W_0). It was due to less biomass and low grain production caused by deficiency of N. In the treatment R_0W_0 the total biomass and grain production was high resulting in dilution and thus low P content in the plant parts.

Changes in available P of soil and P budgeting

The available P status of the alkali soil showed significant changes initially as a result of gypsum application and later on due to differential P application. Before the imposition of the P fertilizer, the P status of the soil decreased from 46 kg ha^{-1} in 1974 to 19 kg ha^{-1} in 1976. Initial drop during the earlier years of reclamation was due to: (i) immobilization of soluble sodium phosphates through its conversion to less soluble calcium phosphates by added gypsum; (ii) decrease in ESP/pH of the soil leading to more sorption of applied P; (iii) movement of P from the surface to the lower layers; and (iv) removal of soil P by the growing plants (Chhabra et al. 1981).

Table 3. Phosphorus (P) content (mg $100g^{-1}$) of rice and wheat as affected by differential P application in a gypsum-amended alkali soil in Karnal, India in 1996.

Treatment[1]	Rice		Wheat	
	Grain	Straw	Grain	Straw
R_0W_0	185	19	230	13
$R_{11}W_0$	268	23	270	22
$R_{22}W_0$	288	31	298	22
R_0W_{11}	263	20	220	19
R_0W_{22}	270	25	295	30
$R_{11}W_{11}$	278	33	320	28
$R_{22}W_{22}$	285	53	350	37
Control ($N_0P_0K_0$)	298	29	298	33
LSD at P=0.05	11	5	30	5

1. Application of P (kg ha^{-1}) to rice (R) and wheat (W).

Olsen's extractable P in 0–15 cm soil, after rice crop, declined continuously and stabilized at 4.5 kg ha^{-1} where no fertilizer P was applied (R_0W_0), while it increased in the plots receiving 22 kg P ha^{-1} to both the crops and reached a level of 32 kg P ha^{-1} (Fig. 3). In the initial years the extractable P was always less after rice than that after wheat crop (Fig. 4). This was mainly due to higher leaching losses during its cultivation and more removal of the soil P from surface layer by shallow rooted rice crop. But later on and in the treatments where lower doses of fertilizer P were added and the soil available P status was medium to low, the differences in the soil available P status of the soil after rice and wheat were not so striking showing thereby that in the low fertility soils the rice plant was also mining P even from the lower depths.

As a result, P removal by the plant from the treatments fertilized with P was more than those from the no P fertilized treatments. Data analysis of 20 years showed that the P removal was directly related to the level of P added in the soil (r = 0.94) (Table 4). Except in treatment receiving 22 kg P ha^{-1} to each crop, there was more removal of P from the soil than the

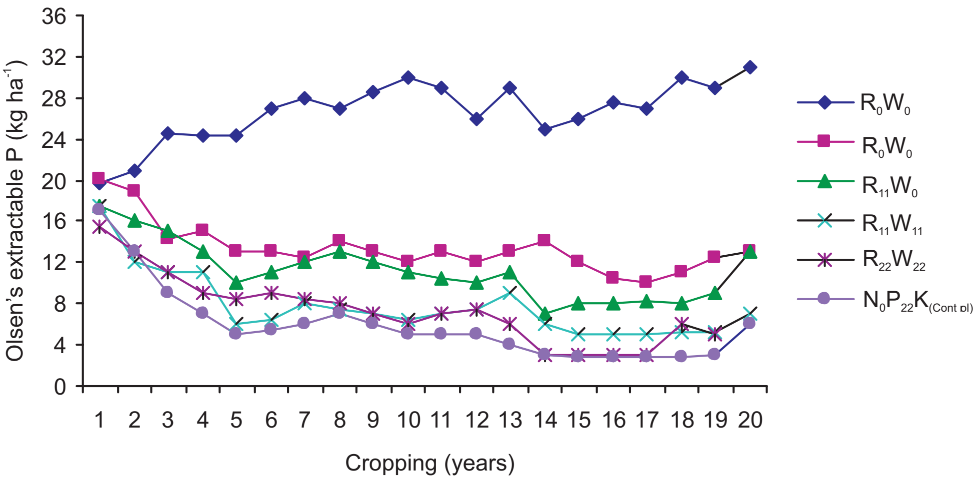

Figure 3. Changes in Olsen's extractable phosphorus (P) of surface soil (0–15 cm) of a gypsum-amended alkali soil as affected by differential P fertilization to rice (R) crop (W=wheat).

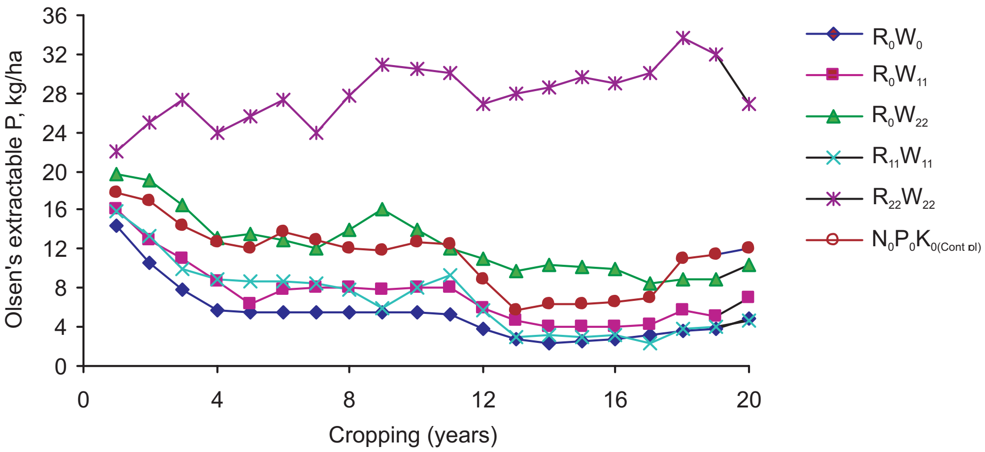

Figure 4. Changes in Olsen's extractable phosphorus (P) of surface soil (0–15 cm) of a gypsum-amended alkali soil as affected by differential P fertilization to wheat (W) crop (R=rice).

Table 4. Effect of phosphorus (P) fertilization on the available P status of the soil in the rice-wheat cropping system over a period of 20 years from 1976 to 1996.

Treatment[1]	P-added (kg ha^{-1})	P-removed (kg ha^{-1})	P-balance (kg ha^{-1})	Olsen's availble P (kg ha^{-1})	
				Initial	After 20 years
R_0W_0	Nil	512.65	–512.65	18.2	4.5
$R_{11}W_0$	220	645.88	–425.88	18.0	8.0
$R_{22}W_0$	440	742.84	–302.84	16.8	15.4
R_0W_{11}	220	615.97	–395.97	19.2	6.9
R_0W_{22}	440	706.69	–266.69	18.2	10.8
$R_{11}W_{11}$	440	741.32	–301.32	19.2	12.0
$R_{22}W_{22}$	880	812.91	+ 67.09	19.4	28.0
Control (no P)	Nil	238.46	–238.46	16.6	5.1
LSD at P=0.05	–	–	–	NS[2]	0.89

1. Application of P (kg ha^{-1}) to rice (R) and wheat (W).
2. NS=not significant.

amount added to it resulting in a negative balance. The soil available P content after 20 years was also directly affected by the amount of P added to the soil. These results showed that 22 kg of P ha^{-1} to both the crops is required to sustain soil fertility. However, to sustain crop production, application of 22 kg P ha^{-1} to either crop is enough as the soil available P status in these treatments is sustained above the critical limit (10 kg ha^{-1}).

Soil pH and ESP and relationship with P availability

Initially, the pH of 0–15 cm soil in the experimental field was 10.3 which decreased to 9.25 as a result of gypsum application and subsequently to 8.5 as a result of rice-wheat cropping for 2 years. No further drop in pH was observed even after 20 years of cropping. This was mainly due to $CaCO_3$ present in the soil which gave a buffering effect to the soil properties. However, the $CaCO_3$ content of the surface 0–15 cm soil decreased from 2.30% to 1.36% indicating the dissolution of native $CaCO_3$ due to the biological action of the roots. No significant differences in the $CaCO_3$ content of the soil were observed due to differential P application.

Beneficial effect of rice-wheat cultivation in reducing soil sodicity and pH was observed not only on the surface but also on the lower layers of the alkali soil. While the initial ESP of the whole profile was more than 80, it came down to less than 20 after 15 years of rice-wheat cropping. Hence, this crop rotation is not only ideal for alkali soils but also it enhances the reclamation process considerably.

Conclusion

It was concluded that alkali soils contain high amounts of extractable P and due to high pH or ESP have low P absorption capacity. Hence, farmers undertaking reclamation of alkali soils and practicing rice-wheat crop rotation can economize on fertilizer P by skipping its application in the initial 3 to 5 years without any loss in yield. Because of application of amendments and raising of wetland rice, there is decrease in extractable P in the surface soil.

Therefore, application of 11 kg P ha^{-1} to rice crop but not to wheat crop, which can mine the available P from the lower layers, is recommended for sustaining rice-wheat yield. However, to sustain crop production and to maintain soil fertility, farmers should apply 22 kg P ha^{-1} to both rice and wheat crops when the surface soil P level falls below 7.5 kg P ha^{-1}, a situation which is arrived at after 3–5 years of rice-wheat cropping. There is increase in P removal with increase in level of P application. Phosphorus budget computation showed that a positive balance can be achieved only when 22 kg P ha^{-1} is applied to both the crops. Because of continuous improvement in soil chemical properties under rice-wheat crop rotation, its adoption should be encouraged together with judicious nutrient management to maintain soil health and sustain crop production.

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