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RESEARCH EXPERIENCES TOWARDS 4R STEWARDSHIP-BASED PHOSPHORUS FERTILIZATION IN RICE - A REVIEW

K Surekha*, V Manasa, R Gobinath, S Vijayakumar, Brajendra and Thaiseen Tabasum
ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad-500030

ABSTRACT

Plant growth is highly dependent on the timely and throughout season availability of essential nutrients. Next to nitrogen, phosphorus (P) is a very important essential element required in large quantities for normal plant growth and development. Need based nutrient application approach by following 4R nutrient stewardship (right rate, right time, right place, right source) will ensure higher yield, nutrient uptake, nutrient use efficiency, and increase the farm income without causing much damage to the environment. Though usage of phosphorus in rice is quite high, 4R stewardship based research on this nutrient is very scarce; though scattered research on different aspects of P application is available. Hence, an attempt was made in this paper to compile and consolidate most of the available research results from the Indian Institute of Rice Research (IIRR) and also by other researchers on various aspects of P fertilisation in rice.

Keywords: Phosphorus, 4R stewardship, Use efficiency

Rice, the most important staple cereal food crop for more than half of the global population occupies about 44 M ha in India, ranking first in the area and second in production after China in the world. In India, rice production has increased near six-fold from about 20.58 million tonnes during 1950-51 to more than 122.27 million tonnes in 2020-21 and this increase in rice production is attributed to the development of fertilizer responsive high yielding rice varieties and to nearly 50% contribution made by fertilizers per se in tapping the high yield potential of varietal technology (Vijayakumar *et al*., 2019). There has been a phenomenal increase in the consumption of fertilizer nitrogen (N), phosphorus (P) and potassium (K) over the years from mere 69,800 tonnes in 1950-51 to the level of 32.54 million tonnes in 2020-21. Rice is grown in almost all types of soils in more than 20 states of India and its average productivity ranges from the highest 4132 kg/ha in the state of Punjab, to the lowest 1810 kg/ha in Chhattisgarh (Directorate of Economics and Statistics, 2021). The increased fertiliser use has played a crucial role in increasing the production and productivity of a large number of crops in the country including rice. But, more than the increased fertiliser use, indiscriminate and imbalanced use of fertilisers resulted in a gradual decrease in the productivity of the soil over the years. Thus balanced fertilizer use is a pre-requisite for sustainable rice production along with improvement of soil quality (Dass *et al*., 2017).

Efficient nutrient management is crucial to achieve maximum nutrient use efficiency, minimal waste of applied nutrients, increased yield, and environmental safety. In this direction, many international organizations are promoting "4R Nutrient Stewardship" (the concept of using the right fertilizer source, at the right rate, at the right time, with the right placement) as the best management practices that help the farmers in improving the economic, social, and environmental performance of their nutrient applications (Vijayakumar *et al*., 2021). This is an innovative and science based approach that enhances environmental protection, expands production, increases farmer profitability and improves sustainability.

4Rs ---- $\boxed{\text{Right Source}}$ + $\boxed{\text{Right Rate}}$ + $\boxed{\text{Right Time}}$ + $\boxed{\text{Right Place}}$

Albeit our research had not aimed exactly to suit the principles of 4R approach, the research work carried out to improve the P use efficiency for achieving higher productivity in rice that coincides with some guidelines of 4R stewardship carried out in IIRR and other centres including All India Coordinated Rice Improvement Project are presented here. Most of the research work in these areas was done for four decades from1980s to the 2020s to improve phosphorus use efficiency. But, these results hold good even today under most situations with slight modifications in the source materials/dose/time/method to suit the local conditions. For rice crop, from the practical management point of view, nitrogen, phosphorus, potassium and zinc are most important. 4R nitrogen and potassium management guidelines for rice were widely studied and documented by many researchers (Bijay Singh *et al.*, 2002; Surekha *et al*. 2016; Surekha et al., 2021: Vijayakumar *et al*., 2021a) and 4R management guidelines for phosphorus is

*Corresponding author : surekhakuchi@gmail.com
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discussed here.

Next to nitrogen, phosphorus (P) is an important major nutrient as it promotes root development, tillering, early flowering and ripening, especially, where the temperature is low (Jinger *et al.*, 2022). It is important in the early growth stage and the addition of P fertilisers is necessary when the rice plant's root system is not fully developed and the native soil P supply is small (Jinger *et al*., 2020). Response of rice crop to P is important only next to N, as applications of both N and P become necessary to get optimum returns. Generally, the recovery of fertiliser P by the current/standing crop is about 15% and hence 85% of applied P remains in the soil for the succeeding crop (Bandeppa *et al*., 2022). The variation in the availability of soil P under rotation of irrigated rice with irrigated dry/upland crops can influence not only direct effects but also the residual influence of P fertiliser. The requirement of phosphorus to rice is not as high as that of nitrogen but deciding its dose, time and method of application are very much crucial for an increased response towards applied phosphorus. The important factors that influence P use efficiency such as right source, rate, time and method of application are discussed here.

Right source of P

The relative efficiency of different sources of P largely depends on soil pH. Generally, water-soluble sources are good for neutral soils while difficultly soluble/insoluble sources like rock phosphate (RP) are suitable for acidic soils (Utomo, 1995; Ditta *et al*., 2018). Basal application of DAP was significantly superior to SSP at Bhubaneswar and Raipur (neutral soils), while at Faizabad, SSP containing 12% gypsum was significantly superior to DAP (DRR, 1981-85). Studies at CRRI during 1973-75 have shown that application of RP to acid soils three weeks before flooding to moist soil rendered RP as good as SSP. In neutral or alkali soils, there is no acidity to perform this conversion but the simultaneous addition of acid-forming materials like pyrites (FeS_2) may bring about such change. Thus, this method opens the way for use of RP in neutral and alkali soils also. Mahapatra and Sahu (1961) on the basis of a 3 years study at Bhubaneswar (Odisha), reported that bone meal, rock phosphate and hyper phosphate were as good as single superphosphate on a slightly acidic sandy loam and that a level of 23 kg P/ha was optimum for the long duration tall indica rice. A judicious combination of soluble source of P combined with Mussoorie rock phosphate (MRP) can give better performance, than conventional source of P-alone, in several cropping systems (Bayan *et al*., 2000).

In Soil Science co-ordinated trials conducted at four locations, RP mixed with pyrite (10:5 w/w ratio) was as effective as SSP (AICRIP, 1976-80). Basal application of RP alone in acid soils of Titabar was similar to that of SSP, however, application of half the dose of P_2O_5 as basal through RP followed by rest top dressed through SSP at tillering stage gave the highest yield (4.2 t/ha) which was significantly superior to SSP (DRR, 1981-85). Ammonium polyphosphates (APP) are another class of complex fertilisers with high use efficiency as they contain orthophosphate for immediate availability to the plant as well as condensed phosphate which undergo hydrolysis in a stepwise breakdown, releasing orthophosphates gradually for subsequent plant uptake. Further, slow hydrolysis permits polyphosphate to sequester from soil cations like Al, Fe, and Ca, thus minimising P fixation. In Soil Science co-ordinated trials, the application of APP was superior to DAP at Raipur, Bhuvaneswar and Patna, (DRR, 1987). In Bhubaneswar and Chiplima, ammonium polyphosphate has shown good promise in acidic soils. Studies conducted at acidic soils of Jorhat in the rice-rice cropping system showed that rock phosphate (RP) and a combination of SSP and RP in 1:2 ratios are as good as water-soluble sources like SSP and DAP. In neutral soil at Bhavanisagar, all the water-

Table 1. Relative efficiency of phosphate source for rice

Phosphorus nutrient carriers	Transplanted rice grain yield (q/ha)	Direct seeded rice grain yield (q/ha)
1. Triple super phosphate (TSP)	62.3	62.1
2. Di ammonium phosphate (DAP)	65.0	59.6
3. Di calcium phosphate (DCP)	57.8	56.9
4. Nitro phosphate (23% WSP)	57.3	-
5. Nitro phosphate (30% WSP)	57.3	59.3
6. Nitro phosphate (36.7% WSP)	60.9	-
7. Nitro phosphate (53.7% WSP)	64.0	60.7
8. Nitro phosphate (75.8% WSP)	62.2	59.8
CD (5%)	5.2	4.9

Source: Rajendra Prasad *et al*. (1980).

Table 2. Yield attributes and yield of rice as influenced by P sources

P sources	Effective tillers/ m^2	Filled grains / panicle	1000 grain weight (g)	Grain Yield (kg/ha)	Harvest index
Superphosphate	326	102	20.0	4307	0.40
Ammonium polyphosphate	363	119	20.8	4839	0.42
CD (5%)	23	2.9	NS	275	0.01

Source: Rama Rao *et al.* (1992)

soluble P sources were equally effective. Application of phosphorus to rice through rock phosphates singly or in combination with lime proved beneficial for increasing rice yield on oxisol (Prakash *et al*., 1994). In an experiment conducted at IARI New Delhi on alluvial soil having a pH of 7.8, it was found that fertilizers with medium to high WSP (DAP and Nitro phosphate 53.7% WSP) were superior to nitro phosphate containing 23 to 30% WSP, Di calcium phosphate (DCP) and Rock phosphate (Rajendra prasad *et al*., 1980). In later studies with direct seeded rice no significant differences were observed between triple super phosphate, di Calcium Phosphate, Tri ammonium phosphate (TAP), Ammonium Poly Phosphate and nitro phosphate (Table 1).

Rao *et al*. (1992) concluded from a comparative study that APP was superior to SSP for lowland rice as SSP application resulted in a higher yield over APP. The favourable effects of APP were attributed to greater availability of P on account of less fixation, slow hydrolysis and direct absorption (Table 2). The favorable effects might also be due to some specific effect of polyphosphate on plant metabolism and possibly to a micro-element nutrition resulting from chelating properties of phosphate.

Sarkar *et al*. (2018) evaluated the effect of single super phosphate and rock phosphate on the growth & yield of rice and found that soil applied with 50% SSP + 50% RP shows significantly higher dry matter and grain yield followed by 25% SSP + 75% RP and 100% SSP. Grain yield, straw yield, biological yield, and harvest index all have increased significantly with the application of 90 kg P_2O_5/ha per year, and it was on par with 60 kg/ha P_2O_5 (Dinesh *et al*., 2018). Recycling crop residue with 50 percent recommended dose of P fertiliser was found to be optimal for rice and lentil in a non-flooded system (Hazre *et al*., 2021). The $NaHCO_3$-Pi, DNRPs & Olsen-P were strengthened due to the use of single fertilizer-P treatment, these was essentially credited to enhanced labile C pool, soil aggregation and microbial biomass carbon.

Integrated use of organics and inorganics

Organic manures are known to partially insulate applied P fertilisers against fixation or reversion to unavailable forms in the soil at least for some time. Mixing of SSP with fresh cow/buffalo dung (at the rate of 50% by weight of SSP) showed promising results in acid soils of Patna, Titabar and Mandya but not in saline soils of Faizabad and Raipur (AICRIP, 1976-80). Rice stubble incorporation combined with the application of RP to supply 50 kg P_2O_5 per ha resulted in the good establishment and higher yields of the second rice crop at Aduthurai (Palaniappan and Balasubramanyan, 1995). Lekha and Palaniappan (1990) showed that green manuring and SSP application gave significantly higher direct and residual effects in rice-rice-green gram system at Coimbatore. SSP applied with organic matter had a higher direct effect while RP with organic manure gave higher residual grain yields (Karuppiah and Thangamuthu, 1987). Chonkkar (1994) showed that certain strains of VAM (*Glomus agarocarpum*) increased rice yields significantly over check in a high P- fixing Vertisol (Raipur) and the combined use of PSB and VAM did not result in any additional yield indicating that both these microorganisms convert the same insoluble P sources of the soil. Yadav *et al*. (2015) reported a significant increase in grain yield and harvest index of aerobic rice with integrated use of rock phosphate and phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) compared to the sole application of RP or DAP (Fig 1). Whereas, among the sole sources, DAP was superior to RP in terms of grain yield and benefit-cost ratio.

Based on 3 years field experiment in New Delhi Sharma *et al*. (2009) reported that the grain yield of rice increased significantly when the rate of P application increased from 0 to 35 kg P/ha either as DAP or Mussoorie rock phosphate (MRP) during 2001 and 2002, whereas during 2003 DAP at 17.5 kg P/ha also significantly increased the yield over control. Further increase in the rate of DAP from 17.5 to 35 kg P/ha in 2003 and of MRP from 35 to 52.5 kg P/ha during all the 3 years did not result in any yield improvement. Incorporation of crop residue had no significant effect on the grain yield but increased the efficiency of MRP. At 35 kg P/ha, DAP and MRP were on par and significantly increased the net returns over the control by 23 and 26% respectively. Further increase in the rate of MRP from 35 to 52.5 kg P/ha did not give additional increase in the net returns of rice. Residue incorporation reduced the net returns

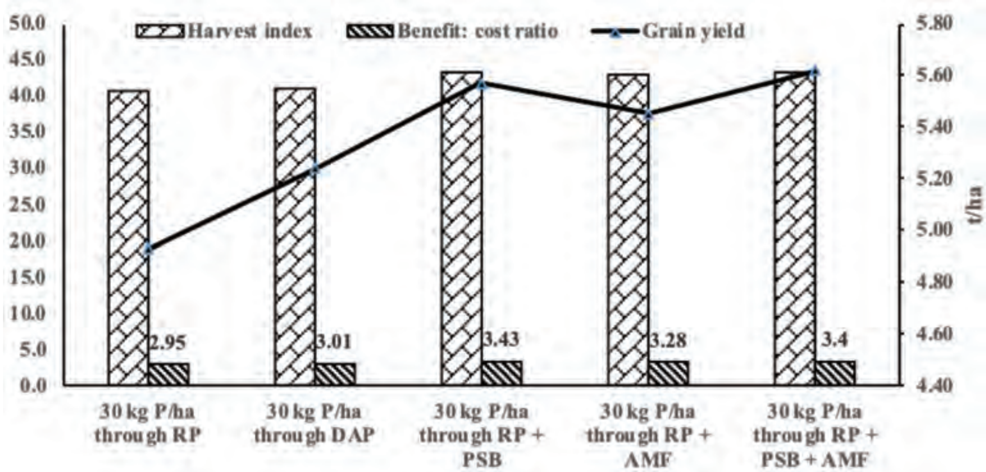

Fig. 1. Effect of rate and sources of P on grain yield and harvest index of aerobic rice Source: Yadav *et al*. (2015).

of rice by 8.3%. Arunakumari *et al*. (2018) conducted a field experiment with 4 sources of phosphorus and 3 levels of phosphorus and reported that application of a lower dose of phosphorus (50% RDP) along with green manure or PSB found at par with that of grain yield obtained at 150% RDP through SSP during both the years of study (Table 3). Inorganic phosphorus source through SSP applied at 50% RDP level found significantly inferior to other levels in increasing net returns per rupee invested. However, when 50% RDP was applied along with green manuring + PSB or green manuring alone or PSB alone gave significantly higher returns per rupee invested than 100% and 150% RDP application at the same level of phosphorus source.

Hazre *et al*. (2021) reported that integrated treatment involving suboptimal fertilizer-P rate (22 kg P ha^{-1} y^{-1}), rice residue recycling, and PSB increased soil P availability in rice (5-6%) and lentil (9-10%) as well as system productivity by 8.3% over the recommended sole fertilizer-P treatment.

Right rate of P

Paddy soils with low to medium in available P, the response of rice to P-fertilization is variable and location-specific. Response to P application is highly erratic due to direct and indirect influences of several factors operating in the soil system on P availability to the plants (Bayan and Lourduraj, 2000). A rice variety with profuse rooting will have the advantage for better uptake of applied phosphatic fertilizer (Mishra, 1991). A significant response to the applied P in terraced upland rice was observed at Ranchi where 40 kg ha^{-1}

Table 3. Effect of sources and levels of phosphorus on rice yield and net returns

Source of phosphorus applied to rice	Grain yield (kg ha^{-1})				Net return (Rs. ha^{-1})			
	Levels of Phosphorus applied to rice (two year pooled data)							
	50% RDP	100% RDP	150% RDP	Mean	50% RDP	100% RDP	150% RDP	Mean
M1- Inorganic phosphorus	3840	4953	5485	4759	26724	37942	43547	36071
M2- Green manuring	6031	6038	6054	6041	60463	54583	52002	55683
M3- Soil application of PSB	5617	5618	5631	5622	53950	47926	45113	48996
M4- Green manuring + PSB	6169	6210	6237	6206	61943	56642	54122	57569
Mean	5414	5705	5852		50770	49273	48696	
	SE m±	CD (5%)	CV (%)		SE m±	CD (5%)	CV (%)	
Source of P (M)	108.4	375	5.7		1610	5572	9.7	
Levels of P (S)	134.2	NS	4.1		1053	NS	7.4	
Interaction								
M*S	235.5	706			2107	6319		
S*M	214.9	769			2356	7574		

Source: Arunakumari *et al*. (2018)

Table 4. **Yield attributes and yield of rice as influenced by levels of phosphorus**

Treatment	Effective tillers/ m^2	Filled grains / panicle	1000 grain weight (g)	Grain Yield (kg/ ha)	Harvest index
Levels of P (kg P_2O_5/ha)					
40	321.0	94.0	20.2	4310	0.40
80	368.0	128.0	21.2	4836	0.42
CD (5%)	23	2.9	0.6	275	0.01

Source: Ramarao *et al*. (1992).

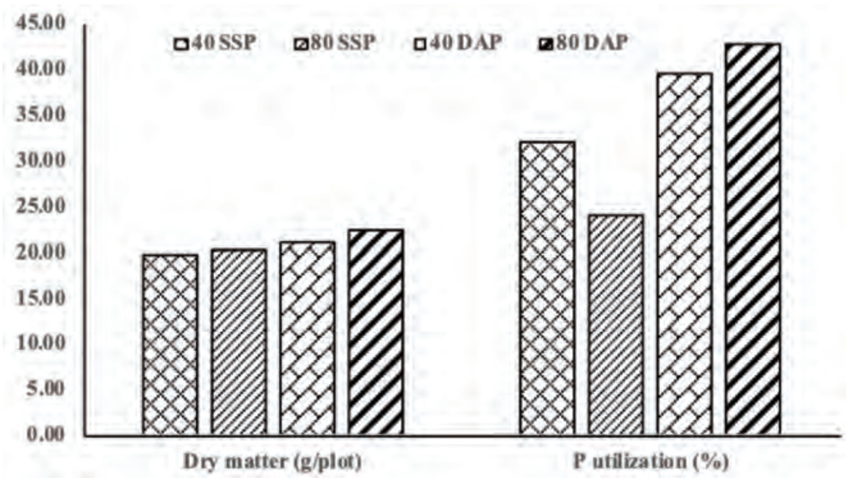

Fig. 2. Effect of P sources and rate on P utilization. (Source: Raju and Kamath (1983)

of P_2O_5 (Mahapatra and Srivastava, 1983) was applied. At Hazaribagh (available P in soil was 30 ppm), the response to applied P was 15 kg P_2O_5 ha^{-1} (DRR, 1994 and 1995). Meelu *et al.* (1992) summarised the results of several experiments in north western India and concluded that rice generally responded up to 30 kg P_2O_5/ha in normal soils while in acidic soils response to P application was observed up to 60 kg P_2O_5/ha. In typic haplustalf (pH 8.1) soils, P applied at 100 per cent recommended dose (38 kg P_2O_5 ha^{-1}) recorded maximum grain and straw yield of rice (Annadurai and Palaniappan, 1994). Panda and Patnaik (1995) indicated that the response of rice in Orissa to applied P_2O_5 ranged from 3-15, 2-7, 4-9 and 4-7 kg grain/kg P_2O_5 at 30, 50, 60, and 100 kg P_2O_5/ha, respectively, indicating a ceiling of 60 kg/ha. In another study on the effect of different levels of phosphorus (0 to 67 kg/ha) applied as broadcast or pellets to black clayey alkali soils observed that level of 50 kg/ha was superior to all other doses (Rao *et al*., 1962). Ramarao *et al*. (1992) reported grain yield increase up to 80 kg P_2O_5/ha in a sandy clay loam soil (Table 4).

Raju and Kamath (1983) reported no significant difference in dry matter yield between 40 and 80 kg P_2O_5/ha either by SSP or DAP while P utilization was more in DAP (Fig. 2.)

Meena *et al*. (2014) reported that the addition of 100% RDP to rice crop at par with 75% RDP but both were significantly superior over 50% RDP and control treatment and integration of moderate phosphorus level (75% RDP i.e. 45 kg ha^{-1}) along with the use of PSB + BGA + FYM (5 t ha^{-1}) proved most remunerative for HUR-105 variety under eastern Uttar Pradesh. Archana *et al*. (2017) conducted a field experiment on a sandy loam soil during *Kharif* 2015 to study the effect of levels of phosphorus (100, 75 and 50% farmers dose and 100, 75 and 50% RDP) and time of application (Farmer practice of split application and basal application) on rice. The crop has given good response to application of 100% farmers dose of P (6.43 t/ha) and it remained at par with the application of 100% RDP (6.41 t/ha), 75% farmers dose (6.42 t/ha) and 75% RDP (6.11 t/ha) (Table 5).

Right time of P application

The most widely recommended practice for P is to apply basally (incorporation during puddling). Delayed application of P is normally associated with reduction in yield. Split application of phosphorus may be useful in cases where initial supply of the nutrient is sufficient to meet the early requirements of the crops. Rice showed a marked response to P application at planting or at tiller initiation whereas delaying of P application up to panicle initiation stage could not meet the requirement of rice (Bharadwaj *et al.,* 1974). However, Goswami

Table 5. Effect of levels of phosphorous and time of application on grain yield (t ha^{-1})

Fertilizer Phosphorus Levels (t ha^{-1})	Time of P Application		Mean
	T1: Split	T2: Basal	
100% Farmer dose (85 kg P_2O_5 ha^{-1})	6.43	6.39	6.41
75% of Farmer dose (63 kg P_2O_5 ha^{-1})	6.42	6.32	6.37
50% of Farmer dose (42 kg P_2O_5 ha^{-1})	6.11	6.06	6.08
100% RDP (60 kg P_2O_5 ha^{-1})	6.41	6.35	6.38
75% RDP (45 kg P_2O_5 ha^{-1})	6.37	6.31	6.34
50% RDP (30 kg P_2O_5 ha^{-1})	5.85	5.81	5.83
	S.Ed$\pm$	CD (0.05)	
Phosphorus levels (P)	0.08	0.17	
Time of P Application (T)	0.05	NS	
PXT	0.11	NS	

Source: Archana *et al*. (2017). No. of Splits: 50% Basal + 50% at Early Tillering Stage

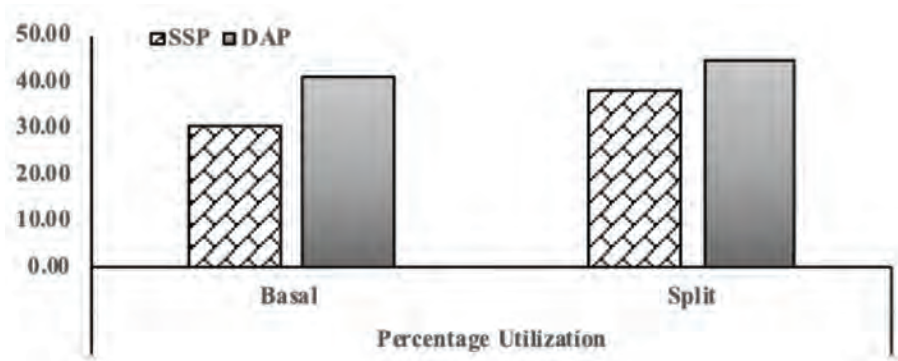

Fig. 3. Utilization of P by rice as affected by method of application. (Source: Goswami and Kamat ,1984).

and Kamat (1984) reported that split application at 60 kg P_2O_5/ha as diammonium phosphate (DAP)/single super phosphate (SSP) gave higher utilisation of fertiliser P in rice as compared to basal application (Fig 3).

In high P fixing soils (Titabar), 30 days delay in application of SSP significantly improved grain yield ranging from 0.5 –1.0 t/ha due to less fixation and better utilisation of applied phosphorus (AICRIP, 1976-80). Regardless of the P-sources used, application of 60 kg P_2O_5 in two equal splits, 50 per cent at transplanting and 50 per cent at tillering, was effective in increasing rice yields at Aduthurai [pH 6.8 and medium in available soil P) (Budhar *et al*., 1992). Split application of phosphorus @ 60 kg P_2O_5 as diammonium phosphate resulted in higher P utilization (Goswami and Kamath, 1984). Annadurai and Palaniappan (1994) observed that application of P at recommended dose (38 kg ha-1) basally and DAP spray (2%) thrice at boot leaf stage, 50 per cent flowering and post milk stages gave the highest yield in wet season (*Kharif*) rice. *Kharif* rice can make better use of residual P because of its increased availability due to higher temperature and submergence of the soils (Dev and Sanders, 1988). In soils that respond to P, fertilizer application should be made not later than the mid tiller growth stage or shortly after flooding for most efficient use of fertilizer P (Slaton *et al*., 1998). Chennabasappa *et al.* (1998) reported that split application of phosphorus failed to bring significant difference in grain yield when compared to basal application at the time of transplanting (Table 6). The lack of response to split applied P was attributed to the fact that the root development requires higher P availability which is possible only when sufficient quantity is available at the time of transplanting.

Kumar *et al.* (2016) reported that between SSP and DAP as phosphatic fertilizer sources, SSP was found superior over DAP with respect to yield and yield attributes of transplanted rice and phosphorus use efficiency. Further, split application of SSP as 45 kg basal + 15 kg P_2O_5 ha^{-1} at tillering was observed superior over rest of the methods (Table 7).

Archana *et al*. (2017) reported that P uptake by the grain was significantly higher in split application than the treatment receiving basal P, although this had no significant influence on the increase in grain yield of rice.

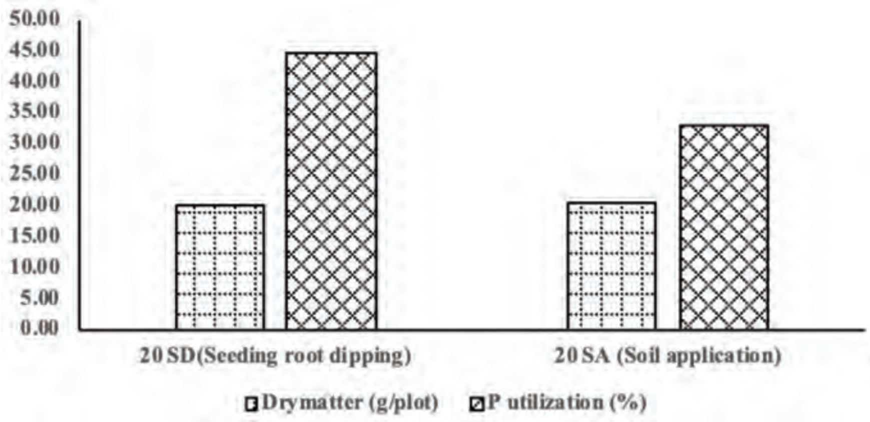

Fig. 4. Effect of different method of P application on P utilisation [Source: Raju and Kamat (1983)]

Table 6. Grain yield of paddy as influenced by split application of phosphorus

Treatment	*Kharif* (93-94)	*Rabi* (93-94)	*Kharif* (94-95)
100% basal	50.8	60.0	53.3
50% basal + 50% at 25 DAT	56.4	59.5	51.2
50% basal + 25% at 25 DAT + 25% at 50 DAT	56.9	60.7	50.8
CD (5%)	NS	NS	NS

Source: Chennabasappa *et al*. (1998)

Right method of P application

The efficiency of P fertiliser is also influenced by the method of its application. Ghosh and Datta (1970) reported that contrary to upland conditions broadcast application of P in rice was found superior. Ghosh *et al*. (1977) reported that for rice, surface application or broadcast and mixing it by puddling was best as it resulted in greater P availability. Application of P in the seed furrow just before seeding of rice was found to be better for upland rice than its broadcasting followed by incorporation into the soil (Mishra, 1999). It has been established by ^{32}P- labeled fertilizer application that surface broadcasting or incorporation of fertilizer before transplanting is more effective than other methods such as deep placement of P at 10 or 20 cm depth either in planting hills or between rows (Sanyal and De Datta, 1991). Deep placement of water soluble N, P and K fertilizers can be agronomically more efficient as compared with their conventional methods of application in rice (Savant *et al*., 1993). Katyal (1978) reported that use of 16 kg P_2O_5/ha, through SSP slurry was as effective as 60 kg P_2O_5/ha in soil as the latter

Table 7. Effect of sources and methods of P application on yield attributes of rice

Treatment	No. of panicle (m^{-2})	grains / panicle (m^{-2})	Grain yield (q ha^{-1})	Production efficiency (kg ha^{-1} day^{-1})
Control	356	75.5	24.1	22.3
60 kg P_2O_5 ha^{-1} basal through DAP	481	85.4	35.1	32.5
45 kg basal + 15 P_2O_5 kg ha^{-1} at tillering through DAP	528	87.2	42.5	39.3
30 kg basal + 15 kg P_2O_5 ha^{-1} tillering + 15 kg P_2O_5 ha^{-1} at PI through DAP	510	83.5	38.5	35.6
60 kg P_2O_5 ha^{-1} basal through SSP	502	84.0	37.7	34.9
45 kg basal + 15 kg at tillering ha^{-1} P_2O_5 through SSP	548	90.5	46.6	43.1
30 kg basal + 15 kg P_2O_5 ha^{-1} at tillering + 15 kg P_2O_5 ha^{-1} at PI through SSP	528	82.0	43.2	40.0
CD (P=0.05)	38.5	11.5	4.18	3.87

Source: Kumar *et al*. (2016)

Table 7. Effect of methods of P application on growth, yield and P uptake of rice

P management method	Root Volume (ml hill^{-1})	Grain yield (t ha^{-1})	Increase in grain yield over control (%)	P uptake in grain (kg ha^{-1})	P uptake in Straw (kg ha^{-1})
Control (no P input)	75.2±4.5a	1.57±0.05a	-	1.30±0.03a	3.37±0.09ab
RP Broadcast	77.0±2.0a	1.70±0.04b	8.3	1.65±0.05b	3.07±0.16a
SSP Broadcast	107.0±5.5bc	2.40±0.06de	52.9	2.74±0.05d	4.98±0.14d
PSB	84.9±3.2ab	1.76±0.04ab	12.1	1.99±0.09c	3.56±0.04b
PSB+RP	91.6±3.5ab	2.08±0.05c	32.5	2.13±0.03c	4.12±0.08c
SSP Soil slurry	127.5±7.8cd	2.32±0.03d	47.8	2.05±0.05c	4.35±0.05c
SSP Soil slurry+ PSB+RP	134.3±8.6d	2.44±0.03e	55.4	2.90±0.08c	5.58±0.08e

Values are means± standard errors. Within a column, values followed by different letters indicate statistically significant difference at P ≤ 0.05. [Source: Kalidas and Thakuria (2018)].

practice is highly conducive for P-fixation. Raju and Kamat (1983) demonstrated that dipping of roots in DAP slurry also contributed more fertiliser P uptake than the soil application of P at the same level (Fig 4).

Rice seedlings root dipping in SSP slurry appeared much effective in increasing the grain yield and P-uptake by crop (Singh *et al*., 1994) and to mitigate Fe-toxicity and P-deficiency in rice during *Kharif* season. Kalidas and Thakuria. (2018) found that rhizosphere-based P method (Seedling root dip in soil slurry + phosphate solubilizing bacteria, PSB + rock phosphate, RP 30 kg P_2O_5 ha^{-1}) performed better than SSP broadcast as basal application (60 kg P_2O_5 ha^{-1}) in terms of grain yield, P uptake and phosphorus use and recovery efficiency (Table 7).

Conclusion

The review highlights the large potential for rice productivity improvement through 4R nutrient stewardship of phosphorus which helps in achieving future production goals with reduced input cost. The use of the right source of phosphorus, applied at right rate, in the right time, and at the right place demonstrated significant yield improvement of rice along with improving P use efficiency. The reduction in fixation and erosion losses as a result of practicing 4R principles of P management could contribute to improving the environmental performance of P use. Although this article covers only the 4R guidelines of P management in rice, a cumulative 4R approach for all the essential nutrients of rice may be followed in ensuring sustainable rice production.

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