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Response of Transplanted Rice to Seedling Root-dip in Phosphorus and Biofertilizer Slurry in Acid Soils of North East India- A Participatory Assessment in Farmers' Field

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ABSTRACT

Background: Rice production is mainly constrained by low P-use efficiency (PUE) and P-recovery efficiency (PRE) in acid soils of the North East hill region of India. Efficient P fertilizer management strategies for rice production is very essential to achieve higher yield per unit of P fertilizer applied. Rhizosphere-based P management in wetland rice is considered as an efficient strategy to minimize the quantity of applied P to obtain a profitable yield.

Methods: Seedling root dipping in P slurry technique in farmers' field condition was studied in comparison to the conventional methods of application of recommended dose of fertilizer (RDF) and the integrated nutrient management (INM) practices to identify a suitable cost effective method of application of phosphatic fertilizer for the acid soils of this hill region of North East India.

Result: The highest plant height, maximum number of effective tillers and root biomass were recorded in SSP root dip+Phosphate Solubilizing Bacteria (PSB) followed by INM practices. P root dip had greater root biomass (4.36 g plant^{-1}) which was significantly higher than RDF (3.82 g plant^{-1}). Root dip application showed higher yields (5.80 t ha^{-1}), compared with INM (5.53 t ha^{-1}) and RDF (5.46 t ha^{-1}) and control (4.25 t ha^{-1}). The result of the present study demonstrated that P-dipping can achieve high applied P use efficiency (1193.42) in transplanted rice compared to conventional incorporation of P (625.43). Thus, P-dipping is a potential strategy to overcome low applied P use efficiency in high P-fixing soils and hence reduces the need for excess P application.

Key words: Acid soils, Phosphorus use efficiency, P-root dip, Rice.

INTRODUCTION

Phosphorus deficiency is one of the major limiting factors for rice production in many parts of the world (Saito *et al*., 2019; Tanaka *et al*., 2015; Vandamme *et al*., 2016). Farmers sometimes apply excess amounts of P to achieve higher production. The world resources of P are finite and therefore, P should be used as efficiently as possible in order to conserve the base resources (FAO, 2017). Efficient P fertilizer management is also key to improving rice yield for smallholder farmers who use little amount of fertilizers. Therefore, it is necessary to develop appropriate strategies for the effective use of P fertilizers in rice production systems. Rice production is mainly constrained by low P-use efficiency (PUE) and P-recovery efficiency(PRE) in acid soils (Fageria *et al*., 2015), because a considerable part of P added to acid soils is fixed as insoluble phosphates of Al^{+3} and Fe^{+2} (Bhattacharyya *et al*., 2015; Redel *et al*., 2016). In the anticipated phosphate crisis by 2050 (Gilbert, 2009), the strategies for P management in agriculture must focus on minimization of quantity of applied-P (Richardson *et al*., 2009), possibly recycling (Ashley *et al*., 2011) and rhizosphere-based P management (Martínez *et al*., 2015).

Several studies have demonstrated significant effects of nursery P and P-dipping to increase rice yields and agronomic P use efficiency (AE_P) as the yield gain per unit of P applied. Excess yield gains with a micro-dosing nursery P may have a risk of P mining from soils. The P-dipping retains the P input-output balance and achieves a consistently high AE_P at 74-152 kg kg^{-1} (Rakotoson *et al*., 2022). Dipping seedling roots into P-enriched slurry just before transplanting (P-dipping) is reported to improve P fertilizer use efficiency in transplanted lowland rice production systems. The P-dipping technique with the slurry attached to seedling roots, assures the P supply after

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transplanting and avoids the P-mining risk (Oo *et al*., 2020a). Various studies on P dipping technology reported significant yield increases by 10-50% with 40-60% reductions in P application rates relative to broadcasting or incorporating P at transplanting (Raju *et al*., 1980; Ramanathan and Kothandaraman, 1984; Balasubramanian *et al*., 1995; De Datta *et al*., 1990).

Application method of P fertilizer is of paramount importance as it can minimize P fixation by soils and thereby increase P efficiency. So, there is a need to develop P application method, which can support better root development and architecture at the early stage of crop growth for exploration of more soil volume and thereby enhancing more nutrient uptake (Kalidas and Thakuria, 2018). Dipping of rice roots in single superphosphate (SSP)-soil slurry just before transplanting can save P-fertilizer up to 40-60% of the recommended P dose applied in conventional practice and increases PUE and PRE (Ru-kun *et al*., 1982; Hooper, 1991; Balasubramanian *et al*., 1995; Talukdar *et al*., 2001). In addition to the P slurry, application of Phosphate Solublizing Bacterial (PSB) biofertilizer may further enhance the PUE in acid soils.

P deficiency in the north east hill region of India is related to the highly weathered soils which are low in bioavailable P contents and high in P-sorption capacity because of soil acidity and high content of Fe and Al oxides (Batjes, 2011; Bekunda *et al*., 2010; Nishigaki *et al*., 2019). Available P content in surface soils of the hill region of Assam is reported to be very low to medium (0.2 to 1760 ppm), but in sub-surface soils it is very low *i.e*. 0.2 to 15.6 ppm (Chakravarty and Baruah, 1987). Inadequate P application due to limited purchasing capacity of the small and marginal farmers of the region is another key issue associated with P deficiency in rice. Under such soil and capital constraints, it is imperative to find effective P fertilizer management practices for rice production that will achieve higher yield per unit of P fertilizer applied. For this goal, field experiments in actual farmers field condition is essential to assess the efficacy, acceptability, yield advantage as well as economic benefits of the applied P fertilizers.

The objective of the experiment was to study the effect of the P-dipping technique in rice in farmers' field condition in comparison to P incorporation and INM and to identify a suitable cost effective method of application of phosphatic fertilizer in rice for the acid soils of the hill region of North East India.

MATERIALS AND METHODS

A participatory field trial was conducted by Krishi Vigyan Kendra, Karbi Anglong during the year 2020 and 2021 in farmers' field of Karbi Anglong district (25°32′N to 26°36′N latitudes and 92°10′E to 93°50′E longitude) under hill zone of Assam which falls in the Eastern Himalayan region of India. The experiments were conducted at representative fields in the region where farmers continuously cultivated rice once a year without crop rotation and with little or no mineral fertilizer inputs prior to the start of the experiments.

The composite soil samples from experimental rice fields were analyzed before and after the experiment for physico-chemical properties (Table 1).

Three different management options of phosphorus were tested in comparison to the farmers existing practice as control in four villages as replications. The management options were application of recommended dose of fertilizers (RDF) for the region (N:P_2O_5: K_2O @ 60:20:40 kg ha^{-1}) (T_1), root dipping in P slurry and microbial consortia (T_2), INM package recommended by Assam Agricultural University (T_3) and farmers existing practice as control (T_4).

For the treatment T_1, entire P (as SSP) and K fertilizer was applied as basal and half of N was applied as basal and remaining half was applied in two splits at maximum tillering and panicle initiation stage. For the root dipping method (T_2), mud slurry bed was prepared in one corner of the main field and SSP (@ 7.0 kg/ha was mixed thoroughly with mud. Roots of uprooted rice seedlings after washing were dipped in the SSP amended mud slurry for over-night (10 hours). The SSP slurry treated roots of rice seedlings were again dipped in biofertilizer amended mud slurry and incubated for 2 hours. After this treatment, seedlings were transplanted with 50 % RDF. INM treatment (T_3) consisted of application of organic manure @ 1tha^{-1} (on dry weight basis) along with mixed inoculum of *Azospirillum amazonense* A-10 and*Bacillus megaterium* P-5 @ 4 kgha^{-1}, rock phosphate @ 10 kg P_2O_5 per ha and muriate of potash (MOP) @ 40 kg K_2O per ha. Rock phosphate component was used along with the biofertilizer as slurry to treat the seedling roots.

Ten hills per plot were marked for recording plant height, number of tillers and root weight. At maturity, grain and straw yields (t ha^{-1}) were determined by harvesting plants from an area of 4 m^2 in the center of each plot. The number of hills per harvested area was recorded for conversion of grain and straw yield per hectare basis. Grain yield is expressed

Table 1: Initial soil properties of the experimental site.

Soil properties	Minimum	Maximum	Mean
pH (1:2.5)	4.9	5.3	5.10
Soil organic carbon (%)	0.56	0.78	0.76
Available N (kg ha^{-1})	172.6	283.4	204.52
Available P_2O_5 (kg ha^{-1})	6.26	17.7	9.24
Available K_2O (kg ha^{-1})	112.30	178.6	132.16

based on filled grain weight, corrected to 14% moisture content by using a grain moisture sensor. The straw yield was expressed on dry matter basis by oven-drying at 70°C for more than 72 h. Grain and straw were separated for each of 10 marked plants at harvest and subjected to nutrient content analysis. For nutrient content analysis, plant samples were sun-dried and washed with 0.01N HCl followed 4 rinses with distilled water. Finally, the cleaned straw and grain were oven-dried at 65°C to a constant weight. The oven dried grain and straw samples were ground in a Willey Mill for analysis of tissue P concentration and uptake.

Harvest index (HI) was calculated as the ratio of grain yield and biological yield multiplied by 100. Uptake of P in biomass (Straw and grain) was determined by multiplying P content (%) with their corresponding yield data. P use efficiency (PUE) and P recovery efficiency (PRE) were calculated by the following equations:

$$\text{PUE} = \frac{\text{Total grain yield (kg ha}^{-1}\text{)}}{\text{Fertilizer applied (kg ha}^{-1}\text{)}}$$

$$\text{PRE} = \frac{\text{Total uptake from fertilized plot (kg ha}^{-1}\text{) - Total uptake from control plot (kg ha}^{-1}\text{)}}{\text{Fertilizer applied (kg ha}^{-1}\text{)}}$$

All statistical analyses were performed using SPSS v. 12.0 (SPSS Inc. Chicago, IL, USA). Data were subjected to analysis of variance (ANOVA) and means significantly different were separated using Duncan's Multiple Range Test (DMRT) (Duncan, 1955).

RESULTS AND DISCUSSION

Growth and yield parameters

Different methods of P application in transplanted rice crop significantly influenced the growth and yield parameters (Table 2). The highest plant height, maximum number of effective tillers and root biomass were recorded in SSP root dip+PSB followed by INM practices. P root dip had significantly greater root biomass (4.36 g plant^{-1}) which was significantly higher than RDF (3.82 g plant^{-1}).

SSP root dip+PSB facilitated higher P uptake during root-dipping just before transplantation, which helped in development of more vigorous root system during early establishment of plant in the main field (Kalidas and Thakuria, 2018). Higher P uptake at the initial stage of crop growth provides an early advantage in root development (Chatterjee and Khan, 2005). Similar to the present result He *et.al.* (2003) reported changes in root morphology and architecture indicated by increased total root length, root fineness and relative root allocation in the high-phosphorus layers, suggesting altered root morphology and preferential root proliferation in the high-phosphorus regions.

The rice seedlings when incubated overnight in SSP amended soil-water slurry before transplanting results maximum possible P uptake which help them in development of robust root system at the early stage of crop growth (Talukdar *et al.,* 2001). Thus, robust root system can explore more soil volume and can uptake more P which is immobile by nature in soil (Arruda *et al*., 2016). This result is consistent with previous observations which observed that P-dipping produced greater shoot biomass (Rakotoson *et al*., 2022) and root biomass (Kalidas and Thakuria, 2018) from a very early growth stage after transplanting and eventually resulted in greater rice yields than those in conventional P application via broadcasting. Higher availability of soil P had direct positive influence on effective tiller numbers (Alam *et al*., 2009).

Grain and straw yields were significantly higher in all P treated plots compared to that in no P input control plots ($P<0.05$, Table 2). The highest grain yield achieved was in SSP-root-dip + PSB plot which was significantly higher than other options of P applications. Highest grain and straw yield of 5.80 and 7.82 t ha^{-1} was recorded with root dip. However, straw yield was comparable with the INM. Similar to our result, Talukdar *et al*. (2001) reported that rice seedlings dipped overnight in SSP amended soil-water slurry just before transplantation recorded grain yield of 2.84 t ha^{-1}, while basal recommended dose of SSP recorded 2.46 tha^{-1} in an acidic alluvium soil of Brahmaputra valley. Balasubramanian *et al*. (1995) reported 13% higher grain yield of rice in SSP-root dip method over that in SSP basal application as broadcast @ 26 kg P_2O_5 ha^{-1}.

Dipping seedling roots in P-enriched slurry transfer a considerable amount of P to the main field in the form of slurry attached to seedling roots at transplanting. The P thus transferred along with the root creates a P hotspot near the root zone which enhances root development and growth and facilitates the P uptake by rice plants even under highly P fixing soils (Oo *et al*., 2020b). Thus, the significantly higher root weight in both the P dipping treatments (T_2 and T_3) may be attributed to the better P availability in the root zone. The

Table 2: Growth and yield of rice (variety: Ranjit) as influenced by phosphorus management methods (pooled over two years).

Treatment	Plant height (cm)	No. of effective tillers	Root weight (g)	Grains per panicle (No.)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
RDF	104±0.12[a]	9.2±0.32[a]	3.82±0.68[a]	136±1.13[a]	5.46±0.14[a]	7.63±0.06[a]	41.71±0.02[a]
INM	104±0.19[a]	9.8±0.28[ab]	4.12±0.76[b]	142±1.02[ab]	5.53±0.17[a]	7.74±0.07[b]	41.67±0.02[a]
Root dip	106±0.22[a]	10.3±0.22[b]	4.36±0.57[b]	148±0.97[b]	5.80±0.08[b]	7.82±0.05[b]	42.58±0.04[b]
Control (FP)	92±0.14[b]	8.5±0.35[c]	3.43±0.85[c]	124±0.92[c]	4.25±0.11[c]	6.92±0.06[c]	38.05±0.05[c]

Values are means±standard errors. Within a column, values followed by different letters indicate statistically significant difference at $P\leq0.05$, based on DMRT.

Table 3: Economics of different phosphorus management methods in rice.

Treatment	Gross cost (Rs.)	Gross return (Rs.)	B:C ratio
RDF	44000	98280	2.23
INM	45200	99540	2.20
Root dip	42750	104400	2.44
Control (FP)	41000	76500	1.86

Table 4: Phosphorus content and uptake in grain and straw of rice crop (variety: Ranjit), Phosphorus use efficiency and P recovery efficiency as influenced by phosphorus management methods (pooled over two years).

Treatment	Soil avail. P at harvest (kg ha^{-1})	P content grain (%)	P content straw (%)	Total P uptake (grain +straw) (kg ha^{-1})	PUE	PRE
RDF	9.48±1.02^{a}	0.231±0.57^{a}	0.082±1.02^{ab}	18.87±0.46^{a}	625.43±1.02^{a}	0.794±0.54^{a}
INM	8.52±0.87^{ab}	0.224±0.76^{a}	0.071±0.96^{a}	17.87±0.38^{a}	1265.44±0.76^{b}	1.366±0.63^{b}
Root dip	8.03±0.94^{b}	0.284±0.86^{b}	0.096±0.84^{b}	23.98±0.42^{b}	1193.42±1.13^{b}	2.48±0.47^{c}
Control (FP)	7.47±1.10^{c}	0.193±0.97^{c}	0.054±0.92^{c}	11.94±0.64^{c}	-	-

Values are means ± standard errors. Within a column, values followed by different letters indicate statistically significant difference at $P \leq 0.05$, based on DMRT.

better root growth might have helped the plants to explore more moisture and nutrients resulting enhanced growth and yield of the crop. The relationship between crop yield and root biomass is often demonstrated to be significant and almost invariably linear (Li *et al.,* 2009).

Grain yield was significantly increased by the root dip method (Table 2). Root dip application showed significantly higher yields (5.80 t ha^{-1}), compared with INM (5.53 t ha^{-1}) and RDF (5.46 t ha^{-1}). The average increase in the grain yield by Root dip, INM and RDF was 36.47%, 30.11% and 28.47%, respectively, compared to the control treatment. Similar to the present result, significant increase in shoot biomass, tiller number and photosynthetic efficiency due to P application, resulting in improved grain yield has been reported in many previous studies (Fageria *et al*., 2013; Andrianary *et al*., 2021). The highest benefit: cost ratio (Table 3) was observed in root dip method (2.44) followed by RDF (2.23), INM (2.20) and lowest was recorded in farmers practice (1.86). Although, higher yield was obtained in INM over RDF but high cost of organic inputs in INM package increased the cost of cultivation which resulted lower B:C ratio. The highest B:C ratio in root dip method was attributed to higher yield as well as reduction of cost of cultivation due to reduced use of chemical fertilizers.

P uptake and P efficiency indices

The P uptake was significantly higher in the root dip treatment (Table 4) and it was increased by 27.08% and 34.19% over RDF and INM, respectively. Highest P uptake in root dip method (23.98 kg ha^{-1}) was significantly higher as revealed from DMRT than RDF (18.57 kg ha^{-1}) and INM (17.87 kg ha^{-1}). However, no significant difference in uptake was observed between RDF and INM. A localized supply of phosphorus affects root morphology and root system architecture and thereby affect phosphorus uptake by rice plants (He *et al.,* 2003). Larger root systems enable plants to access a greater volume of soil and to acquire more nutrients from various depths. Enhanced root growth could have enabled these plants to avail themselves of otherwise-unavailable subsoil P that could not be accessed by plants grown with conventional methods of P application (Barison and Uphof, 2011). The result of the present study (Table 4) demonstrated that P-dipping can achieve high applied P use efficiency (1193.42) in transplanted rice compared to conventional incorporation of P (625.43). Thus, P-dipping is a potential strategy to overcome low applied P use efficiency in high P-fixing soils and hence reduce the need for excess P application. PRE is linked with the crop P uptake efficiency and it was higher in root dip (2.480) compared to INM (1.366) and conventional incorporation of P (0.794) probably as a result of increased P uptake by the crop mediated through better root growth and availability of applied as well as native soil P.

CONCLUSION

P-root dipping method of P application was found to be resource-efficient fertilizer management practices compared to P broadcasting in improving growth, grain yields and applied P use efficiencies on P-deficient lowlands in the hill zone of Assam with high P fixing soils. This new method of P application is a practical approach which will overcome the low P use efficiency in lowland rice production and help farmers for maximizing the return with higher B:C ratio. Besides, this method is affordable for smallholder farmers in the hill region of Assam, as they have little financial capacity to purchase commercial fertilizers.

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Conflict of interest

The author declares that they have no conflicts of interest.

REFERENCES

Alam M.M., Ali, M.H., Amin, A.K.M.R. and Hasanuzzaman, M. (2009). Yield attributes, yield and harvest index of tree irrigated rice varieties under different levels of phosphorus. Advanced Biological Research. 3: 132-139.

Arruda, B., Rodrigues, M., Soltangheisi, A., Richardson, A.E., Andreote, F.D. and Pavinato, P.S. (2016). Biological and morphological traits of sugarcane roots in relation to phosphorus uptake. Journal of Soil Science and Plant Nutrition. 16: 901-915.

Ashley, K., Cordell, D. and Mavinic, D. (2011). A brief history of phosphorus: from the philosopher's stone to nutrient recovery and reuse. Chemosphere. 84: 737-746.

Balasubramanian, V., Rabeson, R., Razafinjara, L. and Ratsimandresy, J. (1995). Rice soil constraints and fertility management in the highlands of Madagascar. In: Proceedings of the Conference on Fragile Lives in Fragile Ecosystems. International Rice Research Institute, Los Baños, Philippines. Pp: 313-324.

Barison, J. and Uphof, N. (2011). Rice yield and its relation to root growth and nutrient-use efficiency under SRI and conventional cultivation: An evaluation in Madagascar. Paddy Water Environ. 9: 65-78.

Batjes, N.H. (2011). Global distribution of soil phosphorus retention potential. Wageningen, ISRIC - World Soil Information (with dataset). ISRIC Report. 6: 42.

Bekunda, M., Sanginga, N. and Woomer, P.L. (2010). Restoring Soil Fertility in Sub-Sahara Africa. Advances in Agronomy. 108: 183-236.

Bhattacharyya, P., Nayak, A.K., Shahid, M., Tripathi, R., Mohanty, S., Kumar, A., Raja, R., Panda, B.B., Lal, B., Gautam, P. and Swain, C.K. (2015). Effects of 42-year long-term fertilizer management on soil phosphorus availability, fractionation, adsorption-desorption isotherm and plant uptake in flooded tropical rice. The Crop Journal. 3(5): 387-395.

Chakravarty, D.N. and Baruah, J.P. (1987). Phosphorus status of the hill soils of Assam, India. Indian Journal of Agricultural Chemistry. 20(2): 131-140.

Chatterjee, A.K. and Khan, S.K. (2005). Evaluation of phosphate rocks compacted with different soluble phosphate and sulphur in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) and rice-rapeseed (*Brassica compenstris var yellow sarson*) crop sequences in Alfisol. Indian Journal of Agricultural Sciences. 758: 493-495.

De Datta, S.K., Biswas, T.K. and Charoen chamratcheep, C. (1990). Phosphorus requirements and management for lowland rice. In: Proceedings of the Symposium on Phosphorus requirements for sustainable agriculture in Asia and Oceania. International Rice Research Institute, Manila, Philippines. Pp: 307-324.

Duncan, D.B. (1955). Multiple range and multiple F tests. Biometrics. 11: 1-42. doi: 10.2307/3001478.

Fageria, N.K., Santos, A.B. and Carvalho, M.C.S. (2015). Agronomic evaluation of phosphorus sources applied to upland and lowland rice. Communications in Soil Science and Plant Analysis. 46(9): 1097-1111.

FAO (2017). Improving the efficiency of soil and fertilizer phosphorus use in agriculture. Fertilizer and Plant Nutrition Bulletin. Pp: 45-52.

Gilbert, N. (2009). Environment: The disappearing nutrient. Nature. 461: 716-718.

He, Y., Liao, H. and Yan, X. (2003). Localized supply of phosphorus induces root morphological and architectural changes of rice in split and stratified soil cultures. Plant and Soil. 248: 247-256. https://doi.org/10.1023/A:1022351203545.

Hooper, J.R. (1991). Progress of Research in Madagascar: Toward Identifying 75 low Input Technological Improvements by 1995. In: Paper presented at the Rice Research Seminar, 4 Apr. 1991. IRRI, Manila, Philippines.

Kalidas-Singh, S. and Thakuria, D. (2018). Seedling root-dip in phosphorus and biofertilizer added soil slurry method of nutrient management for transplanted rice in acid soil. Journal of Soil Science and Plant Nutrition. 18(4): 921-938.

Li, S., Wang, Z., Malhi, S.S., Li, S., Gao, Y., Tian, X. (2009). Nutrient and Water Management Effects on Crop Production and Nutrient and Water Use Efficiency in Dryland Areas of China. Adv. Agron. 102: 223-265.

Martínez, O.A., Crowley, D.E., Mora, M.L. and Jorquera, M.A. (2015). Short-term study shows that phytate-mineralizing rhizobacteria inoculation affects the biomass, phosphorus (P) uptake and rhizosphere properties of cereal plants. Journal of Soil Science and Plant Nutrition 15(1): 153-166.

Nishigaki, T., Tsujimoto, Y., Rinasoa, S., Rakotoson, T., Andriamananjara, A. and Razafimbelo, T. (2019). Phosphorus uptake of rice plants is affected by phosphorus forms and physicochemical properties of tropical weathered soils. Plant Soil. 435: 27-38.

Oo, A.Z., Tsujimoto, Y. and Rakotoarisoa, N.M. (2020a). Optimizing the phosphorus concentration and duration of seedling dipping in soil slurry for accelerating the initial growth of transplanted rice. Agronomy. 10(2): 240.

Oo, A.Z., Tsujimoto, Y., Rakotoarisoa, N.M., Kawamura, K. and Nishigaki, T. (2020 b). P-dipping of rice seedlings increases applied P use efficiency in high P-fixing soils. Science Reports. 10: 11919.

Raju, A.S., Murali Mohan Rao, G.V., Sathe, A. and Subba Rao, I.V. (1980). Root dipping: A technique to supply P to low land rice. Journal of Nuclear Agriculture and Biology. 9(4): 141-143.

Rakotoson, T., Tsujimoto, Y. and Nishigaki, T. (2022). Phosphorus management strategies to increase lowland rice yields in sub-Saharan Africa: A review. Field Crops Research. 275(1): 108370.

Ramanathan, P. and Kothandaraman, G.V. (1984). Application methods to improve phosphorus uptake in rice. International Rice Research Newsletter. Soil and Crop Management. 9: 21.

Redel, Y., Cartes, P., Demanet, R., Velásquez, G., Poblete-Grant, P., Bol, R. and Mora, M.L. (2016). Assessment of phosphorus status influenced by Al and Fe compounds in volcanic grassland soils. Journal of Soil Science and Plant Nutrition. 16: 490-506.

Richardson, A.E., Hocking, P.J., Simpson, R.J. and George, T.S. (2009). Plant mechanisms to optimize access to soil phosphorus. Crop and Pasture Science. 60: 124-143.

Ru-kun, L., Bai-fan, J. and Ching-Kwei, L. (1982). Phosphorus management for submerged rice soils. Institute of Soil Science, Academia Sinica, Nanjing, China. pp: 11.

Saito, K., Vandamme, E., Johnson, J., Tanaka, A., Senthilkumar, K., *et al*. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. Geoderma. 338: 546-554.

Talukdar, N.C., Thakuria, D., Bordoloi, L. and Goswami, C. (2001). Half a Decade Research on Utilization of Soil Biological Agents as Components of Nutrient Management for Quality and Resilience of Agro and Forest Ecosystem. In: Three Decades of Research in Biofertilizers and Organic Farming in Northeast India. [Yadav, A.K., Roychoudhury, S. (eds)] Jointly Published by Assam Agricultural University, Jorhat, Assam and Regional Biofertilizer Development Centre, Imphal, Manipur. pp: 7-33.

Tanaka, A., Diagne, M. and Saito, K. (2015). Causes of yield stagnation in irrigated lowland rice systems in the Senegal River Valley: Application of dichotomous decision tree analysis. Field Crops Research. 176: 99-107.

Vandamme, E., Wissuwa, M., Rose, T., Ahouanton, K. and Saito, K. (2016). Strategic phosphorus (P) application to the nursery bed increases seedling growth and yield of transplanted rice at low P supply. Field Crops Research. 186: 10-17.