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REVIEW
Potential Utilization of Local Phosphate Rocks to Enhance Rice Production in Sub-Saharan Africa

Satoshi NAKAMURA, Monrawee FUKUDA, Fujio NAGUMO and Satoshi TOBITA*

Crop, Livestock & Environment Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki 305-8686, Japan)

Abstract

It is known that phosphate rock (PR) deposits that account for most world's PR production are found in African countries. However, the rate of phosphorus (P) fertilizer use in Africa is typically low, despite the high requirement for application of the same there. This applies particularly to sub-Saharan Africa (SSA), where P deficiency has been suggested as one of the key constraints to crop production, despite the many PR deposits. There have been many excellent reviews on PR utilization in SSA, but hardly any have focused on its effectiveness in lowland rice cultivation. Given this lack of information, we reviewed the potential of PRs produced in the SSA region, focusing particularly on the utilization of PRs for rice cultivation in this region. Our review indicates that PR direct application in lowland rice resulted in high performance, regardless of the PR reactivity and the location investigated. A Phosphate Rock Decision Support System can help disseminate information on PR utilization in SSA; however, there is room for further improvement in predicting agronomic efficiencies in lowland rice cultivation, with consideration of the unique changes in soil condition such as the reduced condition that occurs in submerged paddy soils. In conclusion, the local PRs produced in SSA can be effectively utilized for direct application on lowland rice cultivation, hence the need to elucidate the PRs solubilization mechanism and therefore clarify the condition that maximizes the effect of local PRs direct application in SSA.

Discipline: Soils, fertilizers, and plant nutrition
Additional key words: lowland rice, phosphate rock direct application, PRDSS

Introduction

Many reports have been issued warning of a phosphorus (P) reserve crisis[3,19,44,46]. Previously, Emigh (1972) also reported that phosphate could be depleted by the end of the 21st century[19]. Using reserve estimates, and based on a prediction of reasonable phosphate consumption, Steen (1998) simulated that world phosphate reserves would be exhausted within a century or so[44]. Recently, Van Vuuren et al. (2010) suggested that almost half the currently available P resources will be depleted by 2100[50]. To cope with P depletion, various approaches for the efficient utilization of P have been conducted, such as P recycling from human waste and/or sewage[39,40], the release of accumulated P in soil[6], the breeding of low P-tolerant crops[38,58], and the excavation of undeveloped phosphate rocks (PR). Among these approaches, PR excavation is the only new source of P entering the food production chain[46]. PR is rock that contains phosphate minerals, usually apatite, which can be commercially exploited, either directly during or after processing, to meet industrial and agricultural demands.

It is known that the PR deposits that account for most world's PR production are in African countries[7,20]. However, in sub-Saharan Africa (SSA), P deficiencies have been suggested as one of the key constraints in crop production, despite the many PR deposits[47,49]. The rate of P-fertilizer use in Africa is also typically low, despite the high requirement for its application[34]. The average annual P loss from African soil is reportedly in the order of 0.6 million tons, whereas annual P-fertilizer consumption is only approximately 0.26 million tons[7].

Previous studies have emphasized the potential use of unutilized PR resources[7,8,16,34] and suggested various constraints as to why local PR deposits have been under-utilized in agricultural production in SSA[7]. Although these include

*Corresponding author: e-mail bita1mon@jircas.affrc.go.jp
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economic and mineralogic difficulties, the major issue seems to be uncertainty of the agricultural effectiveness of the direct application of PRs in SSA because the direct application of PRs is affordable and an acceptable technology for local farmers. The effectiveness of the direct applications of PRs depends on the following factors: (1) mineralogic composition of PR, (2) soil physicochemical properties, and (3) the cultivated crop. Regarding the chemical composition, PRs produced in SSA are generally inadequate for direct use on agricultural land due to their low solubility[48].

Many studies have reported well-documented information on PR dissolution and the agronomic effectiveness of PRs on various upland crops, such as rape[14], maize[51], millet[5], and upland rice[8]. These studies have also reported that PR application proves inefficient in some cases due to diverse factors affecting agronomic efficiency, including its solubility[14] and/or soil conditions[15].

However, the effects of PR on lowland rice (*Oryza sativa* L.) cultivation are less well known. Several attempts to determine the effectiveness of local PRs on lowland rice have been conducted in Asian countries[17,27,32,33,43,56,60] and in SSA[42,52]. These investigations have reported the high effectiveness of PR application on lowland rice production, which is comparable to water-soluble chemical P fertilizers. Accordingly, these reports suggest that PR application has the potential to be effectively utilized for the lowland rice cultivation system.

Rice demand has been soaring in SSA in recent years[54], and many countries are spending large amounts of valuable foreign currency to import it. The Coalition for African Rice Development (CARD), launched in 2008, is a Japanese initiative aiming to double annual rice production in SSA from 14 to 28 million tons within a decade. If local PRs were adequately managed, application of these PRs would help enhance rice cultivation in SSA.

Although many excellent review articles exist concerning the agricultural utilization of local PRs[7,20], they do not discuss the effectiveness of lowland rice production in depth. Therefore, this paper reviews the benefits and constraints of local PRs produced in SSA, focusing particularly on their use for lowland rice cultivation, as follows: 1) the problems of PRs in SSA, 2) treatment for solubilizing PRs, 3) comparing the effect of PRs between upland crops and lowland rice, 4) prediction of the PR direct-application effect on lowland rice cultivation, and discusses their potential for agricultural use in the lowland rice systems of SSA.

Bottlenecks in the usage of local low-grade PRs in SSA

Although the African continent accounts for over 70% of the world's known PR deposits (Figure 1), PRs produced

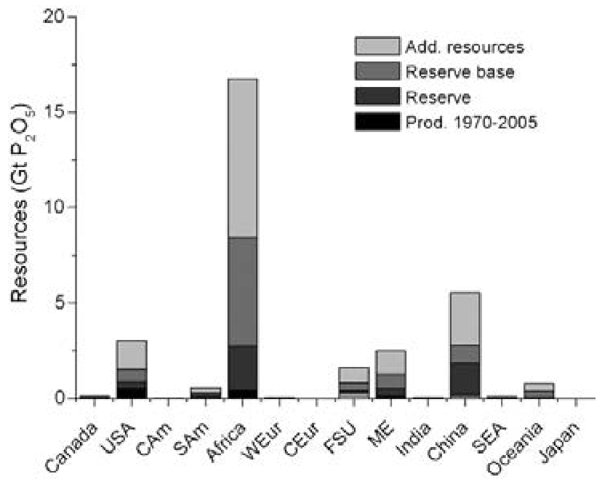

Fig. 1. Available phosphorus (P) resources per region (medium assumption)

Source: Van Vuuren et al. (2010)

Reserve; the minable resources based on current economical extraction. Reserve base; the resources extractable in future, assuming new extractive technology development or rising production costs. Add. Resources; additional resources usually referred to as inferred reserve base, undiscovered resources and unconventional occurrences.

USA, United States of America; CAm, Central America; SAm, South America; WEur, Western Europe; CEur, Central Europe; FSU, Former Soviet Union; ME, Middle East; SEA, Southeast Asia

there are utilized in only a few countries in the region. Moreover, it is known that approximately 80% of the soils in tropical Africa lack sufficient available P[34].

The utilization of PR resources is constrained by a complex range of interrelated commercial, technical, environmental, and sociopolitical factors that determine the economic potential of individual PR deposits[7,49].

In SSA in particular, various scales of PR deposits are known to exist (Table 1). However, the quality of the produced PRs is often insufficient for industrial and/or direct agricultural use[7]. As shown in Table 1, the P_2O_5 content in PRs varies from 4.5 to 33.0%, mainly due to the mineralogical-genetic processes, such as those in sedimentary and igneous rocks. Moreover, some of the undeveloped PRs in SSA contain high concentrations of elemental impurities, such as iron, aluminum, silica, and carbonates, which may make the industrial processes difficult and expensive to manufacture fertilizer of the required quality. In addition, environmental aspects, such as the contents of harmful elements, particularly cadmium and uranium, are among the greatest concerns[7].

Appleton (2002) has suggested that the difficulty of handling PRs is also a major constraint in local PR utilization. Most local PRs are well grounded to have better solu-

Table 1. Measured phosphate rock (PR) resources in sub-Saharan Africa

Country	Deposit	Resources Mt PR	Average $\%P_2O_5$	Resources Mt P_2O_5
Angola	Quindonacaxa	200.0	22.5	45.0
	Cabinda	16.0	23.0	3.7
Benin	Mekrou	5.0	23.5	1.2
Burkina Faso	Kodjari	80.0	27.5	22.0
	Diapaga	224.0	15.0	33.6
	Arly	4.0	29.0	1.2
Burundi	Matongo-Bandaga	25.0	11.0	2.8
Congo	Holle	15.0	23.0	3.5
	Sintou-Kola	0.3	21.0	0.1
Guinea Bissau	Farim	112.0	30.0	33.6
Liberia	Bomi Hill, Bambuta	1.0	32.0	0.3
Malawi	Tundulu	0.8	20.0	0.2
Mali	Tamaguelet	20.0	24.0	4.8
Mauritania	Near Matam (Senegal)	1.0	26.5	0.3
	Ornolde	4.0	26.5	1.1
	Bofal & Loubboira	94.0	19.5	18.3
Mozambique	Evate, Monapa	155.5	9.0	14.0
	Muande, Tete	83.0	5.0	4.2
Niger	Tahoua	100.0	26.0	26.0
	Tapoa	1,250.0	23.0	287.5
Nigeria	Abeokuta	1.0	27.0	0.3
Senegal	Matam	40.0	29.0	11.6
	Taiba	100.0	24.0	24.0
	Lam Lam	4.0	33.0	1.3
	Pallo, Thies Plateau	90.0	28.0	25.2
South Africa	Palabora	13,000.0	6.8	884.0
	Genover	3.0	33.0	1.0
	Bandolier Kop	0.1	18.0	0.0
	Schiel	36.0	5.0	1.8
	Varswater (Langebaan)	37.5	10.0	3.8
	Sandheuwel, Cape Province	23.6	6.0	1.4
	Paternoster, Cape Province	10.0	5.0	0.5
	Duyker Eiland, Cape Province	3.6	9.5	0.3
	Constable Hill, Cape Province	0.3	27.5	0.1
	Mamre, Cape Province	0.1	24.0	0.0
Tanzania	Minjingu	10.0	20.0	2.0
	Panda Hill (Mbeya)	125.0	6.0	7.5
	Morogoro	2.0	6.5	0.1
Togo	Hahotoe-Kpogame	100.0	30.0	30.0
Uganda	Sukulu	230.0	12.0	27.6
	Bukusu, Busumbu	150.0	9.0	13.5
Zaire	Lueshe Valley	30.0	7.0	2.1
Zambia	Chilembwe	1.6	12.0	0.2
	Mumbwa North	0.6	5.0	0.0
	Nkombwa	200.0	4.5	9.0
	Kaluwe	6.6	5.1	0.3
Zimbabwe	Dorowa	73.0	6.6	4.8
	Shawa	20.0	10.8	2.7
SSA Total		16,688.6		1,558.3

Mt, Million tons Source, Appleton (2002), Table 1, partly modified bility, whereas farmers in Mali have not accepted local PRs because they were dusty and easily scattered when applied to their land[7]. However, our recent surveys in northern Ghana revealed that most farmers were willing to use the fine-powdered Burkina Faso PR (BPR)[25]. That investigation was conducted to show the potential for the use of BPR to cultivate Ghanaian rice. Bationo and Mokwunye (1991) classified BPR as a low-reactive PR[10] according to Diamond's classification[18]; similar to most other PRs in SSA. The results showed that 100% of investigated Ghanaian farmers accepted PR utilization (Table 2), even though the BPR exhibited dusty characteristics. However, the accessibility and affordability of BPR was 0% in three communities because ground PRs are not generally marketed in Ghana. However, the accessibility and affordability of water-soluble P-fertilizer are also very low, suggesting few differences in the difficulties of local PR utilization compared to those with water-soluble P fertilizer. The main problems with regard to enhancing PR utilization for agricultural use were accessibility and affordability.

In addition, these PRs are normally inadequate for direct application (without processing) in agricultural use[48] due to their inherent low solubility. Many studies showed that the PRs produced in SSA have low solubility. Truong et al. (1978) compared the solubility of several varieties of PRs and concluded that most PRs produced in SSA are unsuitable for direct application[48]. In addition, Bationo & Mokwunye (1991) reported that the reactivities of PRs in West Africa are low, except some PRs with medium reactivity[10]. They suggested that only the medium-reactive PRs were suitable for direct application. This low solubility of the PRs might be one reason why PRs in SSA are currently under-utilized there.

Enhancement of the solubility of PRs

Biological treatment to enhance the solubility of PRs

Various ways to enhance the availability of PRs have been developed, including biological, chemical, and physical procedures[20]. As a biological PR-solubilizing technology, composting has been well tested and is expected to enhance the dissolution of low-reactive PRs[11] by promoting the dissolution of PRs by the heat and organic acids produced during microbial growth. In recent studies, particular phosphate-solubilizing microorganisms, such as *Tricoderma viride*[61] and *Aspergillus niger*[25], have been specifically inoculated for use in PR-enriched compost.

A number of studies have been conducted on the use of organic acids secreted from plant roots, including citric[22,23], malic[22], and piscidic[59] acids. These can be expected to form complex cations of PRs, as well as lowering rhizosphere soil pH. Further, there are also P-solubilizing soil microbes[57], such as bacteria, including *Bacillus* spp. and *Pseudomonas* spp., and fungi, including *Actinnomycetes* spp., *Penicillium* spp., and *Aspergillus* spp.[37], that promote PR dissolution in soil.

The incorporation of organic matter, such as legume biomass, has also been shown to enhance the rate of P release from Nigerian PR[4], which is probably due to the addition of organic acids by the organic matter itself and soil microbes. Wickramatilake et al. (2010) showed that the

Table 2. Distribution (%) of accessibility, affordability, and acceptability of two types of phosphorus sources in three rice farmer communities of northern Ghana

	Nabogu		Gbrimah		Fuu		All comunities	
	Yes	No	Yes	No	Yes	No	Yes	No
					Accessibility†			
Water soluble P ferttilizer	10	90	20	80	5	95	11.7	88.3
Phosphate Rock	0	100	0	100	0	100	0.0	100.0
					Affordability†			
Water soluble P ferttilizer	20	80	25	75	10	90	18.3	81.7
Phosphate Rock	0	100	0	100	0	100	0.0	100.0
					Acceptability†			
Water soluble P ferttilizer	100	0	100	0	100	0	100.0	0.0
Phosphate Rock	100	0	100	0	100	0	100.0	0.0

Source: JIRCAS (2010)

Investigation was conducted for 30 households for each community.
†; distribution of farmers considering the material is accessible, affordable, or acceptable, "Yes" means the material is accessible, affordable, or acceptable, respectively.

P uptake from low-grade Chinese PR by African Millet (*Eleusine coracana* Gaertn) is enhanced by poultry and cattle manure compost and that it is strongly related to microbial biomass P and the population density of P-solubilizing bacteria[57]. Moreover, the addition of sulfur to PRs, which promotes the dissolution of PR due to the sulfuric acid that is produced by *Thiobacillus* spp. in soil, has been tested in Australia[45]. These products have been commercialized as Biosuper[36,45].

Physicochemical treatments to enhance the solubility of PRs

The most popular chemical methods used to convert PRs into chemically reactive and/or soluble fertilizers are chemical acidulations with sulfuric or phosphoric acid. In addition, the partial acidulation of PR (PAPR) has been introduced to produce a composite of acidulated water-soluble phosphate and unacidulated sparingly soluble PR. This method is cost-effective because it requires less sulfuric or phosphoric acid for the acidulation and boosts effectiveness as a fertilizer[9]. The International Fertilizer Development Center (IFDC; Muscle Shoals, AL, USA) has accordingly advocated the use of PAPR in developing countries, including SSA. Unlike the full acidulation process, PAPR can even be used to treat low-grade PRs that contain higher levels of impurities[13], such as silica, aluminum, and iron.

Physical methods include the fine grinding of PRs and mixtures of water-soluble fertilizer[21]. Grinding PRs is one of the simplest processes when applying them directly to agricultural fields. The particle size of PRs has been considered one of the important factors in their dissolution[26]. As discussed above, the difficulty in its handling resulting from fine grinding has been suggested as one of the major constraints in local PR utilization[7]. However, our recent surveys in northern Ghana revealed that most farmers were willing to use the fine-powdered BPR.

The insufficient solubility of PRs can be improved in various ways, as mentioned above. However, more or less, all technologies for the solubilization of local PRs require cost, energy, and time. Therefore, the direct application of PRs has greater advantages because it is likely to minimize additional costs. The direct application of PRs in SSA would be better promoted if a specifically effective location or condition was clarified for local PR.

Effects of PRs originating from SSA on upland crops

Local PRs produced in SSA were evaluated for various crops[5,8,14,51]. However, no common understanding of the local PR application effects was achieved due to the complicated interactions of diverse soil properties, climate, crop, and the PR chemical composition.

For example, PRs that originate from Nigeria (Sokoto and Ogun) were tested for the direct application on maize, millet, and oil palm compared to single super phosphate (SSP), which is a water-soluble P-fertilizer[5]. The results showed that these PRs can be conveniently used for direct application when the rainfall exceeds 1,200 mm, whereas the low rainfall in the semi-arid zone would make their solubilization inadequate. It has been shown that Togo PRs (TPRs) effectively increase arbuscular mycorrhizal fungi infections and the biomass production of Mucuna (*Mucuna pruriens*) and Hyacinth bean (*Lablab purpureus*) in the northern Guinea Savanna zone[51,52]. However, a report was also compiled by Abekoe & Tiessen (1998) that presented an opposite view of the same PRs, suggesting that TPR is ineffective, as the relative agronomic effectiveness (RAE) was 63% of the SSP for sorghum cultivation in northern Ghana[2]. The RAE is calculated as follows:

$$\text{RAE (\%)} = \frac{\text{Yield with PR} - \text{Yield with Control}}{\text{Yield with SSP or TSP} - \text{Yield with Control}} \times 100$$

These experiments with Nigerian PRs and TPRs suggest that PR solubility is affected in various ways by diverse factors, even if the same PRs are applied. Accordingly, the effectiveness of the direct application of PRs would vary based on a submerged or upland location and lowland or upland crop agricultural systems.

BPRs, which are low-reactive PRs[10] for direct application, were also evaluated for various crops[12], such as maize, millet, sorghum, cotton, groundnut, soybean, and rice. The RAE values of the BPR application were 79% for maize, 55% for millet, and 63% for sorghum[12] respectively. However, the direct application of the same BPR to lowland rice has been shown to have a relatively higher RAE value of 94%[53].

Effects of PRs direct application on lowland rice

Table 3 summarizes the results of studies on the effects of the direct application of PR on lowland rice growth. The direct application of PR in lowland rice cultivation has generally shown high effectiveness. The agronomic efficiencies relative to SSP or TSP were almost 100% on average (Table 3). The agronomic efficiencies relative to chemical P fertilizer are calculated as follows:

$$\text{Agronomic efficiencies to SSP or TSP (\%)} = \frac{\text{Yield with PR}}{\text{Yield with SSP or TSP}} \times 100$$

These results suggest that PRs can be used as alterna-

Table 3. Previous studies on direct application of various types of PRs for lowland rice cultivation

No.	References	Investigated Country	Type of Experiment	Type of PR	Solubility % and Diamond's classification† NAC††	2% Citric	Type of soil investigated	Soil pH	Soil available P (mg kg^{-1})	Dose of PR application (P_2O_5 kg ha^{-1})	Yield of rice (t ha^{-1} or g pot^{-1})	Agronomic Efficiency to SSP/TSP (%)*
1	FAO (2004)	Burkina Faso	Field	Local-Kodjari	2.08 L	6.00 L	Flooded rice soil	-	-	29.8, 59.5, & 89.3	2.4 t ha^{-1}	97
2	Somado, et al (2003)	Ivory Coast	Field	Tilemsi (Mali)	3.10 M	8.30 M	Ultisols (Uquults)	4.7	4.0 (Bray 1)	206	3.5 t ha^{-1}	78
3	Somado, et al (2003)	Ivory Coast	Pot	Tilemsi (Mali)	3.10 M	8.30 M	Ultisols (Uquults)	5.2	4.0 (Bray 1)	137 (eq.)***	14.7 g pot^{-1}	91
4	Khalil, et al (2002)	Pakistan	Pot	Local-Kakul	2.54 L	5.80 L	Clay loam	7.9	4.03	1.3 g kg^{-1} soil	13-15 g pot^{-1}	115-138**
5	Dahanayake, et al (2001)	Sri Lanka	Field	Local-Eppawala	2.73 L	6.06 M	Reddish Brown Latosolic	5.5	-	29 & 48	5.3 t ha^{-1}	111 & 117
6	Sri Adiningsih, et al (2001)	Indonesia	Field	Local	- -	- -	Hidromorphic	-	-	10, 20, & 30	7 t ha^{-1}	105-107
7	Sri Adiningsih, et al (2001)	Indonesia	Field	Local-Ciluar	- -	- -	Acid sulfate soil	-	-	67.5	3.8 t ha^{-1}	103
8	Sri Adiningsih, et al (2001)	Indonesia	Field	Local-Ciamis	- -	- -	Acid sulfate soil	-	-	67.5	3.8 t ha^{-1}	103
9	Yusdar, et al (2001)	Malaysia	Field	North Carolina & Jordanian	9.30 H	13.10 H	-	-	-	90	6 t ha^{-1}	100
10	White, et al (1999)	Cambodia	Field	Local	- -	- -	Typic haplustalf	6.3	1.0 (Olsen)	20	2.3 t ha^{-1}	100
11	Medhi and De Datta (1997)	Philippines	Field	Morocco	6.68 H	7.18 M	Acid soil	5.5	1.9 (Olsen)	23 - 366	5.4 t ha^{-1}	95 & 98
12	Medhi and De Datta (1997)	Philippines	Field	Morocco	6.68 H	7.18 M	Inceptisols	5.6	‘’	23 - 183	3.6 t ha^{-1}	97
13	De Datta, et al (1992)	Indonesia	Field	Morocco	6.68 H	7.18 M	Acid soil (Sakamandi)	5.0	14.7 (Olsen)	-	-	99% (RAE)****

*Agronomic efficiency to SSP/TSP (%) is calculated from the difference in grain yield (t ha^{-1} or g pot^{-1}) of PR to SSP or TSP and multiplied by 100, **used for PR incorporation with others amendments or various planting techniques e.g. farm yard manure, green manure, and P-solubilizing microorganism, liming, or inter-cropping with etc., ***eq. refers to the equivalent rate of applied P_2O_5 of pot which calculated into kg ha^{-1} compared to the field experiment, ****Relative Agronomic Efficiency (RAE, %) = [(test P fertilizer – control)/(standard P fertilizer – control)] × 100, †classified according to Diamond (1979), †† NAC; Neutral Ammonium Citrate

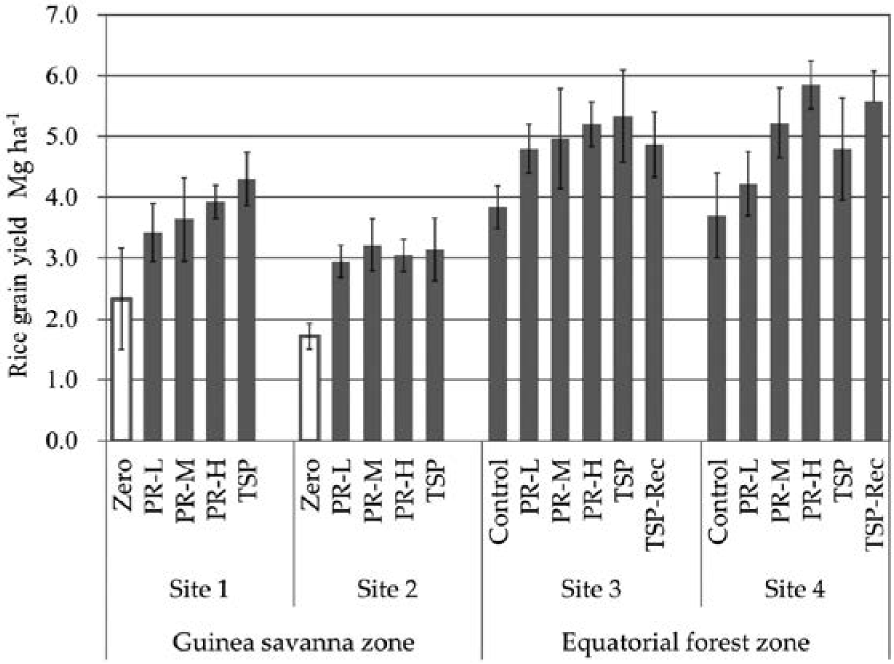

Fig. 2. The effects of direct application of Burkina Faso Phosphate Rock (PR) on rice yield in the Guinea savanna zone and Equatorial forest zone in Ghana (Nakamura et al., 2013)

The error bars indicate standard error (n = 3).

The plots are listed as follows: Zero is zero application, which is an absolute control; Control is nitrogen (N) and potassium (K) application without any P source; and PR-L, PR-M, and PR-H are PR applications at the rates of 67.5, 135, and 270 kg P_2O_5 ha^{-1}, respectively. TSP is the TSP application at 270 kg P_2O_5 ha^{-1}. TSP-rec indicates TSP application at 60 kg P_2O_5 ha^{-1}. All plots except for Zero received N and K application at recommended levels.

tives to chemical fertilizers with comparable effects on lowland rice yield. Moreover, unlike the results with upland crops, the effectiveness of PR application has been shown to be almost equivalent to those of other highly reactive PR applications, although some of the studied PRs were classified as having low reactivity in Diamond's classification. Based on these results, it may be possible to consider that PR application on the lowland rice system has an advantage compared to its use for upland crops.

The above suggestion was also supported by a study by Nakamura et al. (2013) that examined the effects of the direct application of BPRs on lowland rice systems in the Guinea Savanna and Equatorial Forest zones in Ghana[35]. As shown in Figure 2, the direct application of BPR at the rates of 67.5 (PR-L), 135 (PR-M), and 270 (PR-H) kg P_2O_5 ha^{-1} considerably increased rice grain yields. In that study, the rice grain yield of the Zero plot was 2 Mg ha^{-1}, which is on a par with the reported farmers' average[1] in the same system, ranging from 0.5 to 2.1 Mg ha^{-1}. In contrast, sites that received BPR applications showed significant enhancements and improvements in rice yields, up to about 3.9 and 3.1 Mg ha^{-1} in 2 sites of the Guinea Savanna zone in PR-H plots and approximately 3.3 and 3.0 Mg ha^{-1} in PR-L plots. In the Equatorial Forest zone, the observed rice yield levels exceeded those in the northern Savanna zone, which was probably due to Sawah eco-technology[55]. The control plot in that study yielded 3.7 Mg ha^{-1} in rice grain, and the yield was increased to 5.2 and 5.8 Mg ha^{-1} in PR-H and 4.2 and 4.8 Mg ha^{-1} in PR-L at 2 sites.

PR dissolution under soil physicochemical conditions in the lowland rice system

It is well known that the soil of paddy fields in the lowland rice system has a unique physicochemical condition compared to those of upland fields, e.g. in terms of its reduction-oxidation potential, water dynamics, and organic matter accumulation. Therefore, P dissolution proceeds with a particular process in lowland rice fields[31]. Submergence causes flushes of easily extractable soil P in a few days, which is a result of the chemical reduction of ferric phosphate and hydrated ferric oxide surfaces[30]. However, this extractable P would be absorbed by the amorphous solid phase[31]. These P sorption and/or desorption reactions in submerged soil strongly interact with the formation changes in iron minerals[6,29] resulting from changes in the soil reduction-oxidation potential.

Potential P dissolution mechanisms of the rice plant have been reported. Huguenin-Elie et al. (2003) showed that rice plants took up P levels that were 3 times higher in flooded soil than in moist soil[24]. They also concluded that P solubilization was consistent with acidification as a result of the oxidation of Fe (II) by O_2 that is released from rice roots and the excess intake of cations over anions in flooded soil, whereas organic anions were excreted from the roots in moist soil[24].

Moreover, Kirk and Du (1997) measured the effluxes of O_2 and H^+ from rice roots in sand culture under P-deficiency conditions[28]. They observed increases in root dry mass per unit shoot dry mass, root length per unit root dry mass, and root O_2 release per unit dry mass[28]. In addition, Hoffland et al. (2006) indicated an increase in citrate exudation under P-deficiency conditions[23]. These results suggested that rice plants have a specific mechanism for obtaining P from the soil, particularly under submerged soil conditions, which is probably similar to upland leguminous crops that can secrete organic exudates, such as pigeon pea.

Previous studies have indicated the potential for local PR application to be effective for lowland rice cultivation due to the unique soil conditions of submerged fields and the P-acquisition mechanisms that are unique to the rice plant. However, few observations can be currently found on this issue, hence the need for further studies to show the universality and reproducibility of the effects of the direct application of PRs on lowland rice cultivation.

A phosphate rock decision support system (PRDSS) and future prospects

It is quite difficult for farmers to decide between PR and chemical P fertilizer utilization as sources of P applied to soils, due to a lack of basic information about the economic and/or agricultural efficiency of local PR usage. To solve this difficulty, a Phosphate Rock Decision Support System (PRDSS) has been developed by the IFDC. The PRDSS is a mathematical model that was derived from datasets of various experiments conducted by collaborating scientists in a number of countries[20,41]. The PRDSS was designed to predict the RAE of PRs with respect to water-soluble P-fertilizers and calculate a simple index usable for preliminary economic comparisons of these 2 types of P sources[41].

The PRDSS includes information on PR sources that vary widely in solubility and on different crop species that are grown in soils of variable properties, and under different rainfall conditions and crop management methods[16,41]. Therefore, the PRDSS can function with a minimum input of only soil pH, the name of the mine where the PR originated, and the crop species to be grown to estimate the RAE roughly. A more accurate prediction of RAE is obtained from the PRDSS when more detailed data describing the soil, crop, and weather are included as inputs, as described in the manual.

Table 4. Predicted percentage of relative agronomic effectiveness (%RAE) of PRs from different origins on lowland rice in some soils of Ghana using the Phosphate Rock Decision Support System (PRDSS)

Agroecological zone (Province in Ghana)	Kodjari (Burkina Faso)	Hahotoe (Togo)	North Carolina (USA)
Guinea Savanna zone (Northern)	16	23	53
Equatorial Forest Zone (Ashanti)	8	12	29

Authors have attemped results from PRDSS predictions that used inputs of some specific soil and PR characteristics, climatic conditions, and crop management methods, targeting lowland rice cultivation in Ghana (Table 4). The results indicated that, in soils of both the Savanna and Equatorial Forest zones, North Carolina PR (NCPR) gave higher RAEs than PRs produced in the SSA, Hahotoe TPR, and Kodjari BPR at 53, 23, and 16%, respectively. This was accounted for by the different reactivities of the PRs (NCPR > TPR > BPR). In addition, the PRDSS predicted that lowland soils in the Savanna zone of Ghana would show higher effectiveness than those in the Equatorial Forest zone. This prediction was derived from the entered soil characteristics, e.g. lower in pH, exchangeable calcium, and other exchangeable bases, which may result in higher PR dissolution and availability of P in soil solution. Accordingly, the PRDSS can easily predict the effectiveness of direct PR application. However, this prediction system has not been fully validated, particularly for rice cultivation.

Nakamura et al. (2013) attempted to compare the observed RAEs with PRDSS-predicted RAEs in lowland rice cultivation of Ghana using the direct application of BPR[35]. The BPR plots at the same P level of TSP (PR-H) produced 87.4 and 97.2% of rice grain yields against TSP plots in the Guinea Savanna zone. In the Equatorial Forest zone meanwhile, the BPR/TSP ratios were 118 and 115% at 2 sites. However, the PRDSS predicted low RAEs for this trial (2–3% for the Guinea Savanna zone and 5–20% for the Equatorial Forest zone). Although the results need to be replicated, the PRDSS prediction showed a significant difference from our observed RAEs. Thus, the PRDSS needs to be carefully validated, particularly for lowland rice cultivation.

The PRDSS uses soil pH, the soil P-fixation capacity, aluminum saturation, and so on as soil factors to calculate PR dissolution[41]. However, this calculation cannot take account of changes in P forms in the reduction-oxidation process. As discussed above, the soil chemical conditions in lowland rice fields have unique properties and processes, mainly due to drastic changes in the soil reduction-oxidation potential. The PRDSS may need to be modified to include additional factors, such as the *Eh* values in soil, to predict the effects of the direct application of PRs on lowland rice cultivation, as well as other agroenvironments, such as flood-prone areas.

In conclusion, the PRDSS appears a very practical and useful tool for predicting the effectiveness of PRs. If users can provide more details of on-farm data and all factors affecting the effectiveness of PR, a powerful dataset can be generated and fitted to each individual site. However, the use of the PRDSS still includes some difficulties for predicting the RAEs of lowland rice cultivation. An improved prediction system is needed to enhance PR utilization in SSA.

Conclusion

Local PRs in SSA would be considered valuable alternatives to chemical P-fertilizer. However, there are many constraints against their utilization, including the quality, quantity, and economics. It is well known that PRs in SSA show diverse properties and must thus be treated appropriately. If the scale and quality of a proper PR deposit suffice for commercial use and industrial manufacturing, it is economically feasible to employ a chemical plant to produce water-soluble chemical P fertilizer near the deposit. However, most PR deposits in SSA have several problems in terms of management for commercial use due to the small scale of the deposit and the substandard characteristics of the PR, such as high impurity contents and/or low reactivity. Therefore, adequate management for direct application needs to be considered to utilize local PRs in SSA. Currently, an optimal method for the direct application of local PRs has yet to be established due to difficulties arising from various factors, such as soil properties, climate, crop, and PR chemical composition.

The PRDSS can help disseminate PR utilization in SSA. However, there remains room for further improvement in predicting the RAEs in lowland rice cultivation with consideration of the unique soil properties under submerged conditions.

The direct application of PRs to the lowland rice system resulted in high performance, regardless of the PR reactivity and location, and so it can be concluded as that local PRs produced in SSA can be effectively utilized for direct application on lowland rice cultivation. Moreover, this was probably due to reduction-oxidation potential changes resulting from submergence. To clarify the universality of this phenomenon, more observations need to be conducted in SSA. Furthermore, the PR solubilization mechanism must also be elucidated to clarify the condition that maximizes the effect of local PRs direct application.

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