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The Use of Phosphate Rocks in East Africa: A Review

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ABSTRACT

The use of locally available phosphate rock (PR) has often been proposed as a cheaper alternative to the more expensive superphosphate fertilizers to alleviate severe phosphorus deficiencies that threaten food security in East Africa. Extensive research has therefore been conducted in the region over the years focusing on the PR sources, their reactivity, agronomic effectiveness and the economics of their use and adoption. The agronomic effectiveness varied with the type of PR, the site, seasons and crop. Minjingu PR was the most promising among the PRs for direct application but others such as Panda, Sukulu and Busumbu PR were largely ineffective. The financial returns due to use of PR ranged from negative to positive but in many cases were economically not attractive. The adoption of PR use among farmers was dismal with the unavailability of the PR in the market and high cost, paradoxically being cited as the main constraints to its adoption. To enhance the chances of adoption, it is recommended that participatory approaches to research that involve the targeted beneficiaries especially the PR marketers and smallholder farmers be used.

Key words: Phosphorus, Phosphate rocks, Relative agronomic effectiveness.

Phosphorus (P) is an essential element for plant growth and plays many important roles in plant nutrition such as photosynthesis, seed and fruit formation, root growth and development (Marschner, 2012). Therefore, P deficiency curtails many metabolic processes within the plant and adversely affects crop productivity in large areas of production on P-deficient soils. In East Africa, where such soils are prevalent, it has been reported (Smithson and Sanchez, 2000; Kihara and Njoroge, 2013) that most soils across farms are severely deficient of P (below 10 mg kg^{-1} Bray or 5 mg kg^{-1} Olsen extractable P). These low P levels have been partly attributed to the low P status of the parent material and mining of soil P through crop harvests, which has been estimated at 1.5-13 kg/ha/year on smallholder farms and P losses by erosion and surface runoff (Smaling *et al*., 1993; Bekunda *et al*. 2010). In addition, P deficiencies in these soils are accentuated by their high P-adsorption capacities due to high content of aluminum and iron oxides and soil acidity (Buresh *et al*., 1997; Kisinyo *et al*., 2014).

On P-deficient soils, use of other nutrient inputs is not usually effective unless P-limitations are overcome. Phosphorus deficiency is generally managed by addition of organic or inorganic fertilizers or their combinations. Sole use of organic inputs is, however, not a practical option due to their low P content (Palm *et al.,* 2001). Phosphorus must, therefore, be added to such soils in concentrated forms either as P-containing fertilizers or phosphate rocks (PRs) (van Straaten, 2002). Soluble phosphate fertilizers such as triple superphosphate (TSP) and diammonium phosphate (DAP) are widely used in East Africa but their use-efficiency in soils with a high P-fixation capacity, such as those that dominate most of East Africa's humid regions, is reduced by P-fixation. As a result, large amounts of P fertilizers have to be applied in order to achieve adequate crop yields therefore increasing costs of production. Consequently, there is increased research interest in finding alternatives to these commercial phosphate fertilizers that are affordable and sustainable. Focus has generally shifted to solutions that utilize more of the local resources such as phosphate rock (PR).

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Phosphate rock is the main source of raw material that is used to manufacture soluble P fertilizers and has apatite as the dominant mineral (van Straaten, 2002). Apatite is insoluble and its P is practically unavailable to plants. It has therefore to be subjected to chemical processing with strong acids such as sulfuric and phosphoric to produce soluble phosphate products (Reta *et al.,* 2018). Since fertilizer P is manufactured by acidulating PR, some researchers postulated that acid soils could be converted to a 'factory' so that the PR could then be applied directly to them and be converted to available P forms, instead of expensively processing it into fertilizer industrially. Use of PR is most effective where soils are acidic and low in P and Ca (Rajan *et al.,* 1996). These conditions obtain in many humid regions of East Africa. The fact that the PR deposits are indigenous and that substantial transports costs associated with importing superphosphates could be avoided made the option of using PRs extremely attractive from an economic view point (Braun 2007). Several studies have therefore been conducted to test their agronomic effectiveness of PRs in East Africa since the 1950's and a wealth of information is now available in several publications, reports and conference proceedings. This review summarizes this information and the progress made so far in utilization of the PRs in East Africa.

Phosphate rocks available in East Africa

Phosphate rocks are a broad class of phosphate-rich minerals that typically contain calcium and fluoride and exhibit high diversity in mineralogy and geographical distribution (van Kauwenbergh, 1991). Phosphate deposits can roughly be divided into four categories: a) igneous, b) marine sedimentary, c) guano and d) deposits derived from weathering of the three first categories (Szilas, 2002). The igneous PRs are more widespread in East Africa. These PRs differ greatly in their suitability as sources of P in P-deficient soils.

In Uganda, the two main PRs are Sukulu and Busumbu (BPR) both found around Tororo. Sukulu PR has an average composition of 12.8% P_2O_5 with a low neutral ammonium citrate (NAC) solubility of 1.6% P_2O_5 (van Kauwenbergh, 1991). There are two types of BPR; the hard rock with 12 to 13.5% P and the soft rock, 7.9 to 9.9% P. The soft rock constitutes nearly 90% of the estimated total deposit of 8.8 million tons of ore (van Straaten, 2002). The soft ore however contains impurities, particularly magnetite. The NAC solubility of BPR is 2.3% which is classified as low (FAO, 2004). Because these PRs have limited citrate solubility they are not considered suitable for direct application.

In Tanzania Minjingu phosphate rock (MPR) and Panda PR are the most promising in terms of agronomic and economic interest. Minjingu is found in northern Tanzania and is biogenic in origin with its phosphate originating from guano associated with bones, feathers and skeletal fragments of fish and birds (Msolla *et al*., 2007). There are two types of ore containing MPR: the soft ore and the hard ore (Jama and van Straaten, 2006). Production has however concentrated on the soft ore. It contains nearly 13% P, with a NAC solubility of about 5.6% (Jama and van Straaten, 2006). The small crystal size, high substitution rates of carbonate for phosphate and strontium for calcium and high NAC solubility of MPR makes it highly reactive (Szilas *et al.,* 2008).

The phosphate resources of Kenya are limited and have hardly been tested for their agronomic effectiveness because of their poor quality**.** Pulfrey (1950) (cited in van Straaten 2002) described small and insignificant phosphate occurrences at the Homa Bay and at the Ruricarbonatite complexes in western Kenya. In addition, some igneous PRs in Rangwa have been identified with a NAC solubility of 0.4% P_2O_5 (van Straaten, 2002).

Enhancing phosphorus availability from phosphate rock

The direct application of PR is suitable under certain conditions including low pH, low available soil P, high CEC and low exchangeable Ca (Anderson *et al*., 1985; Rajan *et al.,* 1996). The rate of dissolution of PR under natural conditions is however often slow, especially for non-reactive PRs. Several physical, chemical and biological approaches have been developed to enhance the solubility of such PRs. These include: 1) partial acidulation with mineral acids 2) mixing with certain acidifying agents such as elemental sulphur and pyrite 3) use of microbial cultures such as phosphate solubilizing bacteria and mycorrhizal fungi 4) blending with soluble fertilizers and granulation and 5) Combining with organic materials (FAO, 2004). Some of the approaches that have been tried in East Africa are reviewed the next.

Partial acidulation

In this approach, the PR is treated with a portion of the phosphoric and/or sulphuric acid required for production of soluble P fertilizers such as single superphosphate (SSP) or TSP. This reduces the cost compared to that of soluble fertilizers. However, a major drawback of this technique is the unavailability of inexpensive local sulphuric or phosphoric acid (van Straaten, 2002). In addition, partial acidulation may not be suitable to PRs such as Busumbu which contain large amounts of Fe and Al oxides as impurities (Menon *et al.,* 1991). Consequently, though promising, partial acidulation has remained experimental in East Africa (Nziguheba, 2007). For example, in Tanzania, Kamosho (1996) tested the effectiveness of partial acidulation of unreactive Panda PR in six P deficient soils and found that it increased the relative agronomic effectiveness (RAE) from an average of 4% to 75% of that of TSP. In Uganda partial acidulation of Sukulu PR gave a lower RAE than compacting it with TSP at a total P ratio of 50:50 (Butegwa *et al.,* 1996).

Blending with water-soluble phosphate products

The blending process involves either compacting or pelletizing the PR with a water-soluble P (WSP) fertilizer such as SSP or TSP (Chien *et al*., 1987). The WSP content of the products will depend on the ratio of PR to WSP fertilizer used. Compaction offers the advantage of using PRs that are not suitable for partial acidulation with H_2SO_4 because of their high Al and Fe sesquioxides content such as Busumbu (Chien *et al*., 1987). There is experimental evidence in East Africa that the application of PR as a dry mixture with WSP fertilizers can increase the effectiveness of the PR. Ngeno (2007) found that the solubility of MPR in MPR-superphosphate mixtures increased with increasing proportion of superphosphate component in the mixtures. This was attributed to phosphoric acid produced from the hydrolysis reaction in soil of monocalcium phosphate in superphosphate which would subsequently dissolve the PR thereby releasing additional P into soil solution. However, in other studies, blending BPR with WSP fertilizers had no positive effect in terms of increasing P availability and uptake by plants (Ngoze, 2002).

Use of sulphur

Sulphur promotes dissolution of PR due to the sulphuric acid that is produced when soil bacteria oxidizes S to H_2SO_4. Inoculants of bacteria have therefore been developed to speed up the dissolution (FAO, 2004). In an incubation study in Kenya, sulphur significantly increased the rate of P dissolution from PR (Githua, 2019). In Uganda, Zake (1988) found that sulphur used in combination with OMs improved the agronomic performance of Sukulu PR. Sulphur containing minerals have also been used to promote dissolution of PR. For example, Kalumuna *et al*. (1998) found that mixing PR with pyrite lowered the pH and increased WSP of the incubation mixture of Panda PR or MPR with pyrite.

Biological approaches

The biological means of enhancing the agronomic effectiveness of PRs have been reviewed by (FAO, 2004). They include: (i) composting organic wastes with PR or combining with organic materials (OMs) (ii) use of phosphorus-solubilizing micro-organisms and (iii) the inclusion in the cropping system of crop genotypes that acidify the soil through exudation of organic acids that increase the solubility of sparingly soluble phosphates by decreasing pH and/or chelation. The approach of composting or combining PR with OMs has received the greatest attention in East Africa and is based on the fact that decomposing OMs produce organic acids that solubilize P from PRs through chelating or complexing action. There is, however, a wide divergence of opinion on the effect of OMs on PR dissolution. Controversy still exists as to whether OMs actually increase effectiveness of PRs in terms of P availability and crop performance (Nziguheba, 2007).

Many early studies reported enhanced dissolution of PR when it was combined with OMs such as FYM. It is, however, now emerging that some OMs, especially those with a high Ca content, e.g *Tithonia diversifolia* green manure (tithonia), can inhibit dissolution of reactive PRs such as MPR (Savini *et al*., 2006, Opala *et al*., 2010a). Opala *et al*. (2012) demonstrated that there was no synergy, whereby the available P did not increase more than the sum of the increase from either of the P sources applied singly when MPR or Busumbu PR were combined with tithonia or FYM (Table 1). In general, the expected increase in the available P due to the additive effects of applying the inorganic and organic P sources separately was always greater than the actual increase obtained by combining the inorganic and organic P sources, at the same total P application rate (Table 1).

Babili and Semoka (2007) similarly found that co-application of MPR and OMs, (*Gliricidia sepium* leaves and maize stover) did not enhance dissolution of MPR but tended to increase available P. This confirmed earlier studies that showed that the increases in available P from co-application of OMs with PR reflect P mineralized from the OM rather than increased dissolution of PR.

Grinding

Grinding increases the surface area of the PRs so that they can be in intimate contact with the soil particles to enhance reaction rates. Amdany (2005) in a study on the effect of particle size on dissolution of Gafsa and Minjingu PRs found that dissolution, yield and P uptake by plants increased with decreasing particle sizes of the PRs. Ngeno (2007) recommended that grinding should be done to ensure that at least 80% of the materials pass through a 100-mesh sieve. Grinding PRs below 100 mesh was however found to be of no beneficial agronomic value (Hammond *et al*., 1986).

Responses of crops to phosphate rocks in East Africa

Table 1: Effect of organic and inorganic P amendments on Olsen P (mg P kg^{-1}) at Bukura and Kakamega in the laboratory incubation study.

Treatment	Bukura			Kakamega		
	4 WAI	16 WAI	∆ Olsen P	4 WAI	16 WAI	∆ Olsen P
Control (no P input addition)	7.3	8.9	1.6	3.2	4.3	1.1
Tithonia (60 kg P ha^{-1})	13.1	14.7	1.6	8.2	9.6	1.4
FYM (60 kg P ha^{-1})	16.0	16.5	0.5	9.5	10.0	0.5
MPR (60 kg P ha^{-1}) + urea	13.4	16.3	2.9	6.9	8.0	1.1
TSP (60 kg P ha^{-1}) + urea	18.2	17.7	-0.5	9.8	10.1	0.3
BPR (60 kg P ha^{-1}) + urea	11.0	11.5	0.5	4.5	6.0	1.5
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	14.1	13.9	-0.2	7.9	6.3	-1.6
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	17.4	15.8	-1.6	8.9	8.6	-0.3
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	12.4	12.6	0.2	4.4	5.1	0.7
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	15.0	15.7	0.7	7.4	9.3	1.9
F YM (20 kg P ha^{-1}) +TSP (40 kg P ha^{-1})	14.5	17.7	3.2	8.0	6.0	-2.0
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha ha^{-1})	13.1	16.1	3.0	5.9	5.8	-.01
Tithonia (20 kg P ha^{-1})	11.2	13.9	2.7	4.6	7.3	2.7
FYM (20 kg P ha^{-1})	12.7	15.6	2.9	5.7	7.5	1.8
MPR (40 kg P ha^{-1})	12.5	14.9	2.4	6.3	6.6	0.3
TSP (40 kg P ha^{-1})	14.2	16.6	2.4	6.7	7.3	0.6
BPR (40 kg P ha^{-1})	9.8	9.6	-0.2	4.4	5.6	1.2
SED	0.9	1.3		0.7	0.7	
Cv %	9	11		10	10	

WAI: Weeks after incubation; FYM: Farmyard manure; TSP: Triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock (Source, Opala *et al.* (2012)).

Numerous field and greenhouse experiments have been conducted to assess the capabilities of PRs to supply P to crops. Although it has been suggested that direct application of PR is more effective with long term perennial crops, most of the research in East Africa has been on annual food crops. Recent experiments, in which direct application of indigenous PRs were evaluated, have yielded variable results, depending on the type of PR, site and duration of study.

Sukulu PR has been found to be generally ineffective when directly applied on acid soils without modification (Zake *et al*. 1988, Butegwa *et al*., 1996) although compacting with TSP improved its performance. Similarly, BPR has been found to be unsuitable for direct application. Use of OMs with BPR did not improve its RAE in acid soils of western Kenya (Opala *et al*., 2010a) and in near neutral sandy soils in eastern Uganda (Oshier, 2002). Opala *et al.* (2013) compared BPR and MPR at two sites and showed that when applied alone or in combination with OMs (tithonia and FYM), maize yields for BPR did not significantly differ with the control (Table 2). The RAE of BPR was -15% in Kakamega and 33% in Bukura confirming the ineffectiveness of BPR at these sites.

In most field experiments, the RAE of unmodified BPR was low (28-45%) (van straaten 2002). Greenhouse testing with BPR blended with TSP and mono-ammonium phosphate at a ratio of 50:50 improved the RAEs of BPR to 80% and more than 90% respectively (Ngoze 2002). Similarly, Panda PR has low RAE but its performance could be enhanced by partial acidulation or compacting with TSP Kamasho (1996). MnKeni *et al.* (2000) found that Panda PR when compacted with TSP, increased wheat, maize and soybean yields and P uptake significantly compared to the uncompacted PR.

Most studies of crop response to direct application of PR in East Africa have used maize as the test crop. However, research has shown that some plants are able to utilize PR better than others as their source of P. Weil (2000) showed that the direct application of Panda PR had no effect on growth or tissue P content in maize, bean and pigeon pea but it nearly tripled these parameters for cabbage on an Alfisol in Tanzania. More pronounced results have been achieved using canola (rapeseed) as the test crop (Mnkeni *et al.* 2000). The results showed that the roots of rapeseed can extract P from blended unreactive PRs. Phosphate rock has been found to be particularly effective with N fixing crops and crops with root systems that can exude organic acids to increase solubility. Tunya *et al. (*2014) reported that legumes (lupin and chickpea) in a sorghum intercrop enhanced the effectiveness of MPR because legumes crops exude acids from their roots providing an acidic environment that allows for MPR solubilization. Ahmat *et al*. (2014) found that at the same level of P input from MPR, P availability under maize-bean intercrop increased above the ones under sole maize.

Minjingu PR is the most tested PR in East Africa. In Tanzania, results of agronomic experiments using MPR for direct application are reported by several workers. In some studies, MPR had a rather poor performance for the first year but improved with time. Msolla *et al.* (2005) tested hard MPR, soft MPR and TSP at several sites in Tanzania and found significant positive responses to application of the three P sources but TSP application resulted in significantly higher P concentrations in leaves and grain yields than MPR in the first year. However, in the second and third years the performance of MPR approached that of TSP and the RAE of MPR increased from 50-70% in the first year to 80-95% in year three. Similarly, Ikerra *et al***.** (2006) found TSP to give significantly higher maize yields than MPR in the first season but by the second season, MPR and TSP did not

Table 2: Effect of P sources on maize grain yield at Bukura and Kakamega.

Treatment		Grain yield Mg ha^{-1}	
	Total P (kg ha^{-1})	Kakamega	Bukura
Control (no P input addition)	0	2.6	1.9
Tithonia (20 kg P ha^{-1})	20	4.2	4.3
FYM (20 kg P ha^{-1})	20	3.5	3.2
MPR (60 kg P ha^{-1}) + urea	60	3.4	2.6
BPR (60 kg P ha^{-1}) + urea	60	2.4	2.2
TSP (60 kg P ha^{-1}) + urea	60	3.9	2.0
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	60	4.7	4.9
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	60	4.1	4.4
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	60	5.4	5.1
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	60	3.7	3.2
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	60	2.7	2.7
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	60	3.8	2.9
SED		0.50	0.49

Note: FYM: Farmyard manure; TSP: Triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock (Source: Opala *et al.,* 2013).

differ significantly. Others have however reported similar yields of TSP and MPR even in the first season in Tanzania (*e.g*. Mkoma, 2015). Ikerra *et al*. (1994) observed that the agronomic effectiveness of MPR increased when it was combined with high quality FYM but not with low quality compost. In Northern Tanzania, Ndakidemi (2015) found no significant difference in dry matter yield of common bean between TSP or Tughutu (a traditional shrub applied at 2.5 t ha^{-1}) combined with MPR but yield from MPR without the shrub were lower than those of TSP.

In Kenya, Bromfield *et al*. (1981) reported a RAE of 75% for MPR applied to maize in a five seasons in western Kenya. Extensive studies on MPR were later conducted by the Kenya Agricultural Research Institute and the International Centre for Research in Agroforestry (ICRAF) in western Kenya in the 1990s and early 2000s in a collaborative research. Although research output declined after the end of this collaboration, other studies on MPR have since been conducted.

The RAE of MPR in comparison to soluble P-fertilizers varied among studies. Sanchez *et al.* (1997) reported RAEs of 65-85% in western Kenya but on the same soils, Mutuo *et al.* (1999) calculated the RAE of MPR in the range of 84-98%. Ngoze (2002) reported a RAE of MPR of 75% and 91% for the long and short rains period respectively. Many other studies in western Kenya have found no significant difference in agronomic effectiveness between inorganic P fertilizer and MPR (*e.g.* Ndung'u *et al.,* 2006, Nyambati and Opala, 2014 and Ademba *et al.,* 2015) or better performance by MPR than TSP (Orandi *et al.,* 2021, Opala *et al.,* 2010b). The better performance of MPR than TSP, where it was reported, was attributed to its high reactivity (Szilas *et al.,* 2008) and liming effect (Nekesa *et al* 2005, Opala *et al.,* 2010a) and the larger amounts of other nutrients in it than TSP such as Ca, Mg, K, Cu and Zn (**v**an Kauwenbergh 1991, Kihara and Njoroge, 2013). The high RAEs reported for MPR in some studies should however be treated with caution. It has been suggested that the RAE derived from most PR studies is normally overestimated if both TSP and MPR are broadcasted as is the case with most studies reviewed here. If TSP application was localized e.g. by banding in order to increase the efficiency of TSP by reducing the contact between soil particles and fertilizer P, the superiority of TSP would be more prominent resulting in lower RAEs.

Where PRs were co-applied with OMs, results have been inconsistent. This could be attributed to the quality of OMs used in combination with the PR. For example, Waigwa *et al.* (2003) found that the application of PR alone and in combination with FYM or stover lowered the effectiveness of PR below that of TSP but Opala *et al.* (2013) found that combining high quality OMs (tithonia and FYM) increased the RAE. In similar studies in western Kenya, Kifuko *et al.* (2007) showed that the application of FYM with MPR gave the highest cumulative maize yields over three seasons, compared to MPR combined with either chicken manure or sugarcane baggase. Not all studies have, however, found MPR to be an effective phosphorus source. In Central Kenya, Peter (2000) found that the RAE for MPR was only 40%. Omenda *et al.* (2021) reported that treatments with sole PR gave low yields and did not differ significantly with the control with no P input. Ndeleko-Barasa *et al.* (2021) similarly reported that TSP had significantly higher grain yields (6.86 Mg ha^{-1}) than MPR (3.0 Mg ha^{-1}) in Upper Eastern Kenya.

Economics and adoption of PRs

Economic analyses were rarely conducted in early studies on PR but some recent studies have analyzed the economics of PR use. The financial benefits, just like the RAEs, of using PRs vary widely. Jama and Kiwia, (2009) found that the agronomic benefits of TSP and MPR were similar but TSP had a slight edge over MPR in financial benefits. Opala *et al.* (2013) reported negative financial benefits over three

Table 3: Net financial benefits (USD ha-1) and benefit-cost ratio (BCR) at Bukura, Western Kenya.

Treatment	First season		Second season		Third season	
	Net benefits	BCR	Net benefits	BCR	Net benefits	BCR
Control (no P input addition)	-	-	-	-	-	-
Tithonia (20 kg P ha^{-1})	144	0.2	-351	-0.6	306	0.5
FYM (20 kg P ha^{-1})	323	3.3	130	1.3	379	3.4
MPR (60 kg P ha^{-1}) + urea	-51	-0.2	-188	-0.6	-196	-0.3
BPR (60 kg P ha^{-1}) + urea	-248	-0.9	-399	-1.5	-514	-0.9
TSP (60 kg P ha^{-1}) + urea	-228	0.7	-284	-0.8	-512	-0.8
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	327	0.5	-232	-0.3	577	0.4
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	172	0.3	-506	-0.7	232	0.3
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	405	0.5	-234	-0.3	711	0.8
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	223	1.2	25	-0.2	161	0.4
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	100	0.6	-95	-0.8	114	0.3
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	138	0.6	-10	-0.1	302	0.8

Note: FYM: Farmyard manure; TSP: Triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock (source Opala *et al.,* 2010b).

seasons when BPR and MPR were used with urea as the N source in western Kenya (Table 3). However, when combined with tithonia, the financial returns were positive for both PRs in seasons with adequate rainfall. The use of MPR was the most attractive treatment in a study by Cheptoek *et al.* (2021) in western Kenya with an average net income of US$ 2122 over two seasons which was 20% higher compared to NPK. Savini *et al.* (2016) similarly, reported that use of MPR by farmers in western Kenya could be profitable for maize and soybean production, given that MRRs were above the 100% minimum acceptable rate of return which is a requirement for farmers to change from one technology to another.

Generally, the adoption rates for PRs in East Africa are low. Braun (2007) conducted an in-depth adoption study on adoption of PRs at the sites where ICRAF had conducted experiments. The adoption rates were disappointingly low. For example, in one instance out of the 13 interviewed farmers, none of them was using MPR despite the fact that 11 of them had heard about it. Some of the identified constraints to the use of MPR were its powdery nature which makes it messy to use, labour intensive, costlier than initially anticipated, lack of availability when needed and initial low and variable responses to application (Braun 2007, Vanlauwe and Giller, 2006). In addition, the presence of heavy metals and radioactive materials could hinder its adoption (van Straaten 2002). Paradoxically, Braun (2007) noted that PRs most touted assets, *i.e*. (local availability and low cost) were found to be the most serious constraints to its adoption.

CONCLUSION

Very few of the PRs in East Africa are suitable for direct application with MPR being the most promising. Various methods of increasing the solubility of the PRs to enhance their agronomic effectiveness have been studied with the use of OMs applied in combination with the PRs receiving most attention. Results have however been inconsistent. Crop responses varied with the type of PR, site and season making it difficult to develop a predictive understanding on the utilization of PRs. The financial returns due to use of PR varied from negative to positive. The adoption of PR among farmers was dismal with the unavailability of the PR in the market and high cost, being the main constraints. Stakeholder engagement, particularly with the targeted beneficiary smallholder farmers and marketers of PRs should be the starting point of knowledge intensive practices such as the use of PRs to enhance their chances of adoption.

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