Chapter 9
Role of Local Agro-minerals in Mineral Fertilizer Recommandations for Crops: Examples of Some West Africa Phosphate Rocks

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Abstract One of the major constraints to enhanced crop productivity in West Africa is low soil fertility and particularly soil deficiency in available phosphorus (P). When P is limiting, crop production is greatly compromised even though the other nutrients are available in large amounts. The use of soluble P fertilizers is hampered by the cost of the P fertilizers commercially available, too high for resource-poor farmers. Therefore, exploitation of the locally available phosphate rock (PR) deposits represents an alternative for soil P supply to ensure mineral plant nutrition. The effectiveness of a particular PR depends mainly on its chemical and mineralogical composition, and to some extent on environmental conditions, crop type and management practices. This communication highlights some results of the research works that have been carried out in the region to enhance the direct use of PR in agriculture and how theses PR can be integrated in fertilizer recommendations for crops. Direct application of phosphate rocks may be an economical alternative to the use of the more expensive imported water-soluble P fertilizers for certain crops and soils.

Keywords Agro minerals • Crops • Rock phosphate • West Africa

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9.1 Introduction

In the Sahelian zones of West Africa, agriculture is practiced under biophysical and socio-economic conditions characterized among others by: (i) erratic rainfall, with very marked spatio-temporal variation, (ii) Soils with a predominantly sandy texture, phosphorus-deficient, prone to runoff and erosion, poor in organic matter, and whose already low inherent fertility is exacerbated by mining agriculture practices, (iii) farmers' low investment capacities, and (iv) lack of incentive-based agricultural policies. In addition, there is pressure on crops by insects, diseases and weeds. Under these conditions, it is not surprising that ensuring food and nutrition security is at the center of Governments' concerns. According to FAO (2004), of the 840 million people who do not meet their energy needs, 790 million live in the developing countries of which 200 million Africans living in a situation of more or less chronic famine. According to AGRA (2014), about 223 million Africans south of the Sahara are chronically under-nourished and this number could be increased by 132 million in 2050 with the impacts of climate change. Food production in Africa has declined over the last two decades despite the global upward trend at the global level. While in Asia and Latin America over the past 35 years per capita cereal production has increased from 200 to 250 kg/person, it decreased in Africa from 150 to 130 kg/person.

In West Africa, only the following five countries have reached the threshold of 2400 kcal/pers. set by FAO: Benin, Côte dIvoire, Ghana, Mauritania and Nigeria (Ag 2004). According to Shrimpton (2002), the proportion of the population living on less than $1/day ranges from 12.3% in Côte d'Ivoire to 60% in Burkina Faso, Mali and Niger.

This explains why Africa received food aid in 2000 estimated at 2.8 million tons, a quarter of the world total. According to WRI (2014), Africa South of the Sahara will have to produce 360% more than it produced in 2006 to feed its population in 2050.

Therefore, one of the major challenges for African agriculture, in particular, in Africa south of the Sahara, and especially West Africa, is "to produce more and better to feed a growing population, while developing an important natural potential not only by using the widest possible scope for progress but also by taking advantage of the rise in agricultural prices."(AFD 2008). Another challenge is to promote a human capital available, through substantial support to family farmers, who in Africa south of the Sahara account for more than 80% of producers and who directly employ about 170 million people.

Despite this rather somber picture of the situation in Africa south of the Sahara, there are more and more success stories on strategies for the development and adoption of integrated soil fertility management technologies. The benefits of improving soil fertility at farm level as well as at national and global levels are increasingly well perceived by the international community.

However, the recommendations of fertilizer formulas must be well adapted to crops, according to the climatic and pedological characteristics of their production areas. These fertilizer formulas must be also economically profitable and enable sustainable production. Local agro-minerals, especially phosphate rocks, because of their availability and quality as soil amendment, allow to reduce crop production costs and contribute to the sustainable improvement of soil fertility.

9.2 Potential for Improving Agricultural Production and Productivity in West Africa

Compared to other continents, the performance of African agriculture is low (Fig. 9.1). While cereal yields have evolved positively from slightly over 2 t ha^{-1} en 1960 to over 6,5 t ha^{-1} en 2010 in the USA and Europe, those observed in

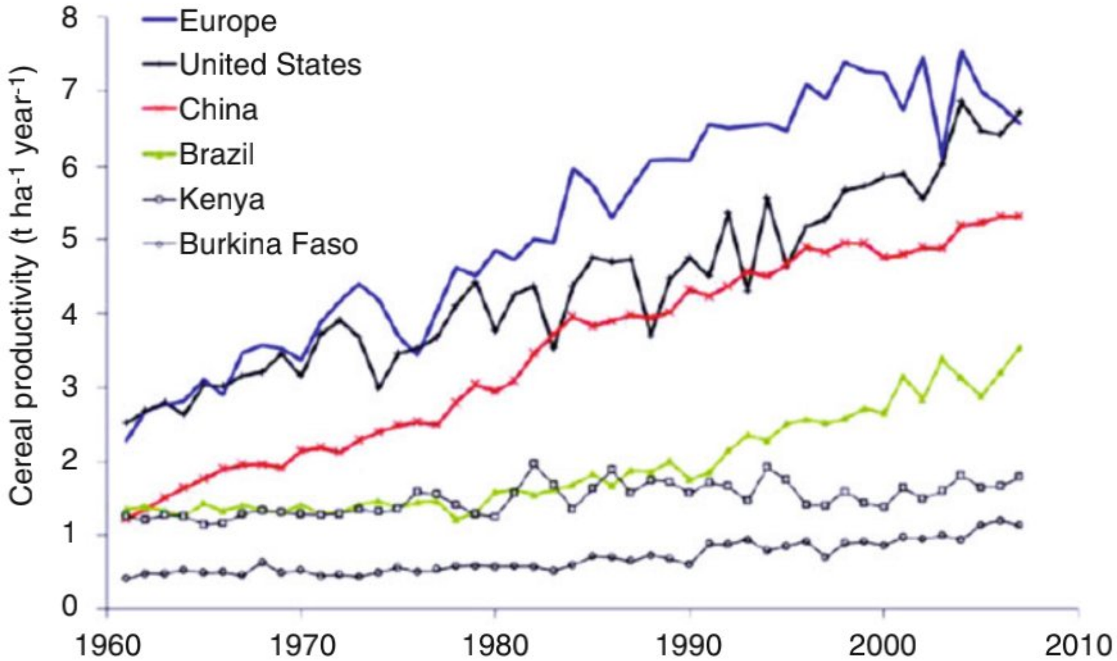

Fig. 9.1 Comparative cereal yields in different continents (Pera 2016)

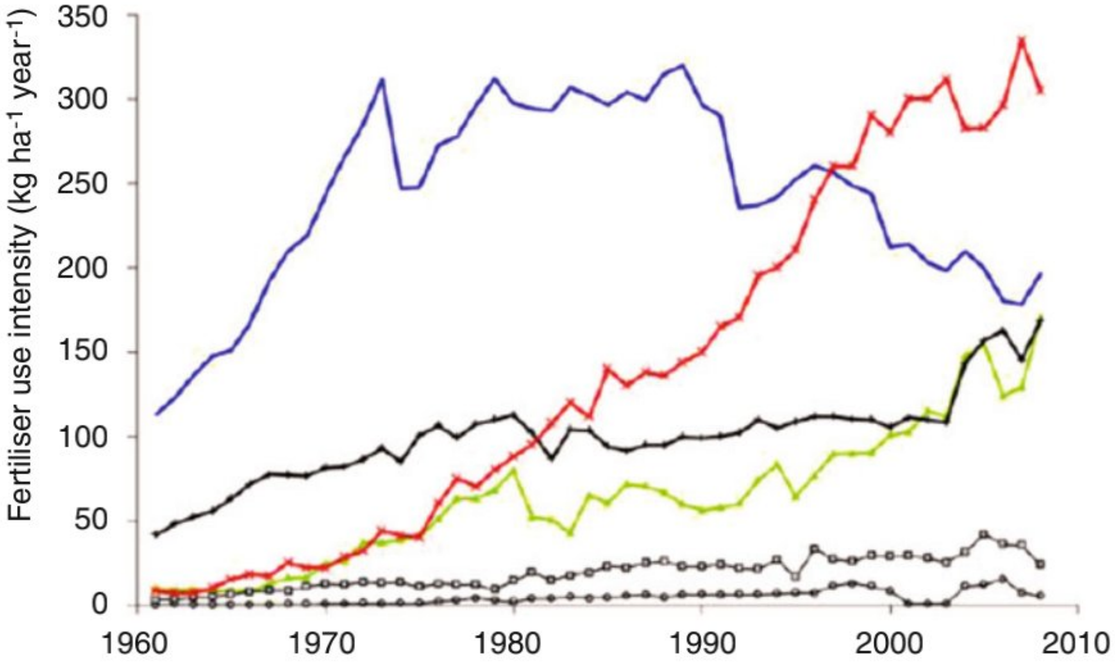

Fig. 9.2 Intensity of fertilizer use in different continents (Source: Pera 2016)

sub-Saharan Africa have increased from an average of 500 kg ha^{-1} to about 1 t ha^{-1} on average over the same period.

Referring to the amounts of fertilizers used in the same situations (Fig. 9.2), while in countries such as the United States, China and Brazil, the intensity of fertilizer use is on average above 100 kg $ha^{-1}an^{-1}$, this intensity is around 10 kg ha $^{-1}an^{-1}$en Afrique. In this context of mining agriculture, the mineral balances are increasingly negative, as shown in Fig. 9.3. Annual losses of 23 kg-N ha^{-1}, 6 kg-$P_2O_5ha^{-1}$, and 16 kg-K_2O ha^{-1}, are recorded in sub-Saharan Africa, mainly due to nutrient exports by productions (straw and grain), erosion and runoff (Henao and Baanante 2006), without any consequent compensation through the use of mineral fertilizers and/or organic amendments. Thus, nitrogen losses per year reach nearly 4.4 million tons compared to intakes estimated at only 0.8 million tons/year.

Considering intensification as an improvement in production per hectare due to an increase in labor, capital or new knowledge/techniques (Tiffen et al. 1994) and in view of the data in Fig. 9.4 showing the current and potential yields of major cereal crops in West Africa, it can be reasonably expected that farmers in this area will improve their living conditions through agricultural activities. Various traditional and improved technologies exist and can be used for this purpose.

Integrated soil fertility management plays an important role in the sustainable improvement of agricultural productivity in sub-Saharan Africa. In Sahelian agricultural production systems dominated by family-type farms, strong pressure on natural resources, especially on soils, has virtually eliminated the practice of fallow previously used to restore soil fertility.

Other factors such as low inherent soil fertility, soil depletion, low rates of return on investments in soil fertility, and low investment capacity of many smallholder

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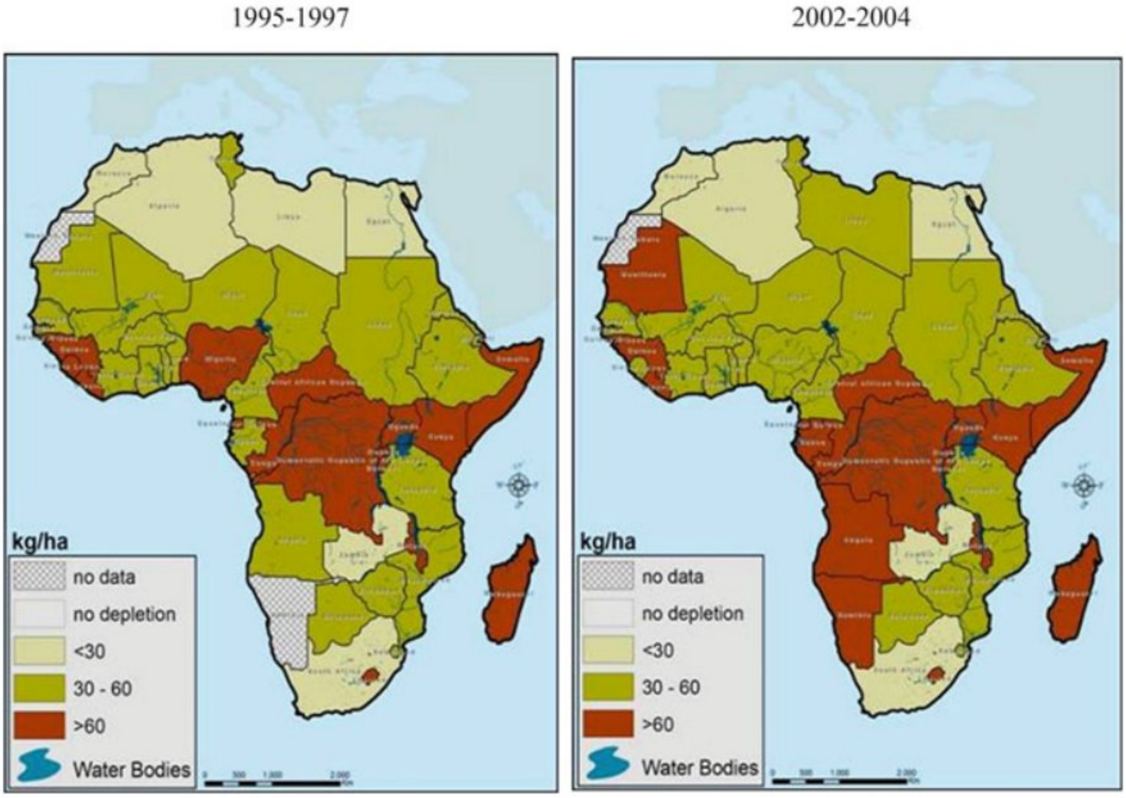

Fig. 9.3 Mineral balances on the African continent (Source: Henao and Baanante 2006)

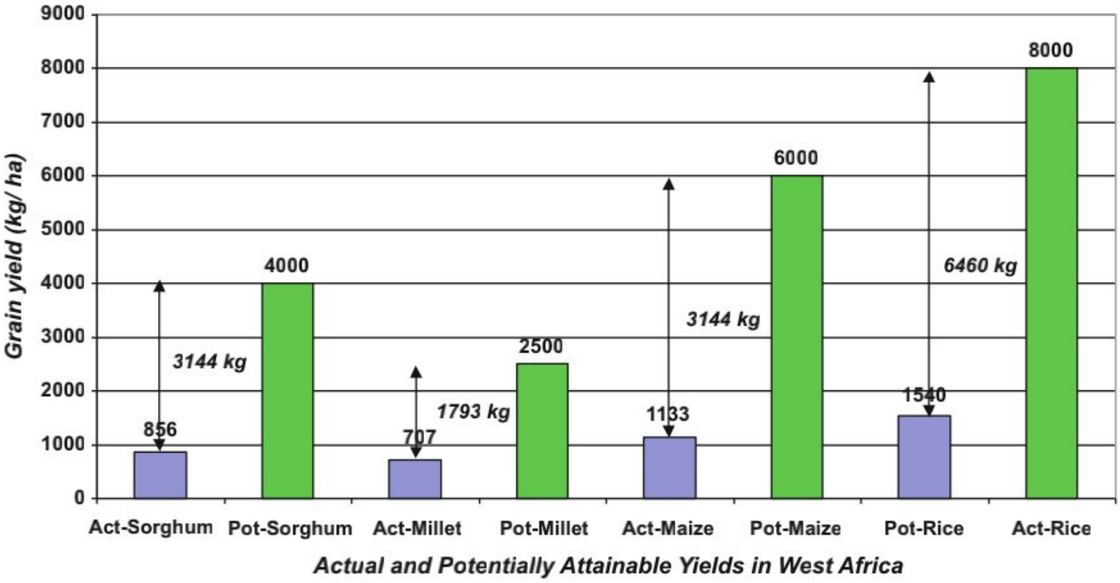

Fig. 9.4 Actual and potential yields of different cereals in West Africa

farmers are contributing to low soil fertility and low productivity in sub-Saharan Africa.

Paradoxically, sub-Sahan Africa has considerable potential for increasing agricultural productivity and production, and thus increase the contribution of agriculture to national wealth.

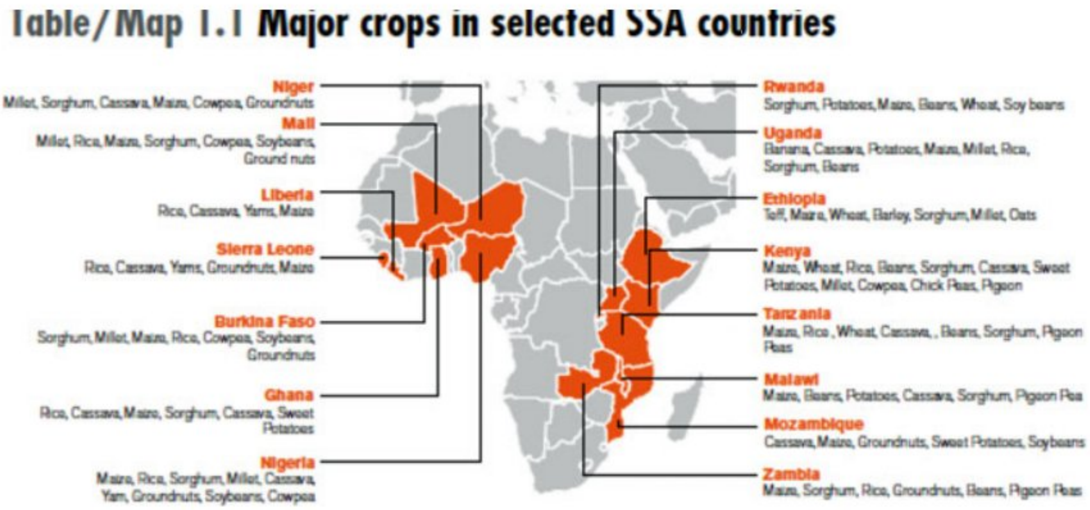

Fig. 9.5 Major crops in Africa south of Sahara (Source: AGRA 2014)

Of the 15 production systems identified in sub-Saharan Africa (Dixon et al. 2001), the most common in West Africa are:

- The agro-pastoral system millet/sorghum: This system is found in the semi-arid agro-ecological zone of West Africa. This area is characterized by an average annual rainfall of between 350 and 800 mm; strong pressure on arable land; high vulnerability of the system due to drought and climate change. Livestock farming is as important as agriculture. Millet and sorghum are the main staples and are intended for self-consumption; they are often cultivated in rotation or in association with cash crops such as cowpea, groundnut and sesame. Short to intermediate cycle maize is increasingly present. Rainfed rice is also increasingly present; it is grown in improved or unimproved wetlands and in the irrigated areas downstream of the water retention systems in increasing numbers.
- The mixed system of cereals-roots or tubers is more common in the sub-humid and humid agroecological zones of West Africa. The average annual rainfall varies between 800 mm and over 1100 mm. There is a wide variety of crops including maize, sorghum, millet, cowpea, groundnut, tuber crops, cotton, rice, fruit and vegetable crops.
- The pastoral system is practiced in the arid agroecological zone with an average annual rainfall of less than 350 mm. The potential for agriculture is very limited; this is the transhumance area.

This rich agro-ecological diversity favors the practice of a wide variety of crops (Fig. 9.5), with different requirements in terms of soil types and cropping practices, including those related to fertilization. These different crops are grown on five types of soils whose distribution in the countries of West Africa is indicated in Table 9.1. To these types of soils, must be added the Vertisols which represent around 1% of the soils in West Africa (Bationo 2008).

Table 9.1 Distribution (%) of the main types of soil in West African countries

Country	Arenosols (Psammients)	Lixisols (Alfisols)	Nitisols (Ultisols + Alfisols)	Acrisols (Ultisols)	Ferrasols (Oxisols)
Benin	**–**	**80**	**6**	**–**	**–**
Burkina Faso	**6**	**46**	**–**	**–**	**–**
Côte d'Ivoire	**–**	**–**	**–**	**72**	**–**
Gambia	**–**	**–**	**25**	**–**	**–**
Ghana	**–**	**52**	**–**	**25**	**–**
Guinea	**–**	**–**	**–**	**22**	**13**
Guinea Bissau	**–**	**55**	**5**	**–**	**18**
Mali	**15**	**–**	**–**	**–**	**–**
Mauritania	**10**	**–**	**–**	**–**	**–**
Niger	**30**	**–**	**–**	**–**	**–**
Nigeria	**13**	**34**	**14**	**5**	**–**
Liberia	**–**	**–**	**–**	**8**	**79**
Senegal	**30**	**–**	**–**	**–**	**70**
Sierra Leone	**–**	**–**	**–**	**–**	**70**
Togo	**–**	**59**	**11**	**–**	**–**

Source: Bationo (2008)

Lixisols (leached tropical ferruginous soils according to the French classification) are found in tropical and subtropical areas, and in high temperature regions with a marked dry season. They are characterized by high levels of low active clays with low nutrient retention capacity but with high cation saturation. The use of Lixisols for sustainable agricultural production requires the application of organic and mineral fertilizers.

Ferralsols (Ferralitic soils according to the French classification) are found mainly in the humid tropics. They are rich in kaolinite and sesquioxides, which are at the root of the high P-binding capacity in this type of soil. Their cation exchange capacity is low and they are most often deficient in molybdenum. Ferralsols have good physical properties (depth, permeability, drainage, ease of tillage, etc.). On the other hand, these soils are chemically poor (low cation retention capacity, low N, K, Ca, Mg and S contents). These are usually acidic soils. The fertility management of ferralsols very often requires the use of lime to fight against aluminum toxicity, but also to increase the CEC. The application of phosphate rocks also allows to correct P deficiency for a number of years.

Acrisols are found in humid tropics and subtropics and in high temperature regions. They are fairly or highly desaturated ferralitic soils in the French classification. They have a clayey B horizon and are usually acidic. They are typically nutrient deficient soils. They have high aluminum content, which gives them high phosphorus-binding capacity.

Table 9.2 Chemical characteristics of granitic soils in different agro-ecological zones of West Africa

Agroecological zone	Depth (cm)	pH H_2O	Org. C. (mg kg^{-1})	Total N (mg kg^{-1})	Total P (mg kg-1)	CEC (cmol kg^{-1})	Saturation level (%)
Equatorial	**0–20**	**5,3**	**24,5**	**160**	**628**	**88**	**21**
Forest	**20–50**	**5,1**	**15,4**	**1,03**	**644**	**66**	**16**
Guinean	**0–20**	**5,7**	**11,7**	**1,39**	**392**	**63**	**60**
Savanna	**20–50**	**5,5**	**6,8**	**0,79**	**390**	**56**	**42**
Soudanian	**0–20**	**6,8**	**3,3**	**0,49**	**287**	**93**	**93**
Savanna	**20–50**	**7,1**	**4,3**	**0,61**	**285**	**87**	**90**

Arenosols are sandy-textured soils including dune soils in desert areas. They are found in arid lands, in humid and sub-humid temperate zones. These are undeveloped mineral soils, and slightly developed soils in the French classification. These are soils with a light texture, high permeability and low water storage and nutrient retention capacity.

Nitisols (Fersial soils in the French classification) are deep, well-drained soils. The clay content of the surface horizon is greater than 30%. These are soils with a high level of inherent fertility. They may exhibit manganese toxicity and high phosphorus binding capacity. Nitisols are found mostly in the tropical zone, especially in uplands.

Vertisols are soils with high agricultural potential. These are soils with high clay content. Their physical properties constitute real constraints which limit their development especially the preparation of this type of soil and water management.

Table 9.2 presents the chemical characteristics of soils in the different agro-ecological zones of West Africa. It clearly shows that the soils of the equatorial, forest and Guinean zones are richer in organic matter, nitrogen and phosphorus than other areas.

Generally, the soils in tropical Africa are very old and come from the alteration of parental materials dating from the Precambrian. Their physicochemical properties are strongly related to these parental materials but also to climate characteristics. Lixisols, Ferralsols and Acrisols contain large amounts of iron and aluminum oxides which only partially cover the surface of the soil particles. In soils where iron and aluminum oxides form a thick and stable envelope around clay particles, there is a strong fixation or even occlusion of phosphorus. Phosphorus deficiency constitutes the major constraint to agricultural production in West Africa. In Africa south of the Sahara, 80% of the soils are P deficient (Bationo 2008).

This P deficiency has been evidenced by numerous authors among them Dabin (1974), Boyer (1981), Bationo (2008). P deficiency originates in the nature of the geological substratum and its evolution in the formation of tropical soils and in the low organic matter content and the depletion of the nutrients reserves of the soils under cultivation. Under tropical conditions characterized by high temperatures and alternating wetting and drying phenomena, the mineralization of soil organic matter (already low) is rapid, leading to soil depletion and subsequent retrogradation of phosphorus from fertilizers. Organic phosphorus, which accounts for 20–60% of total soil P, is related to the content and the level of development of soil organic matter.

Boyer (1982) reports that soils resulting from long pedogenesis (as is the case with most tropical soils) are characterized by a predominance of P-forms linked to aluminum (P-Al) and iron (P-Fe) which are not easily accessible to plants.

Paradoxically, in sub-Saharan Africa the use of phosphate fertilizers is the lowest (1.6 kg per ha per year) compared to 7.9 kg and 14.9 kg $ha^{-1}an^{-1}$ respectively in Latin America and in Asia.

The phosphate fertilizers used on crops (TSP, DAP, etc.) are imported, while Africa has large deposits of phosphate rocks which unfortunately are not sufficiently exploited.

9.3 Review of Agromineral Potential in Africa

Africa has significant agro-mineral deposits that can provide nutrients (N, P, K, Ca, Mg, S) for crops. Some of these deposits are present in West Africa (Mokwunye and Bationo 2006). Van Kauwenbergh (2006) and Van Straaten (2007) have made an inventory of these agro-mineral resources and their use.

Thus, according to Van Kauwenbergh (2006), the enormous potential in terms of coal, hydrocarbon and natural gas in Africa represented 8%, 9% and 6% of the world's reserves at one point in time. These resources can be used for the industrial production of nitrogen (N) for plants. Large deposits of hydrocarbon and natural gas exist in the coastal zones of West Africa. Large deposits have also been recently discovered in continental countries such as Niger, Mali, Chad, etc.

Regarding potassium (K), two important deposits exist and are exploited in the Democratic Republic of Congo and in Ethiopia/Eritrea. Egypt and Morocco also have potassium deposits. According to Van Straaten (2011), sources of K exist in Togo, but they have low solubility. The same author reviews the sources of sulfur (S) other than organic matter, which exist in Africa. Deposits of elementary S are limited; they are found in Mauritania and Egypt. On the other hand, the sulphated form (gypsum) is widespread in Africa, notably in Mali, Mauritania, Niger, Nigeria and Chad. It should be noted that phosphogypsum is a by-product of phosphate industries in Senegal. The sulphides exist on the continent in the form of pyrite and/or chalcopyrite and are associated with other minerals such as gold or zinc. This source is often used for the production of sulfuric acid which is used for the production of soluble phosphate fertilizers. Despite these important sources of sulfur in Africa, they are not exploited for agricultural production.

Sources of calcium (Ca) and magnesium (Mg) also exist in Africa, in the form of calcium and/or magnesium carbonates. But the minerals containing these two elements, which are very important for soils and plants, are used more for the production of cement and tiles than for agricultural production.

Phosphate rocks (PR) deposits, a source of phosphorus for crops, exist in Africa and have been the subject of numerous studies since the beginning of the twentieth century both for their direct application and for the improvement of their agronomic efficiency (association with organic matter, partial acidification, PR solubilizing bacteria, use of mycorrhizal fungi, soil management methods, etc.). The results of these studies have often been a subject of controversy because of the complexity of phosphate rocks but also of the soils in which they are used (Hammond 1978). The following section of this document presents the major results achieved in the agricultural use of phosphate rocks with a view to promoting their use in the formulation of fertilizer formulas but also in the restoration of soil fertility.

9.4 West Africa's Phosphate Rocks as Inexpensive Source of Phosphorus in Fertilizer Recommendation Formulas

Africa has 80% of the world's phosphate rock reserves (Van Straaten 2011), which can be inexpensive sources of phosphate fertilizers locally available for crops. Figure 9.6 and Table 9.3 show respectively the localization of phosphate rock deposits in Africa and those existing in West Africa with their reserves, their P_2O_5 contents and their exploitation status.

These reserves are estimated at 1 million tons at 32% P2O5 for Rambuta reserves in Liberia; 200 million at 23% P2O5 for the Tapoa deposits in Niger. Some of these deposits are commercially exploited. These include the deposits of Hahotoé and Kpogamé in Togo, and Taïba and Thiès in Senegal. The deposits of Kodjari in Burkina Faso, Tilemsi in Mali and Tahoua in Niger are exploited through traditional mining, especially for local consumption. Johnson (1994) has identified over 20 other deposits in West Africa which are not yet exploited. Despite the wealth of West African countries in phosphate rocks, these countries, paradoxically, import phosphate fertilizers for political, economic and technical reasons.

9.5 Use of West Africa's Phosphate Rocks

Due to the presence of important deposits with interesting grades in sub-Saharan Africa, phosphate rocks constitute a valued local source of phosphorus for the countries that have them. However, it should be pointed out that virtually all phosphate rocks in West Africa have PO4/CO3 $>$ to 5 ratios making them unreactive or slightly reactive phosphates. Chien (1977) showed that the solubility of phosphate rocks in ammonium citrate is directly correlated to this PO4/CO3 ratio. Table 9.4 gives the percentages of solubility as well as the PO4/CO3 ratios of some of these phosphate rocks. According to Diamond (1978) cited by Bationo (2008), the fitness of phosphate rocks for direct application in agricultural

Fig. 9.6 Phosphate rock deposits in Africa (Source: Van Kauwenbergh 2006)

production is said to be high when the solubility in ammonium citrate is > 4%; it is average when this value is between 3.2 and 4.5%; it is low when the solubility is <2.7. On the basis of this classification it can be said that only the phosphates of Tilemsi and Sokoto have an average reactivity.

Given the complex biogeochemical cycle of phosphorus, there are several models for the representation of soil phosphorus flows and stocks. According to the model proposed by Banque Mondiale et al. (1994) and shown in Fig. 9.7, three major forms of phosphorus can be distinguished: agricultural phosphorus, capital phosphorus and inert phosphorus. The proportions of these three forms depend on many factors, including the type of soil, the degree of alteration of the substratum, the climate, and the importance and nature of the mineral colloids (clays).

Table 9.3 Major phosphwithe rock deposits in West Africa

Localiswithion	Reserves in millions of tons	Exploitwithion stwithus
Benin		
Mékrou	5 with 18% de P_2O_5	Unexploited
Pobé	–	Unexploited
Burkina Faso		
Kodjari	103 with 18–23%P_2O_5	Artisanal mining
Arly	4 with 15–32% P_2O_5	Unexploited
Guinea Bissau		
Farim-saliquinhe	112 with 30% P_2O_5	
Ghana		
Sekondi		Unexploited
Liberia		
Bambuta-Bomi Hill	1 with 32% P_2O_5	Artisanal mining
Mali		
Tilemsi	20 with 15–32% P_2O_5	Artisanal mining
Assakerei	–	Unexploited
Mauritania		
Bofal-Loubboira	100 with 19–20% P_2O_5	–
Niger		
Askia-Tinamou	–	–
Tahoua	5 with 25% P_2O_5	Artisanal mining
Tapoa	200 with 23% P_2O_5	Unexploited
Nigeria		
Abeokuta	–	–
Sénégal		
Taiba	100 with 18–39% P_2O_5	1,5 millions of t/an
Thiès	100 with 28% P_2O_5	0,5 millions of t/an
Pire Goureye	25 with 34%P_2O_5	–
Mwitham	36 with 28% de P_2O_5	Unexploited
Togo		
Hahotoe	130 with 28% P_2O_5	2 millions of t/an
Bassar	10 with 38%P_2O_5	Unexploited

Source: McClellan and Notholt (1986) and Truong (1989)

Table 9.4 PO_4/CO_3 ratios and % of solubility in ammonium citrate of some phosphate rocks of West Africa

Phosphate Rocks	PO_4/CO_3	Solubility (% P_2O_5)
Kodjari	23,00	1,9–2,7
Parc W	15,20	1,4–2,8
Hahotoe	12,30	2,5–3,2
Tahoua	4,88	1,9–3,6
Tilemsi	11,20	4,1–4,6
Sokoto	11,50	3,2–3,7

Source: Bationo (2008)

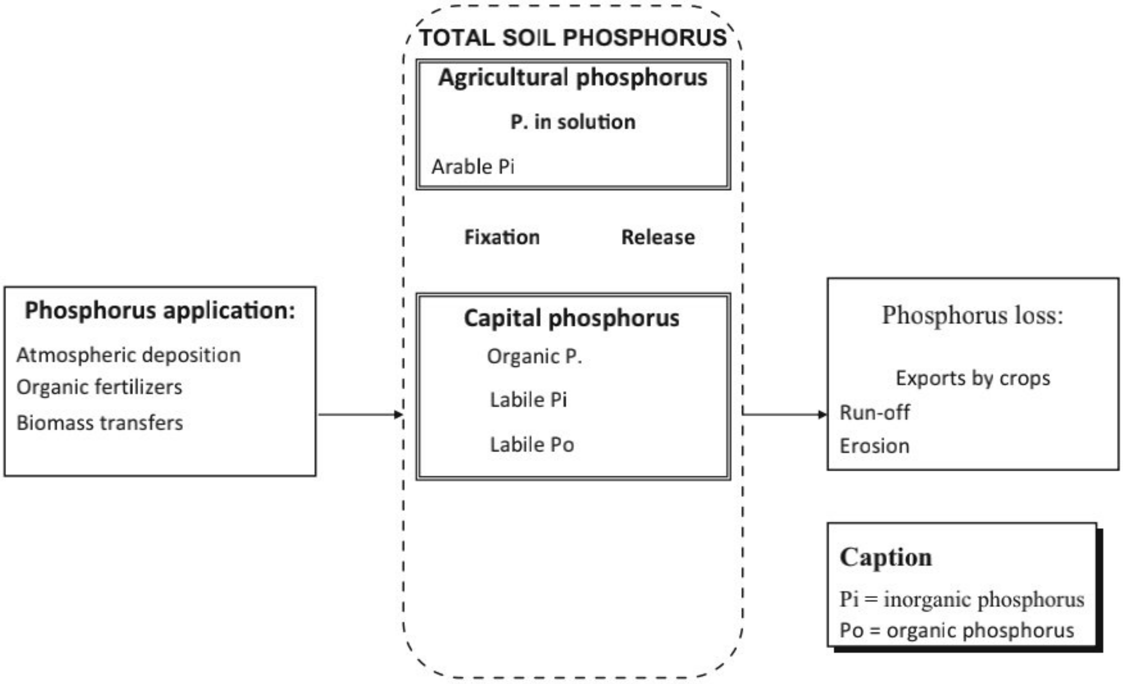

Fig. 9.7 Sources, flows and stocks of phosphorus in soils Banque Mondiale et al. (1994)

Agricultural phosphorus is the phosphorus available for crop production during a crop cycle. It is composed of phosphorus in solution and available phosphorus. The capital phosphorus is, by analogy with the management of farms or companies, the "business assets", the reserve or even the phosphorus stock. This stock supplies the agricultural phosphorus pool.

Therefore it appears clearly that the application of phosphate rocks, especially those with slow reactivity, will influence the "capital" phosphorus rather than the "agricultural" phosphorus.

The ability of phosphate rocks to supply phosphorus to plants depends on several factors including the physical and chemical characteristics of the ore, soil properties, climatic conditions, agricultural practices, cropping systems and plant type. Figure 9.8 shows the factors involved in the solubilization of phosphate rocks.

Numerous studies have been carried out in many West African countries to determine the agronomic efficiency of phosphate rocks and the best methods for their use (Truong et al. 1978; Truong 1989; Bationo and Mokwunye 1991; Bationo et al. 1994; Bationo and Kumar 1999). These studies were carried out through a range of methods including solubility tests in different reagents, incubations of different soil types, controlled pot experiments, research station experiments. Multilocal on-farm experiments were carried out taking into account different pedoclimatic conditions and cropping systems, and different cultivation practices. Most of these studies show that despite the low reactivity of most phosphate rocks in West Africa, they can contribute to improve crop yields (Mokwunye 1996; Mokwunye and Bationo 2011).

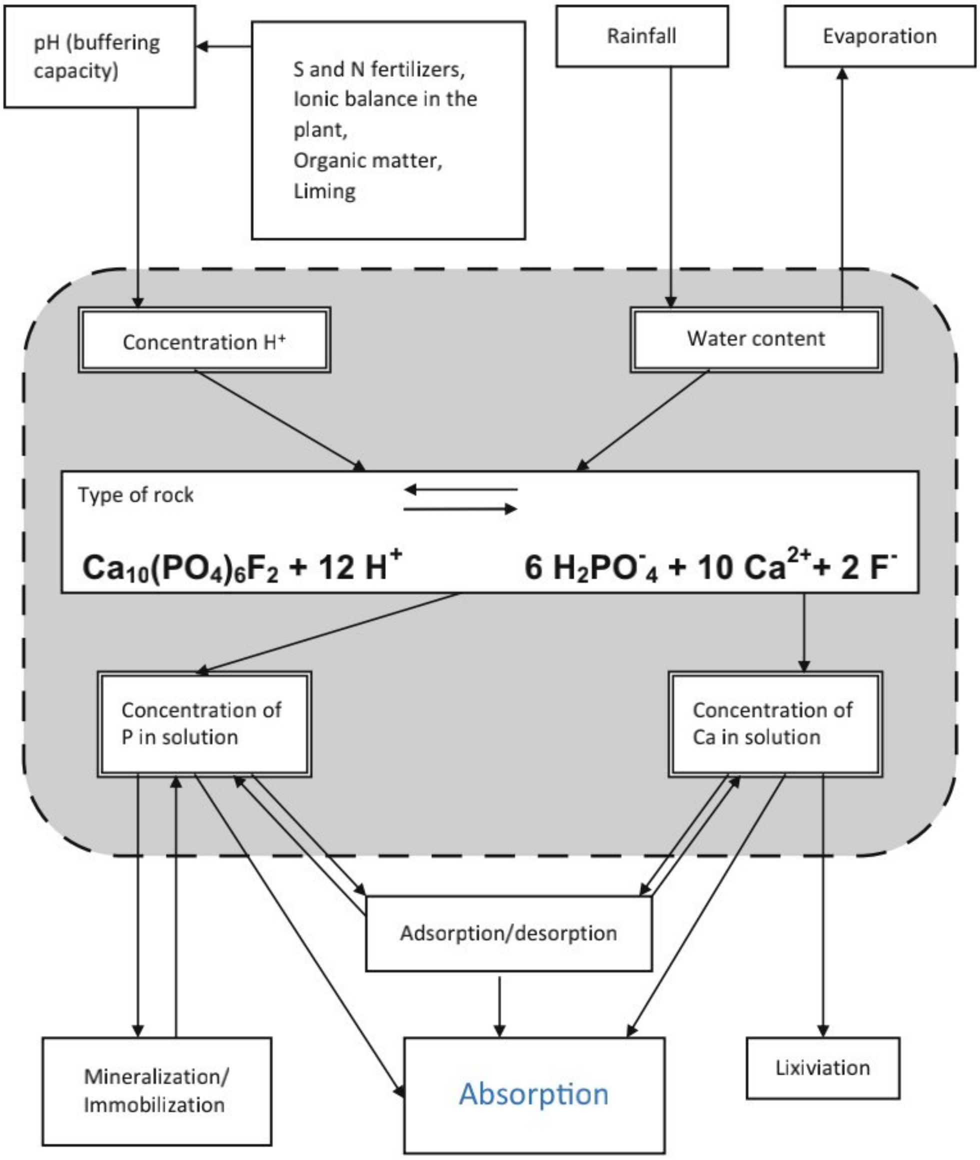

Fig. 9.8 Factors limiting the solubilization of phosphate rocks in soils (in the dotted area) and variables (outside the dotted area) influencing these factors (Source: Adapted from Bolan and Hedley 1990)

9.5.1 *Use of Phosphate Rocks for Crop Fertilization in Niger*

Numerous studies have also been carried out in Niger by the team led by André Bationo and his collaborators. Thus, the agronomic efficiency of Tahoua phosphate rocks (TPR) when combined with nitrogen was demonstrated. The data in Table 9.5 show that phosphorus application increases cowpea residue yields by 930 kg ha^{-1}. This increase is 765 kg ha^{-1} with the application of the same amount of P from the TPR. On the contrary, there is no difference between the sources of P on grain yields of millet in Gaya (685 and 665 kg ha^{-1}, respectively). It is noted that the

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Table 9.5 Effects of combinations of different sources of phosphorus on grain yields of millet and residue yields of cowpea

	Karabedji		Banizoumbou
	Millet	Cowpea	Millet
Treatments	Grain yield	Residue yield	Grain yield
1 Absolute control	255	2250	276
2 30 kg N ha^{-1}	435	3031	432
3 12 kg P ha^{-1}	600	3594	708
4 12 kg P ha^{-1} PRT + 30 kg N ha^{-1}	520	4000	417
5 9 kg P ha^{-1} PRT + 3 kg P + 30 kg N	810	4531	583
6 6 kg P ha^{-1} PRT + 6 kg P + 30 kg N	893	4906	625
7 3 kg P ha^{-1} PRT + 9 kg P + 30 kg N	973	5438	760
8 12 kg P ha^{-1} + 30 kg N	708	4125	708
Standard deviation	24	135	59
CV	7%	7%	21%

Source: Bationo (2008)

combination TPR (50%) with soluble phosphate (50%) enables to obtain a yield of 770 kg ha^{-1}.

Bationo (2008) reported the results of its research in three agroecological zones of Niger, concerning the agronomic efficiency of the TPR and the Kodjari phosphate rocks (KPR), compared to SSP. The results achieved indicate that the agronomic efficiency values of the TPR were higher on millet than on legumes. Regarding millet grain yield varied from 63% to 80% and from 60% to 68% for the total production of biomass. For cowpea, it was between 42% and 73% for the production of residues and 52% to 72% for the total production of biomass. Whatever the site, the agronomic efficiency of the TPR is typically higher than that of the KPR. Similarly, the effects of two sources of P (PRT) and triple superphosphate (TSP) on yields and P use efficiency (PUE) by rice (Table 9.6). It was found that the highest PUE value (89 kg grain/kg P) was achieved with the TPR rate of 26 kg P ha^{-1}. With the triple superphosphate, the highest PUE (64 kg grain kg^{-1} P) was achieved with the rate of 22 kg P ha^{-1}.

The phosphate rocks of Kodjari (KPR) and those of Tahoua (TPR) were also evaluated by Bationo et al. (2011), through two modes of application, broadcast application (B) and localized application per pocket (P). On millet grain production, P use efficiency (PUE) from broadcast application of simple superphosphate (SSP) at the rate of 13 kg P ha^{-1}, was 26 kg kg^{-1} P. The efficiency of SSP application per pocket at the rate of 4 kg P ha^{-1} was 98 kg kg^{-1} P and 142 kg kg^{-1} P with the NPK blend applied per pocket. With broadcast TPR, the PUE was only 10 kg kg^{-1} P to reach 35 kg kg^{-1} P when the complex NPK fertilizer was applied per pocket, in addition to the TPR at the rate of 4 kg P ha^{-1}. For the production of cowpea residues, PUE values with broadcast SSP and NPK complex were 96 and 163 kg kg P^{-1} respectively. However, their application per pocket at the rate of 4 kg P ha^{-1}

Table 9.6 Effects of different rates of two phosphorus sources on rice yields and on phosphorus use efficiency (PUE)

Sources of P	P Rates (kg ha^{-1})	Grain yield (kg ha^{-1})	PUE Kg grain kg^{-1}P
PRT	0	1740	–
	26	4057	89
	39	4147	62
	52	4525	54
	65	5458	57
TSP	78	4853	40
	22	3150	64
	44	4222	56
	65	3810	32

PRT Phosphate rocks of Tahoua; *TSP* triple superphosphate

Table 9.7 Effects of sources and modes of P application on yields and P use efficiency for millet and cowpea in Karabedji, Niger

Treatments	Millet		Cowpea	
P Sources and application modes	Grain yield (kg ha^{-1})	PUE (kg kg^{-1} P)	Residues (kg ha^{-1})	PUE (kg kg^{-1} P)
1 Absolute control	444		1781	–
2 SSP (V)	776	26	3031	96
3 SSP (V) + SSP (V)	1151	42	4063	134
4 SSP (P)	834	98	3188	352
5 15–15-15 (V)	980	41	3906	163
6 15-15-15 (V) + 15-15-15 (P)	1510	63	5313	208
7 15-15-15 (P)	1010	142	3875	523
8 PRT (V)	569	10	2344	43
9 PRT (V) + SSP (P)	923	28	3000	72
10 PRT (V) + 15–15-15 (P)	1043	35	3625	108
11 PRK (V)	569	10	2375	46
12 PRK (V) + SSP (P)	1005	33	3094	77
13 PRK(V) + 15-15-15(P)	1094	38	3625	108
SE	28		167	
CV	6%		10%	

SSP simple superphosphate, 15-15-15: N_2 P2O5 K_2O complex fertilizers; *TPR* Tahoua Phosphate rocks; KPR: Kodjari Phosphate rocks; *B* Broascast application (13 kg P/ha); *P* Application per pocket (4 kg P/ha); *PUE* Phosphorus use efficiency (Grain yield/kg P applied)

gave PUEs of 352 and 523 kg kg^{-1} P. These data clearly show that localized application per pocket allows to improve PUE and that localized application of small amounts of soluble phosphate can also improve the agronomic efficiency of phosphate rocks (Table 9.7).

Table 9.8 Effect of Burkina Faso phosphate rocks combined with manure on soil chemical characteristics in Saria, Burkina Faso

Treatments	pH Eau	C tot. (%)	N tot. (%)	P tot. (mg kg^{-1}	Pav. (mg kg^{-1})	Ca cmol kg^{-1})	Mg cmol kg^{-1})
Absolute control	4.5	1.17	0.42	197	1.42	1.67	0.34
NPK disseminated	4.2	0.21	0.20	198	3.40	1.29	0.23
BP yearly	5.0	0.21	0.19	252	4.78	2.15	0.34
BP yearly + manure	4.8	0.28	0.17	241	6.79	2.42	0.38
BP correction + BP yearly	5.0	0.20	0.14	215	5.71	2.16	0.38
BP correction + BP yearly + manure	5.2	0.25	0.09	222	6.30	2.16	0.31
Initial soil (1982)	5.5	0.82	0.21	–	–	1.70	0.68

Source: Lompo et al. (1994)

9.5.2 *Use of Phosphate Rocks for Crop Fertilization in Burkina Faso*

Several studies on Burkina phosphate rocks, known as Burkinaphosphate (BP), show that it improves crop production as well as the physical, chemical and biological properties of soils (Hien et al. 1992; Lompo 1993; Bationo et al. 1987; Lompo et al. 1994; Bonzi et al. 2011). As shown in Table 9.8, BP (i) improves soil structure when combined with manure; (2) stabilizes cereal production when applied as basal dressing combined with manure, with increased levels of total P, Ca and magnesium in soils; (3) stimulates the activity and proliferation of microbial strains contributing to the decomposition of organic substrates.

In addition, a number of multi-site and multi-year trials were conducted to assess the agronomic efficiency of BP on different crops compared to other sources of phosphorus available in Burkina Faso.

9.5.3 *Effects of Phosphate Rocks on Irrigated Rice*

The works of Bado (1991) in the irrigated area of the Kou Valley in southwestern Burkina Faso allowed to compare BP with TSP (triple superphosphate) over three (03) cropping seasons. The results are given in Table 9.9.

The relative efficiency ratios of BP versus TSP on irrigated rice are shown in Table 9.10**.**

Table 9.9 Yields (kg ha^{-1}) of paddy rice - Kou Valley, Burkina Faso

	Burkina phosphate (BP)			Triple Super Phosphate (TSP)		
Kg P_2O_5 h_a^{-1}	HS88	DS88	HS89	HS88	DS89	HS89
0	4975	944	1020	4975	994	1020
30	5122	1216	1023	4634	1726	1676
60	5131	1461	1214	4979	1390	1389
90	4807	1817	1133	4556	1707	1268

HS humid season; *DS* dry season

Table 9.10 Relative efficiency ratios of phosphate on irrigated rice in the Kou Valley in Burkina Faso

P_20_5	Humid season 1988	Dry season 1989	Humid season 1989	TSP
Kg ha^{-1}	BP	BP	BP	
30	114	7	40	100
60	110	133	78	100
90	124	121	80	100

Bado (1991)

Paddy rice yields, relative efficiency ratios, and production functions linking phosphate to grain yields led to the following conclusions:

- BP is not efficient on irrigated rice at rates below 500 kg ha^{-1};
- BP is more efficient than TSP when applied at high rates.

The inefficiency of low rates of BP on irrigated rice would be related to the type of soils found in these areas. Indeed, these are hydromorphic soils, very rich in clays and hydroxides, thus raising their binding capacity. Consequently, much of the soluble P would be very quickly fixed in the soil and temporarily or permanently escaped from the plant. Thus, the small amounts of soluble P contributed by BP are totally fixed, hence its inefficiency. At high rates, BP can saturate the binding sites and the insoluble P being solubilized remains available for rice. Indeed, in this hydromorphic environment, the presence of sulfur ions and other hydroxides and the continuous dissolution of carbon dioxide (carbonic gaz) from the air in water create favorable conditions for the attack and solubilization of BP. To that must be added the dissolving capacity of irrigation water reported by Kouma (2000). BP is more suitable for acid hydromorphic soils at the rate of 500 kg ha^{-1} as basal dressing in the first year plus 200 kg ha^{-1} as supplementary annual dressing in the other years, the soluble sources being exposed to P fixation.

9.5.4 *Effects of Phosphate Rocks on Rainfed Rice*

The trials on rainfed rice carried out on ferralitic soils slightly acidic yielded interesting results (Table 9.11).

Table 9.11 Effect of phosphates on yields of paddy rice in ferralitic soil at Farako-Bâ (kg ha^{-1}) in Burkina Faso

	BP		TSP	
$P_2 0_5$ (kg ha^{-1})	1988	1989	1988	1989
0	2533	1643	2533	1643
30	2735	2269	2799	2065
60	3301	2562	3054	1593
90	3014	2387	3128	2471

Source: Bado (1998)

Table 9.12 Synthesis of three (03) years of on-farm trials in several sites across Burkina Faso

	Maize 50 sites		Millet 52 sites		Sorghum 127 sites	
Treatments	Grain yield. kg ha^{-1}	Eff. ratio (%)	Grain yield kg ha^{-1}	Eff. ratio (%)	Grain yield kg ha^{-1}	Eff. ratio eff. %
Absolute control	1020	–	542	–	812	–
BP	1759	79	723	55	1095	63
NPK	1973	100	869	100	1260	100

Source: Hien et al. (1992)

These results show that BP is as efficient as TSP in these soils. The recommended rate is 600 kg ha^{-1}. BP is highly efficient on rainfed rice in acidic ferralitic soils at an optimal rate of 600 kg BP ha^{-1} as basal dressing in the first year plus 300 kg BP ha^{-1} as supplementary annual dressing in subsequent years.

Numerous trials with BP as a source of P were carried out throughout Burkina Faso as part of the Food Crop Fertilizers Project for three successive years. Table 9.12 summarizes the results of these trials conducted in three agro-ecological zones:

A: annual rainfall <600 mm
B: $600 <$ annual rainfall <800 mm
C: rainfall > 800 mm

The agronomic efficiency ratio (Eff. Ratio) is evaluated in relation to NPK as the source of soluble P. The main conclusions that can be drawn from these on-farm trials are the following:

- BP is efficient on maize in the rainiest areas and on millet, a plant with high root density;
- With sorghum, the responses to the BP-based formula are variable depending on the area and could be rather based on pH and soil P deficiency levels.

9.6 Agronomic Performance of Some Partially Acidified Phosphate Rocks of West Africa

The low reactivity of most phosphate rocks in West Africa limits their agronomic efficiency when used directly in annual fertilization on annual crops. Partial acidulation, which aims to improve phosphate solubility, consists in attacking the minerals by mineral acids (H_2SO_4, H_3PO_4, HCl). This attack is called partial because the amount of acid used lower than that required for the production of TSP (in the case of sulfuric acid) SSP (in the case of phosphoric acid) for which the attack by acids is total. A variety of partially solubilized phosphate rocks having different compositions and agronomic efficiencies are thus obtained.

Paul (1998) carried out an important research work on the characterization and evaluation of partially acidified phosphate rocks from Anecho (Togo), Tilemsi (Mali) and Kodjari (Burkina Faso). He reported the results of the evaluations of these products in vase vegetation and on farms managed by IFDC and IRAT.

For Togo phosphate rocks, efficiencies on crops of products obtained through partial acidification, compared to TSP or SSP are between 51% and 90% depending on the percentage of acidification and the type of acid used. On-farm trials comparing the effects on different crops (groundnut, cotton and maize) of different sources of P (including NPK complex, phosphates solubilized at 50% with H_2SO_4), show that the yields obtained with the soluble P source are higher than those obtained with the partially solubilized phosphate. The efficiency ratios for soluble phosphate are 68% for cotton, 86% for maize and 90% for sorghum and groundnut (Truong 1984).

For the Mali phosphates, the results obtained by Samaké (1987) indicate equivalence between the phosphate rocks of Tilemsi acidified at 27.3% with H_3PO_4 and SSP.

Regarding the Burkina phosphate rocks, trials carried out under the Food Crop Fertilizers Project focused on the comparison between TSP and the BP partially solubilized by a mixed attack (H_2SO_4 + H_3PO_4). The agronomic results show that sometimes partially acidulated phosphate rocks are practically equivalent to superphosphates.

9.7 Conclusion and Perspectives

Considerable amount of research works have been carried out on West Africa's phosphate rocks. They have demonstrated the relative agronomic efficiency of these phosphate rocks despite their low reactivity. Phosphate rocks are well suited for improving soil fertility by enabling to recharge the pool of "capital P", which in turn will feed the pool of agricultural P as the plants feed on this agricultural P. These two pools are the main sources not only for supplying P to crops but also for correcting soil P deficiencies in West Africa. The replenishment of P stocks by direct application of phosphate rocks is a very profitable investment, especially when PR applications are combined with organic matter supplies, water harvesting and other nutriment management techniques, and good agricultural practices.

Despite this scientific evidence, most phosphate rock deposits in West Africa are not exploited. Policy makers and fertilizer manufacturers are challenged to take account of these agro-mineral resources, including the important potential of the sub-region regarding dolomite and sulfur. Pre-feasibility studies for phosphate rock- based fertilizer plants exist for some of the natural phosphate deposits. The construction of fertilizer formulation plants should provide a basis for the establishment and implementation of public-private partnerships. The issue of land tenure security is also an issue that policymakers should address to promote the adoption of technologies and innovations by farmers; especially regarding land recapitalization (e.g. through the large-scale use of phosphate rocks).

Many phosphate rock deposits remain poorly known in terms of their characteristics and agronomic values. Chude et al. (2008) suggest the following research lines: (1) better mineralogical characterization, (2) evaluation in different ecologies, (3) better understanding of constraints to adoption by agricultural producers, (4) defining management options to improve PR efficiency, and (5) assessing the environmental effects associated with heavy metal and radioactive elements contents. These suggestions also hold for other phosphate rock deposits in West Africa. This should be combined with efforts to be made by research and development entities to include these phosphate rocks in fertilizer recommendations for crops. The role that farmers must play individually or through their organizations is also fundamental. Support from the Government and its technical and financial partners is essential, but their commitment to the transformation of agriculture is equally essential.

As long as farmers are confident that they will have access to product, fertilizer and financing markets, they will be willing to produce more not only to ensure their food self-sufficiency and that of their countrymen, but also to further contribute to the economic development of their country's economy. For this, political decision-makers and technical and financial partners need to put agriculture at the center of their agenda and the various national and regional policies, strategies and programs developed must be effectively operationalized.

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