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Effectiveness of combined application of Kodjari phosphate rock, water soluble phosphorus fertilizer and manure in a Ferric Lixisol in the centre west of Burkina Faso

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ABSTRACT

Increasing soil phosphorus and organic matter content for crop production while reducing the cost of production are required to facilitate the achievement of green revolution in Africa. Field and pot experiments were laid out during 2012 and 2013 to assess the effects of combined application of Kodjari phosphate rock (PR) and water soluble phosphorus on sorghum yields, P uptake and Lixisol characteristics in the centre west of Burkina Faso. Five P fertilizers treatments (zero P, 100% TSP (triple super phosphate), 100% PR, 50% PR + 50% TSP, 75% PR + 25% TSP) and two cow manure treatments (zero, 5 t ha^{-1}) were tested. In field experiment, 50% PR + 50% TSP was as effective as 100% TSP in increasing sorghum yield above the control by 30% in 2012 and 50% in 2013 and P uptake by 30% in both years. Manure had an additive effect on phosphorus fertilizers in increasing sorghum yields and P uptake. In pot experiment, increases of Ca uptake, soil pH and microbial P were observed with the application of 50% PR + 50% TSP. Our results suggest that formulation of fertilizer combining phosphate rock and mineral P would improve sorghum yields and income of smallholders.

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Phosphate rock; triple super phosphate (TSP); manure; Lixisol; Burkina Faso

Introduction

Phosphorus is one of the nutrients that severely limits crop production in sub-Saharan Africa, Indeed, soil total and available P in this region are low and cannot sustain good crop production (Compaoré et al. 2003; Schlecht et al. 2006; Lompo 2009). Substantial P inputs are therefore needed to enhance soil total and available P pools in order to improve crop production. It was shown that an application of water soluble fertilizers in those soils can lead to important increase in crop yields (Buerkert et al. 2001). However, the high cost of fertilizers and inappropriate market policies are major limitations of the use of water soluble fertilizer by smallholder farmers (Kelly 2006). The use of local resources such as phosphate rock could be considered as an alternative solution to the high cost of water soluble P fertilizers especially when Africa is endowed with many phosphate rock deposits (Van Kauwenbergh 2006; Mokwunye and Bationo 2011). Some of these phosphate

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rocks (eg, Tilemsi in Mali, Minjingu in Tanzania) are suitable for direct application (Kone et al. 2011; Savini et al. 2016). However, most of them are not effective when applied directly without any treatment, because of their low solubility in water. The phosphate rock of Kodjari in Burkina Faso which is estimated to be 180–200 million tonnes containing more than 20% of P_2O_5 (Bikienga 2011) belongs to the category of the less reactive phosphate rocks (Compaoré et al. 1997; Bikienga 2011). A partial acidulation of this phosphate rock for agricultural purpose was tested and was found to be efficient for yields improvement. The study of Compaoré et al. (1997) showed that the phosphate rock of Kodjari has no effect on cowpea and maize biomass production at soil pH of 6.2 but become effective after a partial acidulation. However, a possible reversion of the soluble P to the insoluble P during the manufacturing of the partially acidulated phosphate rock containing high rate of Fe_2O_3 + Al_2O_3 has been shown (Hammond et al. 1989). Other low cost approaches such as the combination of phosphate rock and water soluble P fertilizers have been shown promising. The water soluble P will fulfill the first requirement in P of plants and allows them later to better beneficiate from phosphate rock products which are slowly released (Chien et al. 1987; Xiong et al. 1996; Zapata and Zaharah 2002). The application of moderately reactive phosphate rock from Huila and Capinota combined with water soluble P fertilizer at a ratio 1:1 on an acidic soil led to maize yields similar to that obtained with a full water soluble P fertilizer application (Menon and Chien 1990). Similar results on the effects of mixing phosphate rock and water soluble mineral P fertilizer on maize yields were reported in South India (Singaram et al. 1995). The combined application of less reactive phosphate rock with organic amendments has also been shown to be a way to increase the effectiveness of phosphate rock (Gikonyo et al. 2010). However, there is a myth surrounding those findings as concerned organic amendments usually have a pH close to neutral or higher and therefore cannot obviously favor the dissolution of P from phosphate rock (Vanlauwe and Giller 2006). In the northern area of Burkina Faso, the combined application of 50% phosphate rock from Kodjari with 50% water soluble P (TSP) led to an increase of 12% of sorghum yields compared to the application of 100% water soluble P (Bonzi et al. 2011). Although the promising results obtained, the reasons of this effectiveness were not highlighted. Therefore, given the promising results obtained, there is a dire need to investigate more on the contribution of this technology to the improvement of soil P status and crop P nutrition in smallholders' farms. One can hypothesize that the combination of phosphate rock and water soluble P leads to increased soil available P pools and plant P uptake leading to increased yields. This study aimed at assessing the effects of combined application of Kodjari phosphate rock and water soluble phosphorus fertilizer on sorghum yields and soils characteristics. It also aimed at assessing the effect of manure on the effectiveness of phosphorus fertilizers.

Materials and methods

Field experiment

The field experiment was conducted in the national agricultural research institute (INERA), located in Saria, in the North Sudanian Zone of Burkina Faso (Latitude 12° 16′ North, Longitude 2° 9′ East). The rainfall pattern in this area is unimodal and irregularly distributed from April to October. The annual rainfall during the experiment was 856 mm in 2012 and 626 mm in 2013 (Figure 1). The soil is classified as Lixisols and is acidic, sandy loam and has low cation exchange capacity, and low organic carbon content (Table 1).

The Kodjari phosphate rock (PR) with 25% P_2O_5 and the water soluble triple super phosphate (TSP) with 46% P_2O_5 were used as source of P. The nitrogen source was urea (46% N) while the potassium source was potassium chloride (60% K_2O). The experimental trial was a randomized complete block design with two factors (mineral P fertilizer and manure application). Each treatment was replicated six times. The first factor comprised the following five treatments: Control (0% PR and 0% TSP), 30 kg ha^{-1} P_2O_5 as TSP (100% TSP), 30 kg ha^{-1} P_2O_5 as PR (100% PR), 15 kg ha^{-1} P_2O_5 as PR and 15 kg ha^{-1} P_2O_5 as TSP (50% PR + 50% TSP), 22.5 kg ha^{-1} P_2O_5 as PR and 7.5 kg ha^{-1}

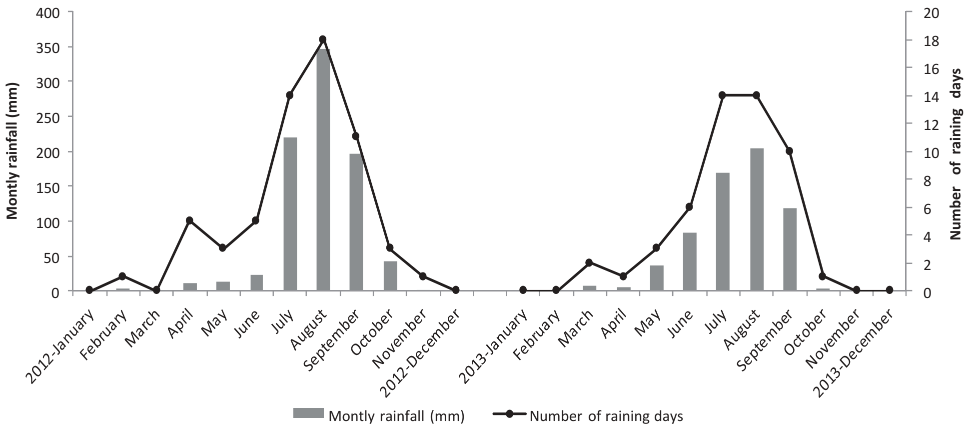

Figure 1. Rainfall distribution during the experimentation.
The bars represent the standard error.

Table 1. Initial soil characteristics of the experimental site.

Characteristics	Values
pH (1:2.5, H_2O)	4.52
C (g kg^{-1})	1.84
Total N (g kg^{-1})	3.3
Total P (mg kg^{-1})	105
Exchangeable Calcium (cmolc kg^{-1})	1.48
Exchangeable Magnesium (cmolc kg^{-1})	0.47
Exchangeable Potassium (cmolc kg^{-1})	0.17
Exchangeable Sodium (cmolc kg^{-1})	0.01
Cation Exchange Capacity (CEC) (cmolc kg^{-1})	2.67
Bases saturation (%)	80
Clay (%)	13.73
Silt (%)	25.49
Sand (%)	60.78
Texture	Sandy loam

P_2O_5 as TSP (75% PR + 25% TSP). The second factor included two treatments: no application of manure and 5 tons ha^{-1} of manure/two years for which the characteristics are shown in the Table 2. The rate of 30 kg ha^{-1} P_2O_5 was chosen based on the recommended rate of phosphorus for sorghum in Burkina Faso and also the fact that sorghum responds positively to increased levels of TSP fertilizers up to 30 kg ha^{-1} of P_2O_5 in the study area (Sedogo et al. 1991).

The trial covered a total surface of 2254 m^2 and a unit plot size of 24 m^2 (6 m × 4 m). The plots were separated by a distance of 1 m while the blocks were separated by a distance of 2 m.

At the beginning of the experiment, 5 tons ha^{-1} of manure was spread uniformly on the plots and incorporated to soil with hoe before sowing. Sorghum (*Sorghum bicolor* (L.) Moench) variety ICSV 1049 was sown at the onset of the rain at a plant spacing of 80 cm × 40 cm. All treatments received a blanket application of 60 kg ha^{-1} of N as urea and 30 kg ha^{-1} of K_2O as potassium chloride. Phosphorus and potassium fertilizers were applied at sowing while nitrogen fertilizer (urea) was

Table 2. Chemical characteristics of manure collected from the cowshed of the experimental station of INERA in the central west area of Burkina Faso.

Characteristics	pH (1:5, H_2O)	Organic C (g kg dry matter^{-1})	Total N (g kg dry matter^{-1})	Total P (g kg dry matter^{-1})	C/N	C/P
Values	7.16	197.1	16.4	2.6	12	76

applied twice; the first (1/2 of the total amount) was applied two weeks after sowing and the second (1/2 of the total amount) at flowering. All the mineral fertilizers were hill – placed and incorporated manually with hoe. Weeding was done three times during the cropping season each year. Sorghum straw and grain were harvested separately on each plot omitting the border rows. The harvested straw and grain were air dried for about two weeks, weighed and expressed in kg ha^{-1}. Composite straw and grain samples were taken at harvest, oven dried at 60°C, ground and packed in plastic bags for chemical analysis. A composite soil sample was taken in each plot from five points at the beginning of the experiment and at harvest in 2012 and 2013. The sampled soils were air dried and sieved through a 2 mm mesh sieve and packaged in plastic bags for chemical analysis.

Pot experiment

The pot experiment was conducted in a greenhouse in the research station of INERA located at Kamboinsé, Burkina Faso. Each pot was filled with 7 kg of soil taken at 0–20 cm depth at the research station of INERA at Saria close to the field experiment. The same P treatments as in the field trial were applied with eight replicates per treatment. No manure was applied.

In each pot five seeds of sorghum were sown and after seeds emergence, thinning was done and two plants were kept per pot. The fertilizers were applied two weeks after sowing. The P fertilizer was added at a rate of 60 mg kg^{-1} soil which is within the range of the rate recommended to study the effects of phosphate rock on plant production (Zapata and Roy 2004). Nitrogen at the rate of 137 mg N kg^{-1} of soil as urea and potassium at the rate of 137 mg K_2O kg^{-1} of soil as potassium chloride. Plants were watered twice a day to maintain moisture at approximately 70% of water holding capacity. Four replicates of each treatment were randomly harvested at 45 and 75 days after sorghum sowing. The 45 days after sowing (30 days after application of fertilizers) corresponded to the growing point differentiation stages and 75 days after sowing (60 days after application of fertilizers) corresponded to the stage of final leaf visible in whorl to half bloom of sorghum growth as described by Vanderlip and Reeves (1972). The above ground biomass was harvested, dried at 60°C until constant weight and dry matter was then measured. The dry biomass was sampled and packed in plastic bags for chemical analyses. The entire soil from each pot was mixed and samples taken and roots and debris were discarded from the soil samples prior to analyses for their pH, available P and microbial P contents.

Soil and plants analysis

Soil pH was measured with a pH-meter (WTW InoLab, Weilheim, Germany) in 2.5:1 water to soil suspension according to Afnor (1981). The soil organic carbon was determined according to Walkley and Black (1934). Soil total phosphorus was determined by first digesting soil samples using a complex of H_2SO_4-Se-H_2O_2 according to Okalebo et al. (2002). Total P was measured in the digest with an automatic colorimeter SKALAR (Skalar SANplus Segmented flow analyzer, Model 4000–02, Breda, Holland).

Soil resin and microbial P was extracted according to the methodology of Kouno et al. (1995). A quantity of 4 g soil was weighted into a 50 ml vial three times and 40 ml of distilled water was added. One resin strip of 6 × 2 cm size was placed in each vial. One milliliter of hexanol was added to the second vial for fumigation and 1 ml of P solution with a known P concentration was added to the third vial for the correction of sorption of the released P during the extraction. The soil suspension was then shaken for 16 hours after which the resin strip was removed and washed with distilled water to remove soil particles. The resin strip was then shaken in 30 ml of a solution of 0.1 *M* NaCl/HCl to remove the fixed phosphorus. The phosphorus content in the solution of NaCl/HCl was measured using a manual colorimeter (Cecil 3021) at 880 nm after developing the color by the blue molybdenum method according to Murphy and Riley (1962). The soil microbial P was calculated as follow: Microbial P (mg) = Pf (mg) – Pnf (mg) where Pf is the measured phosphorus in fumigated soil solution; Pnf is the measured phosphorus in non-fumigated soil solution. The rate of water content was determined and used to calculate the contents of resin and microbial P per dry soil.

Soil cation exchange capacity (CEC) and exchangeable bases were determined using the Silver Thiourea method (Rayment and Higginson 1992). The concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined using an atomic absorption spectrometer (Perkin Elmer, AAS 100). The concentrations of potassium (K^{+}) and sodium (Na^{+}) in the filtrate were determined using a flame photometer (Jencons PFP 7, Jenway LTD, Felsted, England).

For the determination of grain and straw phosphorus contents, 200 to 500 mg of substrate was burned at 550 °C for 5 hours in an electric furnace. Phosphorus in the resulting ash was extracted with 2 ml of concentrated HNO_3 (65%) and the volume was made up to 100 ml with distilled water. Phosphorus concentration in the extracts was measured with an automatic colorimeter (Skalar SANplus Segmented flow analyzer, Model 4000–02, Breda, Holland). Calcium concentration was determined using an atomic absorption spectrometer (Perkin Elmer, AAS 100).

Statistical analysis and calculations

The data were analyzed using the 9th edition GENSTAT software. The least significant difference (Lsd) was used to compare the means at 95% of confidence level when the factor effect was significant at $P \leq 0.05$. As data of microbial P were not normally distributed, a square root transformation was performed prior to ANOVA. The Apparent P Recovery (APR) of the different treatments in the field experiment was calculated according to Begum et al. (2004) as follows:

$$\mathrm{APR}(\%) = \frac{\text{P uptake of the treated plot} - \text{P uptake of control plot}}{\text{Amount of P applied as fertilizer (PR and/or TSP)}} \times 100$$

The Relative Agronomic Efficiency (RAE) of the different combinations of phosphate rock and water soluble phosphorus was computed using TSP as the reference (Aye et al. 2009) as follows:

$$\mathrm{RAE}(\%) = \frac{\text{Yield of treated plot} - \text{Yield of control plot}}{\text{Yield of TSP treated plot} - \text{Yield of control plot}} \times 100$$

Results

Field experiment

Sorghum grain and straw yields responses to P fertilization

Sorghum grain and straw yields were significantly affected by the P and manure treatments ($P < 0.05$) (Table 3). The interaction between phosphorus and manure application was not significant ($P > 0.05$). The highest yields were recorded in 2012 compared to 2013. The application of 100% PR did not significantly increase sorghum yields when compared to the control. The treatments receiving 50% PR + 50% TSP and 100% TSP were similar regarding sorghum yields. Both treatments showed significant yields increase compared to the control plot (42 and 30% respectively for grain and straw yields). The treatment 75% PR + 25% TSP significantly increased sorghum grain yields in 2012 but not in 2013. The manure significantly increased sorghum grain yields by about 40% and straw yields by about 20% in 2012 and 2013 as well. The relative agronomic efficiencies resulting from the different treatments are shown in the Table 3. The treatment 50% PR + 50% TSP was 105 and 94% as effective as 100% TSP respectively in 2012 and 2013. The treatment 75% PR + 25% TSP was 72 and 21% as efficient as 100% TSP, respectively in 2012 and 2013. The treatment 100% PR was 15 and 22% as efficient as 100% TSP respectively in 2012 and 2013.

Sorghum P uptake and P recovery as affected by fertilizer treatments and manure

The results of P uptake and Apparent Phosphorus Recovery (APR) are shown in the Table 4. Phosphorus uptake was generally low in all treatments in both years and significantly varied with phosphorus sources ($P < 0.05$). The P uptake in the treatment 100% PR was not significantly

Table 3. Sorghum grain, straw yields and relative agronomic efficiency (RAE) as affected by the application of phosphate rock, water soluble P fertilizer and manure.

Treatment	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		RAE	
	2012	2013	2012	2013	2012	2013
Phosphorus fertilizer						
Control	2152	1521	4615	3461	-	-
100% TSP	2801	2339	5857	4631	100	100
100% PR	2312	1585	4736	3831	15	22
50 % TSP + 50 % PR	2798	2340	5951	4508	105	94
25% TSP + 75 % PR	2507	1614	5617	3789	72	21
Manure						
Without Manure	2089	1513	4874	3636		
With Manure	2940	2246	5836	4452		
***P* values**						
Phosphorus	0.034	0.036	0.022	0.023		
Manure	<0.001	0.002	0.004	0.002		
Phosphorus × Manure	0.425	0.109	0.916	0.120		
Lsd (0.05)						
Phosphorus	241.8	714.7	1013.4	806.3		
Manure	308.0	452.0	640.9	510.0		
Phosphorus × Manure	NS	NS	NS	NS		

NS: Not Significant

Table 4. Sorghum P uptake and apparent P recovery as affected by the application of various combinations of phosphate rock, water soluble P fertilizer and manure.

Treatment	P uptake (kg ha^{-1})		APR (%)	
	2012	2013	2012	2013
Phosphorus fertilizer				
Control	5.15	4.33	-	-
100% TSP	6.91	6.34	13.5	15.0
100% PR	5.36	4.18	1.6	−1.0
50% TSP + 50% PR	6.73	6.00	12.1	13.0
25% TSP + 75% PR	6.01	4.57	6.6	2.0
Manure				
Without Manure	5.21	4.42	-	-
With Manure	6.85	5.74	9.0	10.0
***P* values**				
Phosphorus	0.006	0.030		
Manure	<0.001	0.016		
Phosphorus × Manure	0.865	0.307		
Lsd (0.05)				
Phosphorus	1.097	1.671		
Manure	0.694	1.057		
Phosphorus × Manure	NS	NS		

APR: Apparent Phosphorus Recovery, NS: Not Significant

different from that of the control. Treatments receiving 100% TSP and 50% PR + 50% TSP were statistically similar and showed significantly higher P uptake than the control. These treatments increased the P uptake by 31% on average over the control. The treatment 75% PR + 25% TSP gave mean P uptake that was intermediary to those obtained from the control and the 100% TSP treatments in 2012. In 2013, the application of 75% PR + 25% TSP did not significantly increased P uptake. The application of manure significantly increased sorghum P uptake corresponding to 32% in 2012 and 30% in 2013 over P uptake from treatment plots without manure addition. The interaction between phosphorus and manure application was not significant ($P > 0.05$)

The apparent recovery of P from the different phosphorus fertilizer sources and their combined application with manure was generally low and less than 25%. The apparent recovery of P was highest in treatments 100% TSP (13.5% in 2012 and 15% in 2013) followed by treatments 50% PR + 50% TSP (12.1% in 2012 and 13% in 2013) and least in treatment 75% PR + 25% TSP (6.6% in 2012 and 2% in 2013) and treatment 100 % PR (1.6 % in 2012 and −1% in 2013). The apparent P recovery for the manure treatment was 9% in 2012 and 10% in 2013.

Soil properties as affected by fertilizer treatments and manure

There was not a significant interaction between phosphorus fertilizers and manure regarding selected soil properties. Only their main effects are presented in the Table 5. Soil pH and organic carbon of the P fertilizer treatments remained similar to the control treatment ($P > 0.05$). The different phosphorus treatments were not significantly different from each other regarding their effects on soil total phosphorus content. However, they significantly increased soil total phosphorus by 18% on average compared to the control. Only the soils receiving 100% TSP gave resin phosphorus significantly higher than that of the control. The application of manure significantly increased soil pH by 0.12 units in 2012 and 0.21 units in 2013. Treatments receiving manure resulted in 14 and 8% more soil organic carbon than the non – amended treatments in 2012 and 2013, respectively.

Sorghum biomass yield, P and Ca uptake and soil properties at 45 and 75 days after sowing

The biomass yields according to the fertilizer treatments in pot experiment are shown in Figure 2. There was no significant difference between the biomass yield of 100% PR and that of the control ($P > 0.05$). The application of 100% TSP and the combined application of 50% PR and 50% TSP were statistically similar in increasing sorghum biomass yield. Both treatments recorded 10 times and 2 times more biomass than the control respectively at 45 days 75 days after sowing. The combined application of 75% PR and 25% TSP resulted in lower biomass production than the 100% TSP treatment at 45 days after sowing but the difference between the two was not significant at 75 days after sowing.

Table 6 shows the effect of phosphorus fertilizer treatments on sorghum P and Ca uptake and soil properties. Sorghum P uptake significantly varied from 2.20 mg pot^{-1} to 54.50 mg pot^{-1} at 45 days after sowing and from 19.3 mg pot^{-1} to 92.2 mg pot^{-1} at 75 days after sowing and was in the following order: control = 100% PR < 25% TSP + 75% PR < 50% PR + 50% TSP < 100% TSP. The Ca uptake ranged from 4.7 mg pot^{-1} to 45.5 mg pot at 45 days after sowing and from 37.1 mg pot^{-1} to 89 mg pot^{-1} at 75 days after sowing. At 45 days after sowing, the treatments were ranked as follows: control = 100% PR < 75% PR + 25% TSP < 50% PR + 50% TSP = 100% TSP; at 75 days after sowing, they were ranked as follow: control = 100% PR < 75% PR + 25% TSP = 50% PR + 50% TSP = 100% TSP. Soil pH remained acidic during the experiment. At 45 days after sowing, the pH in the 100% PR and 75% TSP + 25% PR

Table 5. Soil characteristics after harvest of sorghum under the application of different combinations of phosphate rock, water soluble P fertilizer and manure.

	pH		C_{org} (g kg^{-1})		Total P (mg kg^{-1})	Resin P (mg kg^{-1})
Treatment	2012	2013	2012	2013	2013	2013
Phosphorus fertilizer						
Control	4.69	4.51	1.92	1.90	98.6	4.86
100% TSP	4.71	4.61	2.08	1.98	116.0	10.76
100% PR	4.63	4.52	1.88	1.90	121.7	5.46
50% TSP + 50% PR	4.70	4.57	2.10	1.90	114.0	5.99
25% TSP + 75% PR	4.74	4.61	2.02	1.98	111.8	5.44
Manure						
without manure	4.63	4.46	1.87	1.86	112.7	6.99
with manure	4.76	4.67	2.13	2.01	112.1	6.01
***P* values**						
Phosphorus	0.462	0.208	0.678	0.240	0.003	<0.001
Manure	0.002	<0.001	0.029	<0.001	0.868	0.073
Phosphorus × Manure	0.95	0.289	0.665	0.07	0.654	0.526
Lsd (0.05)						
Phosphorus	0.118	0.111	0.355	0.104	11.18	1.691
Manure	0.075	0.070	0.224	0.066	7.07	1.070
Phosphorus × Manure	NS	NS	NS	NS	NS	NS

NS: Not significant

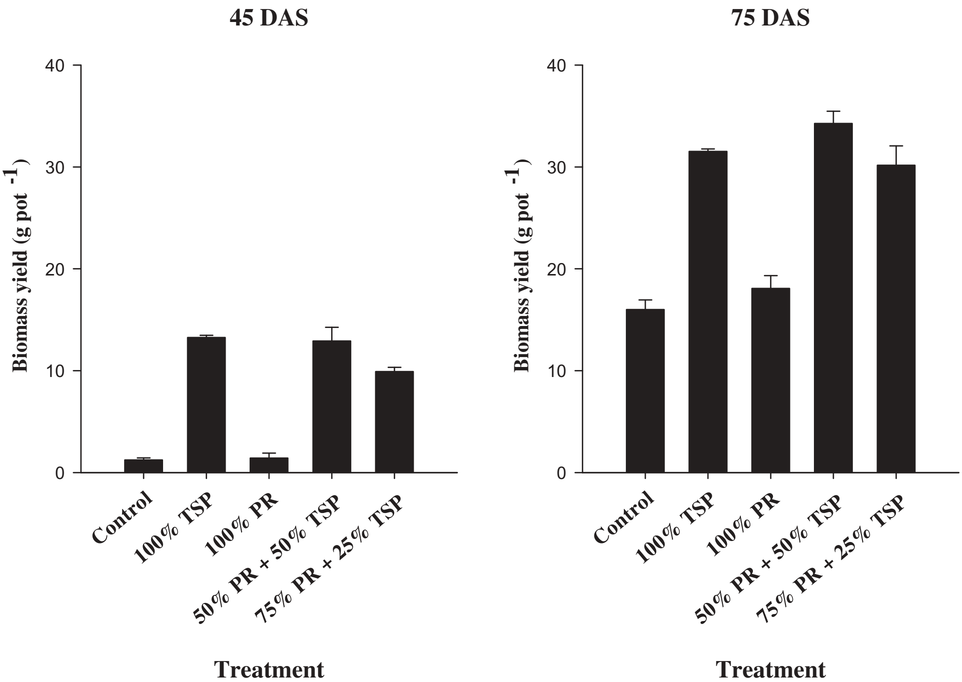

Figure 2. Sorghum biomass yield at 45 and 75 days after sowing as affected by the application of phosphate rock and/or water soluble P fertilizer.

treatments were not significantly different from that of the control. The treatments 100% TSP and 50% TSP + 50% PR which were similar in their effects, significantly increased soil pH by 0.2 units above the control. At 75 days after sowing, soil pH in all the phosphorus fertilizer treatments was significantly higher than that observed in the control treatment. Soil resin P was significantly affected by phosphorus fertilizer treatments at 45 and 75 days after sowing. At 45 days after sowing, the resin P of the soil receiving 100% PR treatment was not significantly different from the resin P measured in the control. The significant increase in resin P over that of the control treatment was 92%, 167%, 428% for 25% TSP + 75% PR, 50% PR + 50% TSP and 100% TSP treatments, respectively. At 75 days after sowing, the increases over the control treatment were 107 and 257% for 50% PR + 50% TSP and 100% TSP treatments, respectively. Soil microbial biomass P was significantly affected by the phosphorus fertilizer treatments at 45 and 75 days after sowing. The microbial biomass P varied from 0.63 mg kg^{-1} in the control treatment to 4.07 mg kg^{-1} in the 100% TSP treatment at 45 days after sowing and from 0.98 mg kg^{-1} in the control treatment to 3.22 mg kg^{-1} in the 50% PR + 50% TSP treatment at 75 days after sowing. The microbial P in the 100% PR treatment was not significantly different from that of the control treatment at 45 days after sowing but it was significantly higher than that of the control at 75 days after sowing. From 45 days after sowing to 75 days after sowing, the microbial biomass P relatively decreased in the 100% TSP treatment while it increased in 50% PR + 50% TSP treatment.

Discussion

Sorghum yields, P uptake and soils characteristics as affected by phosphorus fertilizer treatments

The low yields of sorghum, P uptake and apparent P recovery observed in the 100% PR treated treatments during the field and pot experiments are in agreement with the earlier reports on the ineffectiveness of phosphate rock of Kodjari (Compaoré et al. 2011; Monrawee et al. 2013). The low

Table 6. Soil characteristics, P and Ca uptake as affected by the application of phosphate rock and water soluble P fertilizer.

Treatment	pH		Resin P (mg kg⁻¹)		Microbial P (mg kg⁻¹)		P uptake (mg pot⁻¹)		Ca uptake (mg pot⁻¹)	
	45 D	75 D	45 D	75 D	45 D	75 D	45 D	75 D	45 D	75 D
Control	4.70	4.58	3.56	2.72	0.63 (0.79)	0.98 (0.99)	2.20	19.30	4.7	37.1
100% TSP	4.90	5.13	18.80	16.09	4.07 (1.99)	2.91 (1.71)	54.50	92.20	45.2	89.0
100% PR	4.60	5.13	4.00	3.53	0.94 (0.95)	2.31 (1.48)	3.40	24.20	5.2	47.2
50% TSP + 50% PR	4.96	5.23	9.52	7.44	2.69 (1.58)	3.22 (1.79)	40.90	57.70	45.5	85.1
75% PR + 25% TSP	4.80	4.96	6.84	4.11	2.57 (1.58)	2.14 (1.45)	23.80	35.50	35.4	72.3
P values	0.002	<0.001	<0.001	<0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	0.16	0.18	4.68	1.85	0.49	0.32	9.790	7.36	6.3	20.8

D: Days after sowing.

effectiveness of phosphate rock of Kodjari is generally attributed to its low solubility which has been reported to be 0.03% in water (Bikienga 2011) and less than 3% in citrate AOAC[1] (van Kauwenbergh 2006; Bikienga 2011). However, the low pH of the studied soil is favorable to the dissolution of the phosphate rock. Numerous studies have indeed reported an increased effectiveness of low grade phosphate rocks in acidic soils (Zapata and Roy 2004). The low effectiveness of Kodjari phosphate rock can be partly attributed to soil adsorption of P. The studied soil is indeed a Ferric Lixisols for which adsorption although found to be low compared to other types of soils, still have some P adsorption patterns which can lead to fixation of released P. Nwoke et al. (2003) have found adsorption maxima value up to 150 mg kg^{-1} in an acid Lixisol of Nigeria. Furthermore, Lompo et al. (2007) observed a decrease with time of soil available P during incubation in Lixisol having received TSP and Kodjari phosphate rock. The released P can also be reabsorbed by phosphate rock products itself as it contains high rate of Fe_2O_3 + Al_2O_3. Hammond et al. (1989) have indeed noted during an acidulation process a reversion of dissolved P to less soluble P with phosphate rock containing high rate of of Fe_2O_3 + Al_2O_3.

The significant increase of sorghum yields over the control with the treatment 50% PR + 50% TSP is in accordance with the results of Bonzi et al. (2011) obtained in the North Sudanese zone of Burkina Faso. Similar results were also obtained by Zapata and Zaharah (2002) with the phosphate rock of Florida on maize on a calcareous soil. From the combined application of phosphate rock and water soluble P fertilizer (50% PR + 50% TSP in this study) it is expected that the water soluble phosphorus supplies P to meet the early P requirements of the crop, thereby favoring the early development of rooting system and subsequently, a wider exploration of the soil environment and acquisition of P from phosphate rock dissolution (Chien et al. 1987; Xiong et al. 1996; Zapata and Zaharah 2002). The increase of crop growth hence roots growth due to the water soluble phosphorus is indeed favorable for P uptake from phosphate rocks because the activities of roots such as P depletion followed by a diffusion gradient in the rhizosphere, the change in P sorption parameters make them more competitive with soil solid phase for P uptake (Hinsinger 2001). These mechanisms might explain the good yield and P uptake observed in the field experiment and need to be investigated for a better utilization of the technology of combining Kodjari phosphate rock with water soluble phosphorus. Xiong et al. (1996) also suspected a possible contribution of other nutrients in the phosphate rocks materials such as calcium and magnesium to the plant growth. The pot experiment has indeed showed an increase level of calcium uptake during the growing period of sorghum with the combined application of 50% PR + 50% TSP. Contrary to the results of this study in 2013, Bonzi et al. (2011) found a good response of sorghum with the application of 75% PR + 25% TSP compared to 100%TSP. The differences of our results and those of Bonzi et al. (2011) could be attributed to differences in soil moisture during the experiment. Indeed the results of Bonzi et al. (2011) were obtained under the conditions of the Zaï and half-moon water harvesting technologies which are known to improve soil moisture conditions (Zougmoré et al. 2014). As this treatment contains a high percentage of phosphate rock, it may have needed more water to be effective. The effect of water in increasing phosphate rock dissolution has been previously reported (Akinrinde and Obigbesan 2006). Furthermore, in the pot experiment where the soil water was maintained at approximately 70% of water holding capacity, the application of 75% PR + 25% TSP where similar to the 100% TSP treatment in increasing sorghum biomass production at 75 days after sowing. The delay in sorghum response to the 75% PR + 25% TSP treatment at 75 days after sowing compared to the 50% PR + 50% TSP treatment for which the positive effect was observed earlier is probably due to the slow release of P from phosphate rock. This rate of release could not probably satisfy sorghum requirement for biomass production within 45 days after sowing.

The increase in soil total phosphorus in the P treated soils in the field experiment compared to the control was expected given the low apparent P recovery by sorghum (Table 4). The combined application of phosphate rock of Kodjari with water soluble phosphorus did not significantly increase soil pH

[1]Association of Official Analytical Chemists.

and soil available phosphorus at harvest in the field experiment. Danso et al. (2010) in Ghana, reported an increase of the pH of a ferric Acrisols through the application of TSP and phosphate rock. From the dissolution of phosphate rock, we expect as well the increase of soil available phosphorus as the increase in soil pH through the release of calcium in soil solution. Regarding the scheme of phosphate rock transformation in soil, the released P can be taken up by plant and/or adsorbed to soil components especially if the soil is very acid as in this study (Zapata and Roy 2004). Plant P and Ca uptake and the redistribution of dissolved P may explain why the resin P and soil pH measured at harvest in the combined application treatments were not significantly the highest. Furthermore, studying the dynamic of soils characteristics during the growing period of sorghum in the pot experiment have shown that the combined application of phosphate rock and water soluble phosphate can significantly increase soil pH and soil resin P above the control treatment. This increase of soil pH with the combined application of phosphate rock and water soluble phosphorus fertilizer during the growth of sorghum may explain partly its effect in increasing sorghum biomass production especially since the study soil was acidic.

Although the increase of soil pH and calcium uptake indicates a possible dissolution of phosphate rock, the increase of soil resin P seemed to be proportional to the quantity of water soluble P in the combined treatments during the growing period of sorghum. The released P from phosphate rock might have been reabsorbed in soil or phosphate rocks components or immobilized by soil micro-organisms. The soil microbial P was indeed higher in the 50% PR + 50% TSP treatment at 75 days after sowing as shown in Table 6. The solubilization and immobilization of P from soil and/or from phosphate rock P by soil microbes has been reported (Vassilev et al. 1997; Khan et al. 2010). The immobilized P in turn will be released in soil through turnover processes (Oberson and Joner 2005) and could be used by crops. The higher microbial P observed in the 50% PR + 50% TSP treatment highlights a good potential for further increase of soil available phosphorus through the release of the immobilized P for sorghum after 75 days after sowing which might be beneficial for sorghum growth especially since the soil resin P in these treatments is below the optimum values for plant growth (above 10 mg kg^{-1} according to Mallarino and Atia 2005). This might explain partly why this treatment performed as well as100% TSP treatment in the field experiment in increasing sorghum yield and P uptake. However this assumption need to be further investigated.

Effect of manure on the effectiveness of P fertilizers

The effect of organic amendments in increasing sorghum productivity on low nutrient soils as shown in this study, has been extensively documented (Fatondji et al. 2006; Lompo 2009) and is attributed to the improvement in soil physical, chemical and biological properties including buffering of soil pH, the increase in soil organic carbon as observed in this study (Table 5) and the increase of nutrients availability. The manure indeed contains 2.6 g kg^{-1} of phosphorus (Table 2) and applying 5 tons ha^{-1} means the addition of 13 kg ha^{-1} of P. We did not find a significant interaction between the phosphorus fertilizers and manure application in increasing sorghum P uptake and yields, suggesting that their effects were just additive. A positive interaction was expected on the basis that the dissolution of phosphate rock is boosted in soil with high organic matter content (Zapata and Roy 2004). Organic amendments can influence phosphate rock by the release of organic acids and consequently will make more P available for plant uptake. In this study, the rate of 5 tons ha^{-1} of manure, even it has increased soil carbon content, this content still remains low (less than 3 g kg^{-1}). Manure also has increased soil pH. This may explain the absence of significant interaction between phosphate fertilizers and manure effects.

Conclusion

In acid lixisols the combined application of Kodjari phosphate rock at the rate 50% PR + 50% TSP is as effective as 100% TSP in increasing sorghum yield and sorghum P uptake, offering an opportunity for recapitalizing soil total phosphorus content. The application of manure at the rate of 5 tons ha^{-1} has an additive effect on that of phosphate rock fertilizers in promoting sorghum growth. The results of this study suggest that effectiveness of the combined application is partly linked to the ability of these treatments to increase soil pH and calcium uptake. The increase in soil resin P is proportional to the quantity of the water soluble phosphorus fertilizer in the combined treatment till 75 days after sowing (60 days after application). However, the combined application of 50% PR and 50% TSP has a good potential to further increase soil resin P through microbial P release after 75 days. It could be then envisaged to reduce the cost of water soluble P fertilizer through formulation combining phosphate rock and water soluble P for improved sorghum yields and the income of smallholder farmers. Further studies should focus on the mechanisms of P release from Kodjari phosphate rocks when combined with soluble phosphorus for a better utilization of the technology.

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