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Valorization of the Natural Phosphate of Tilemsi (PNT) for the Development of the Agricultural Productions in Mali

Traoré Lamine[1], Koné Mama[1], Bouhsane Mohammed[2], Richardson Jed[2], Marie France[3], Jay Hosanee[2]

[1]IER / Sotuba, BP. 262, Bamako, Mali
[2]GREAT QUEST Fertilizer Ltd, Suite 303, 95 King Street East, Toronto, ON, M5C1G4 Canada
[3]GREAT QUEST / Mali SA, ACI Baco-djicoroni West, Street 616, Contiguous Door 451, Ma-Bamako 2006-B-6037

Abstract: In Mali, the deficiency of agricultural soils in phosphorus is one of the limiting factors in crop production. They respond well to phosphorus fertilization, but the high price of imported chemical fertilizers limits their use by the producers. However, Mali has large deposits of natural phosphate in the Tilemsi Valley (PNT) in northern Mali. Faced with this situation, the Government encouraged the use of local fertilizing resources including the PNT. Despite the satisfactory results of several years of research and popularization, the PNT was poorly adopted by the producers because of its powdery appearance, which made it difficult to apply in the field, its low solubility in the soil, which made its effect noticeable on crops in the second year of its application and its brown color reminiscent of that of earth made the producers believe that it had no fertilizing value. Faced with these problems relating to the physical appearance and the low solubility of the PNT, the laboratory work of GREAT QUEST Fertilizer SA resulted in the development of simple formulations based on enriched granular PNT 27% P_2O_5 (average content) and 35% P_2O_5 (high content) for direct application and NPK complex formulations based on granulated enriched PNT 35% P_2O_5 mixed mainly with urea, potassium, and sometimes with other nutriments like sulfur and boron (NPK 15-15-15; NPKSB 14-18-18-6-2) with a solubility in citric acid of 71.1%. The results of four years of experimentation of enriched granular PNT in the research stations and in the peasant environment showed a greater or equal effect than the other popular fertilizers. This project aims to improve phosphate nutrition and crop production by using granulated formulations of enriched PNT 27% P_2O_5 and 35% P_2O_5.

Keywords: Deficiency, Phosphorus, Phosphate Rock, New Formulations, Soil Fertility

1. Introduction

Phosphates exist in two forms: the soluble form (superphosphates) and the insoluble form (natural phosphates). Superphosphates are synthetic phosphorus fertilizers. They are mainly composed of hydrated mono-calcium phosphate [Ca (H2PO4) 2, H2O] and generally contain 43-50% of P_2O_5 (Budavari, 1996). Superphosphates can be ordinary or triple depending on their P_2O_5 composition. They are applied to the soil and used in soil fertilization as a source of phosphorus directly available to plants (Tisdale and Nelson, 1985). Natural phosphates (PN) are an inexpensive option for soil fertilization, particularly in countries where raw material is available (Truong et al., 1993). However, these PNs have a very low solubility. But some soil properties may affect the solubility of natural phosphates such as pH, reaction time or Ca ++ ion absorption capacity, Nahas (1996). Solubility also depends on the degree of fineness of the phosphate and its origin (GREAT QUEST, 2011). PNs of sedimentary origin may be more soluble than phosphates of woody or metamorphic origin (Hammond et al., 1986). Among the West African NPs, that of Tilemsi (PNT), in Mali, occupies a good place. It is one of the best natural phosphates and most receptive (Truong et al., 1978). PN deposits in the Tilemsi Valley have been detected since 1930 but, for several reasons, including differences in quality assessment, they have not been exploited (SONAREM, 1988). However, SONAREM, for agronomic testing purposes, produced a certain amount of PN between the 1960s and 1970s. These tests yielded some encouraging results and, starting in 1976, the production of PNT was undertaken. The deposit in operation is that of Tamaguilet, a residual plateau located in the valley of Tilemsi in northern Mali, some 120 km from Bourem. Its geographical coordinates are O ° 15 'East

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Traoré Lamine (Correspondence)
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longitude and 17 ° 38' North latitude. The deposits of this PN are estimated at between 20 and 25 million tons, of which 2 to 5 million are located on the edges of the plateau and can be mined outdoors (Bathiono et al., 1997). PNT is rich in phosphorus. 100 kg PNT contain 25 to 30% P_2O_5, 42% calcium and also 0.0081% iron and aluminum oxides (Jenny, 1973). Following their work to characterize and classify tricalcic natural phosphates from West Africa, Truong et al. (1978) have shown that PNT has chemical and mineralogical characteristics that theoretically rank it among the best natural phosphates in Africa. Indeed, the PNT is the only one to have solubility in formic acid, higher than the limit of 55% retained by the European Commission for the direct employment in agriculture (Pieri, 1989). These same authors found that, among the phosphates of different solubility originating from Anecho in Togo, Kodjari in Burkina Faso, Tahoua in Niger, Tilemsi in Mali and Matam in Senegal, only the phosphates of Tahoua and Tilemsi are suitable for direct application. Both of these phosphates have solubility in citric acid of 3.2 to 5% (average solubility). For the PN to be able to serve as a source of phosphorus and to optimize the growth of plants, it is necessary that its conditions of use, in direct application or in acidulated form, favor its dissolution (Bationo et al., 1998). These conditions are physical, chemical and biological (Morel, 1996). Thus the following factors may affect the agronomic efficiency of phosphates: (1) The reactivity of phosphates, the chemical composition and the particle size determine their reactivity. Phosphates of sedimentary origin are generally more reactive and therefore better intended for direct application (PNT is that). The work of Lehr and McClellan (1972) and Chien (1977) have shown that the smaller the particle size, the greater the contact between phosphates and the soil and the higher the solubilization rate; (2) soil properties, according to FAO (2004) studies, for a phosphate to be agronomically effective, it must not only be dissolved but also available to plants. The properties of the soil that favor the dissolution of phosphates are the pH (less than 5.5), the low concentration of the Ca ++ ion in soil solution, the low soil level in P and the high content of organic matter. With respect to cation exchange capacity, recent studies by Perrott (2003) have suggested that a high level of exchangeable magnesium (Mg) in the soil solution can accelerate the dissolution of phosphates; (3) Climatic conditions, it was reported by Weil et al. (1994) that rain is the most important climatic factor influencing the dissolution of phosphates and their agronomic efficiency. Increasing the amount of soil water by rain or irrigation water increases the dissolution of phosphates. Hinsinger and Gilkes (1997) reported that the maximum agronomic effectiveness of phosphates with crops partially reflects the acidifying nature of soils and the high root density. The high root density facilitates the intensive exploitation of a larger soil volume for phosphorus because of the presence of a high number of fine roots per unit volume of soil; (4) Soil management practices and fertilizers, according to FAO (2004) studies, 4 management practices influence the agronomic efficiency of phosphates: the placement of phosphate relative to the plant, the dose of application, application period and liming. To maximize the agronomic efficiency of phosphates, they must be spread evenly over the soil surface and then incorporated at a depth of 10 to 15 cm. The incorporation of phosphates on the soil facilitates greater dissolution by improving contact between soil and phosphate particles. It also improves the uptake of P from the large volume of phosphorus-enriched soil and gives the roots greater chance of being in contact with the dissolved phosphate particles. According to FAO (2004), the average relative agronomic efficiency of phosphates is about 80%; (5) the activity of soil microorganisms, for phosphate rock to serve as a source of phosphorus and to optimize plant growth, conditions of use must stimulate microbial activity (Germida and Jansen, 1993). The texture and structure of the soil act on the microbial activity either directly or indirectly. Thus, in sufficiently moist sandy soil, there is a rapid spread of microbial activity while in clay soil, clay forms with organic substances organo-mineral complexes in which these substances become less accessible to microorganisms causing a slowdown in microbial activity (Morel, 1996). Each microbial species has specific pH limits between which it is active. A relatively low pH of the soil and mainly rhizosphere promotes the activity of microorganisms dissolving inorganic phosphates. Some researchers (Hedley et al., 1990, Doumbia et al., 1993, Toro et al., 1998) have shown that stimulation of microbial activity leads to a decrease of exchangeable calcium in the soil and favors the dissolution of natural phosphates. Regarding biological factors, the solubilization of natural phosphates must be a function of the microbial species and cultivars used Traoré (2010, 2012, 2014). The work of Flash et al., 1987 showed that sorghum mobilizes natural phosphates more efficiently than maize. According to Richardson (2001), some plants release into the rhizosphere organic acids capable of mobilizing phosphorus from soils rich in iron and aluminum phosphates. According to Boiffin and Sebillotte (1977), the incorporation of very high C/N residues into the soil can lead to phosphate deficiencies in plants by acting on the growth of soil microorganisms, which are the key to improving soil nutrients. efficiency of natural phosphates. Thus, the increasingly important role played by microorganisms in agriculture has led to their use in many parts of the world (Johri et al., 1999, Nautiyal, 1999). Komy (2005) has shown that the combination of the inoculation of a nitrogen-fixing bacterium (Azospirillum spp.) With that of a solubilizing bacterium of inorganic phosphates significantly improves plant growth. Since 1977, the Institute of Rural Economy (IER) of Mali and its partners have conducted several studies on the agronomic value of the PNT in controlled conditions and in peasant environment in the different agro-ecological zones and cropping systems of Mali. The results of these studies showed that the agronomic efficiency of the NTP was highly dependent on rainfall. This work has shown that the PNT incorporated in the soil at the rate of 300 kg/ha has a maximum effect in the second year and minimum effects in the first and third years. SAFGRAD, (1985), Bagayoko and Coulibaly's (1995) research results indicated that the low efficacy of PNT was mainly related to its low solubility in soil. Thus research has been conducted to improve its physical appearance and solubility in soil by Sanogo et al., (1978); IFDC-IER (1982, 1989); IER-FED (1986); LUXCONSULT SA (1985) and Samaké (1987). Despite the satisfactory results of research and extension efforts, the PNT has been poorly adopted by producers because of its powder form that made it difficult to apply in the field, its brown color reminiscent of that of the soil, suggesting that the PNT has no fertilizing value and its low solubility in direct application because its effect was observed only at the second year of its use. Faced with these problems related to the physical and chemical aspects of the PNT, GREAT QUEST Fertilizer SA, after having developped its metallurgical process to enrich the PNT that is based on operations of washing and screening the phosphate that reduce mainly the minerals oxides which consequently ameliorate the solubility and its granulation process that allows mixing phosphate with other nutriments in one granule , had interred in collaboration with the IER to implement a program of agronomical trials to use its granular formulations based on enriched natural phosphate. 27% P_2O_5 enriched PNT (medium grade), 35% P_2O_5 (high grade) for direct application and PNT-enriched 35% P_2O_5 mixed with urea, potassium, sulfur and boron (NPK 15-15-15, NPKSB 14-18-18-6-2) as normal fertilizer. This project falls within the framework of a valorization of the PNT for the increase of the agricultural production in Mali.

2. Material

2.1. Experimental sites*:* The enriched granular PNT fertilizer formulations were tested for two (2) years in the seven (7) agronomic research stations and tested in a peasant environment for two (2) years in seven (7) agricultural regions, representing the different agro-ecological zones of Mali. The regions hosting the project activities from 2013 to 2017 are shown on the following map of Mali.

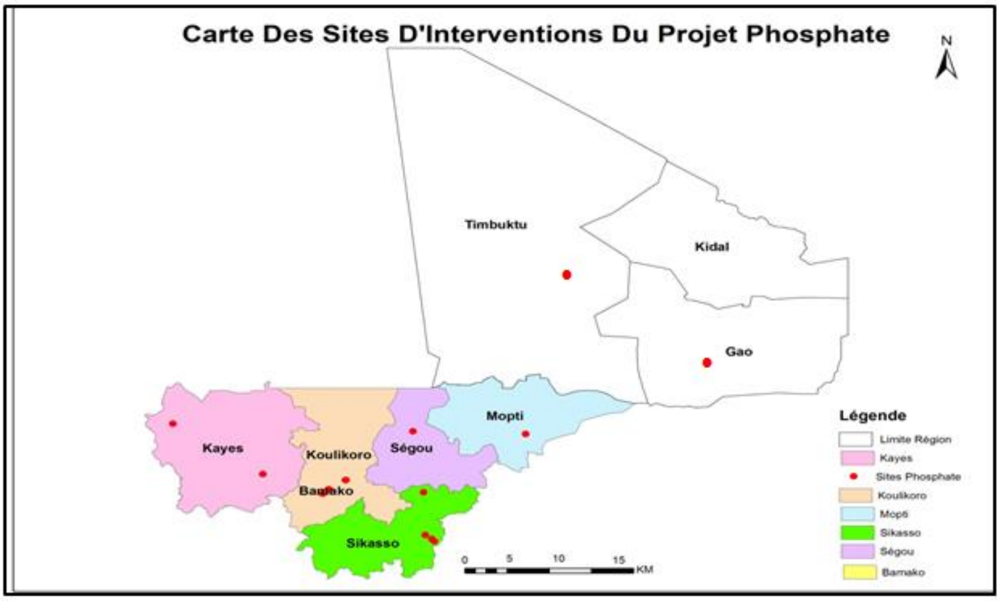

Figure 1: Agronomic Test Sites, 2013-2017 Campaigns • regions that have received the PNT on station trials and On-Farm tests

2.1.2. Plant material: it consisted of all the most commonly used popular varieties of cereals, cotton and seed legumes (peanut, cowpea) given in Table 1 below.

Table 1: Crops and varieties used in field trials and On-farm tests

Crops	Varieties
Maize	Sotubaka, Brico, Niéléni, Dembanyuman, Tiématié
Sorghum	Sangatigui, CSM-63E, Niorma, Grigan, Sekifa, Déréni, Telimani, Betrozo, Drongo, Telimani, Niodjè, Pablo, Diakoumbè
Millet	Toroniou de Ningari.
Cotton	STAM-59-A, NTAM-59-A R2, NTA-90-5, G440 R2, N'TA-905, NTA -93-15 R2
Groundnut	Fleur-11, 47-10, Niétatiga
Cowpea	Korobalen
Raifed rice	Nerika- 4
Lowland rice	Nerika L2,
Irrigated rice	Kogoni, Wassa, Kogoni 91-1, Nio19, PSB, KHAOR1, Swétachoké, KHAOR2, ADNI11, BG-90-2, IR2
Wheat	TETERA

2.1.3. Soil samples: Soil samples were taken from the test plots of the agronomic research stations at a depth of 0-25 cm for physicochemical analyzes.

2.1.4. Fertilizers: The simple and complex formulations of enriched granulated PNT fertilizer of GREAT QUEST SA were used namely: 27% P_2O_5 (0N 27P 0K); 35% P_2O_5 (0N 35P 0K); 35% NPK 15 15 15 (35% P + Urea 46% N + Potassium 60% K); 35% NPKSB 14 18 18 6 2 (35% P + Urea 46% N + Potassium 60% K + Sulfur 6% + Boron 2% ; the popularized ones: DAP (18N 46P), NPK (15N 15P 15K) and NPKSB (14N 18P 18K 6S 2B).

3. Methods.

The participatory research method, including gender, was used by involving rural development actors in determining the effect of the enriched PNT on the main crops on the research stations and On-Farms. They were researchers, technical services of rural development operations, offices, producers, decision-makers of the administration (governorates and town halls), NGOs, chambers of agriculture; private sector (fertilizer distributors), etc. This through open field days or inter-farmers visits organized in the different regions of the country.

3.1. Sampling: Soil samples were taken from 0 - 25 cm at a rate of 3 per elemental plot on the diagonal, and then a 500-g sample from the first 3 samples was taken for analysis in the laboratory.

3.2. Experimental design: The experimental design consisted of Fisher blocks with 4 replicates and 11 completely randomized treatments/replicate for the station trials and the dispersed blocks with 4 treatments per farmer for the On-Farm tests and 2-treatments/farmer for the demonstrations plots. Each treatment was 5 m x 4 m for the trials and 20 m x 10 m for the On-farm tests and 20 m x 20 m for the demonstrations plots. The formulations of the enriched granulated PNT 27% P_2O_5, 35% P_2O_5, 35% NPK 15-15-15and 35%NPKSB 14-18-18-6-2 were each tested at the doses of 100 kg/ha, 150 kg/ha and 200 kg/ha in comparison with the standard doses of the popularized fertilizer: DAP 18-46-0 fertilizer or NPK 15-15-15 (complex cereal) or NPKSB 14-18-18-6-2 (complex cotton) at the rate of 100 kg/ha, or the PNT powder at the rate of 300 kg/ha, according to the cultures for the on station, On-farms tests and demonstration plots. For the first year trials, a dose of sulfur and M_4 bacteria was added to 27% P_2O_5 at a rate of 1g/kg PNT; a quantity of sulfur and of M4 bacteria at the same dose and of boron 0.2 g/kg of PNT were added to 35% NPK 15 15 15. The bacterium M4 is a Bacillus subtilis which is a bacterial strain recognized for the production of the substances favoring growth and production of the plant.

Table 2: Station trials treatments

			Dose/20 m^2 +
T1 = Engrais vulgarisé DAP, NPK, NPKSB	100-150 kg/ha	=	130 g
T2 = 27% P_2O_5 *	100 kg/ha	=	200 g
T3 = 27% P_2O_5	150 kg/ha	=	300 g
T4 = 27% P_2O_5	200 kg/ha	=	400 g
T5 = 35% P_2O_5**	100 kg/ha	=	200 g
T6 = 35% P_2O_5	150 kg/ha	=	300 g
T7 = 35% P_2O_5	200 kg/ha	=	400 g

T8 = 35% NPK 15-15-15***	100 kg/ha	=	200 g
T9 = 35% NPK 15-15-15	150 kg/ha	=	300 g
T10 = 35% NPK 15-15-15	200 kg/ha	=	400 g
T11 = PNT poudre	300 kg/ha	=	600 g

** average content = PNT enriched at 27% P2O5; ** high content = PNT enriched at 35% P2O5; T=treatment*
**** Complex fertilizer based on enriched granular PNT = 35% NPK 15-15-15; + plot size or treatment*
NB : For the cotton, T8, T9, et T10 were 35% NPKSB 14-18-18-18-6-2

3.3. Management of tests and tests: The sowing of maize, millet, sorghum, was made on line with the aid of a graduated rope at a rate of 3 seeds per hill, at distances of 80 cm x 50 cm, 1 m x 1 m and 75 cm x 50 cm respectively, thinned at 2 plants per plant. Fertilization consisted on the base application of the enriched PNT and the popularized fertilizer according to Table 2. The urea supplement (150 kg/ha) was provided in two fractionations with 50 kg/ha at seeding and 100 kg/ha at steam elongation for maize, 50 kg/ha for sorghum and millet one month after the first application. 2 to 3 weedings at the intervals of 15 days. The 3rd weeding was done to recover the urea after application. Irrigated rice, lowland rice and submersion rice were transplanted on line using a graduated rope at a spacing of 20 cm x 20 cm for irrigated rice, lowland rice and submersion or 25 cm x 25 cm and transplanted using a clump of 3 to 4 plants per hole from a nursery of plants aged 15 to 21 days. The amount of seed for the nursery was 40 kg/ha. As for rainfed rice and wheat, sowing was done on line using a graduated rope at 25 cm x 25 cm spacing and at a rate of 3 to 4 seeds per hill. The quantity of seed was 50 kg/ha. For fertilization, phosphate fertilizers were used as bottom fertilizer. The urea supplement was provided at a rate of 200 kg/ha in 2 fractions: early tillering and panicle initiation for irrigated rice; 100 kg/ha in 2 fractions: early tillering and panicle initiation for rainfed and lowland rice: 150 kg/ha for wheat: early tillering and panicle initiation. The plots were maintained for the first weeding 15 days after transplanting and the others on demand for irrigated rice; 7 to 10 days after sowing and others on demand for lowland rice and rainfed rice. Seeding of cotton, peanut and cowpea was done in rows using a graduated rope at 80 cm x 30 cm spacings for cotton, 40 cm x 150 cm for peanut and 75 cm x 50 cm for cowpea with a 2-seedling per hill 15 days after sowing for cotton and cowpea and 1 seedling per hill for peanut. Phosphate fertilizers are applied as base fertilizer and the supplement urea 50 kg/ha was brought in early bloom cotton. The plots received 2 to 3 weeds at 15 day intervals after sowing.

NB: Enriched granular PNT, DAP, NPK and NPKSB formulations are provided as seedbed fertilizer (10-15 days after sowing); The system was to put the fertilizer in a furrow traced along and 5 cm from the crop line and then close.

3.4. Data Collection: Soil samples from all IER agronomic research stations were collected the first year prior to planting for physico-chemical analysis by the Soil-Water-Plant Laboratory in Sotuba. The agronomic data collected included the following variables: Number of plants after thining, Vigor of plants (1-5), plants height (m), number of days to 50% bloom, number of plants harvested/plot, number of ears harvested/plot, number of pods/plant, ear aspect (length and size), pod or grain yield (kg/ha), effects related to biotic (diseases, insects, Striga) and abiotic (climate) factors.

3.5. Data Analysis: The data collected were analyzed using the MSTATC statistical software using the analysis of variance method, and the ranking of averages with the Duncan test at the 5% threshold. To get an idea of the economic profitability of using the tested fertilizers, a partial economic analysis of the results was made using market prices for the concerned crops and the fertilizers used. The parameters considered for this analysis were: production or yield (kg/ha); the value of production = yield kg/ha x price (FCFA/kg of grain) of the crop; fertilizer cost/ha = CFAF/kg of fertilizer) x quantity of fertilizer used (kg/ha); net profit/ha = value of production (FCFA/ha) **-** fertilizer cost (FCFA/ha); difference in gain vs popular fertilizer = benefit from PNT **-** benefit from popular fertilizer.

4. Results

4.1. Pysico-chemical analysis of the research stations soils

The results of soils analysis have shown that the IER stations and substations used in the different regions for agronomic trials have acid soils of pH 5.5 to 4. 8 or even lower in some cases. They are very poor in organic matter, in total nitrogen and in available phosphorus. Only cation exchange capacities (CEC) for exchangeable calcium (Ca), magnesium (Mg) and potassium (K) are at acceptable levels (Table 3). Thus, given the unfavorable conditions of these soils, the production of a food or industrial crop requires the application of phosphate fertilizers to correct phosphorus deficiencies and urea fertilizers to correct nitrogen deficiency. This clearly justifies the use of new formulations based on enriched PNT plus (+) complementary doses of urea.

Tableau 3 : Pysico-chemical analysis of the research stations soils

Stations/Sous-stations	Regions					
	Kayes	Koulikoro	Sikasso	Ségou	Mopti	District de Bamako
Spécifications	0 - 25 cm	0 – 25 cm	0 - 25 cm	0 - 25 cm	0-25 cm	0 - 25 cm
pH (eau)	5,65	5,19	5,49	6,06	5.26	4,79
Organic matter % C	0,37	0,16	0,50	0,29	0.09	0,36
Total nitrogen % N	0,01	0,01	0,01	0,00	0.01	0,01
Available phosphorus ppm P	6,65	2,04	3,80	9,59	2.13	12,07
Total phosphorus ppm P	81,41	63,03	121,47	170,71	91.92	141,93
CEC Ammonium acetate. meq/100	6,16	6,02	8,70	14,58	2.58	6,12
Exchangeable Ca "	1,15	1,35	1,71	6,45	0.45	1,35
Mg "	0,52	0,61	0,84	3,19	0.21	0,63
K "	0,15	0,12	0,18	0,23	0.08	0,23
Na "	0,16	0,11	0,11	0,12	0.15	0,08
Available Potassium mg/100g K	10,94	6,53	6,50	9,45	5.13	14,04
Sand% > 0.05mm	70,88	62,50	56,44	48,50	90	47,25
Fin limon % 0.05-0.02 mm	19,00	28,75	23,25	24,50	6	39,75
Clay % < 0.02 mm	9,63	8,50	20,25	26,50	4	12,88

4.2. Rainfall situation of the sites

All research stations in the agricultural regions (Kayes, Koulikoro, Sikasso, Segou, Mopti, Gao, Tombouctou and the Bamako District) are located in the Sudanian zone. In this zone, the rainfall varies from 700 to 1100 mm. The rainy season is 3 to 5 months in the North; 5 and 6 months in the South. The temperature difference goes from 20 ^{0} C in the dry season and decreases considerably to 10 ° C (Soumaré 2014). Rainfall averages recorded in 2013 range from a minimum of 580 mm in Mopti to a maximum of 1050 mm in Sikasso distributed respectively in 36 days and 80 days of rain. In 2014, 503.1 mm in Mopti and 936.6 mm in Sikasso in 37 and 71 days of rain respectively. The year 2016 recorded 707.1 mm in Koulikoro and 1350 mm in Sikasso, respectively in 32 days and 63 days of rain. For 2017 finally 527.5 mm in Kayes and 1006 mm in the District of Bamako in 37 and 45 days of rain respectively (Figures 2 and 3). In general, the rainfall pattern in the area was characterized by a moderate frequency and intensity of rainfall with a marked deficit in May and June, a good distribution of rains from July to September with an early stop towards the end leading to premature drying of the plants (Figure 2).

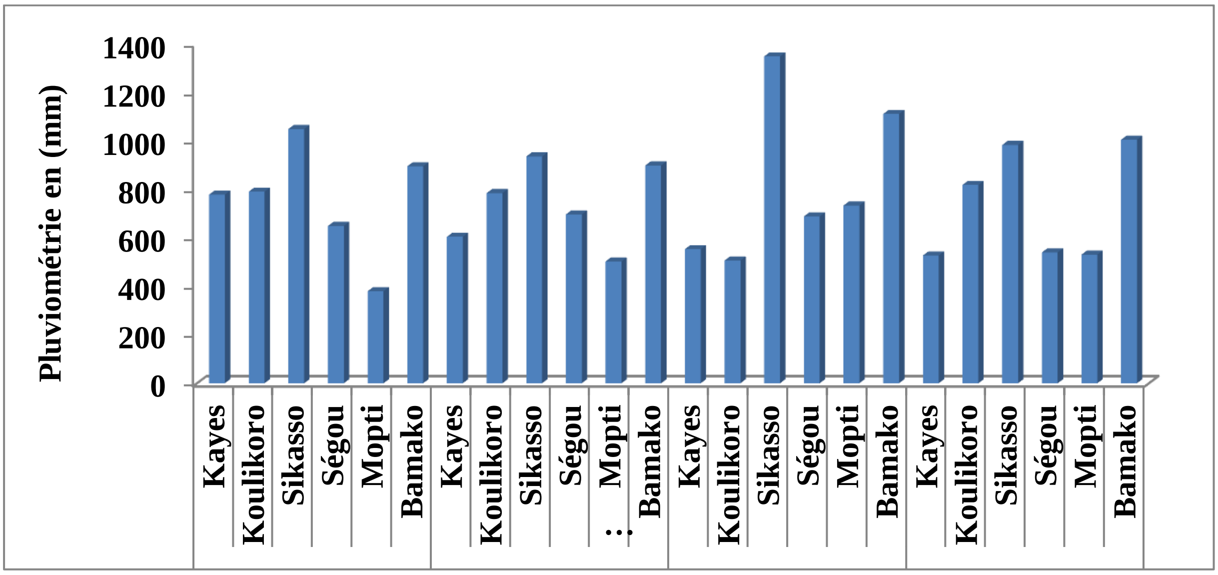

Figure 2 : Average annual rainfall of the research sites.

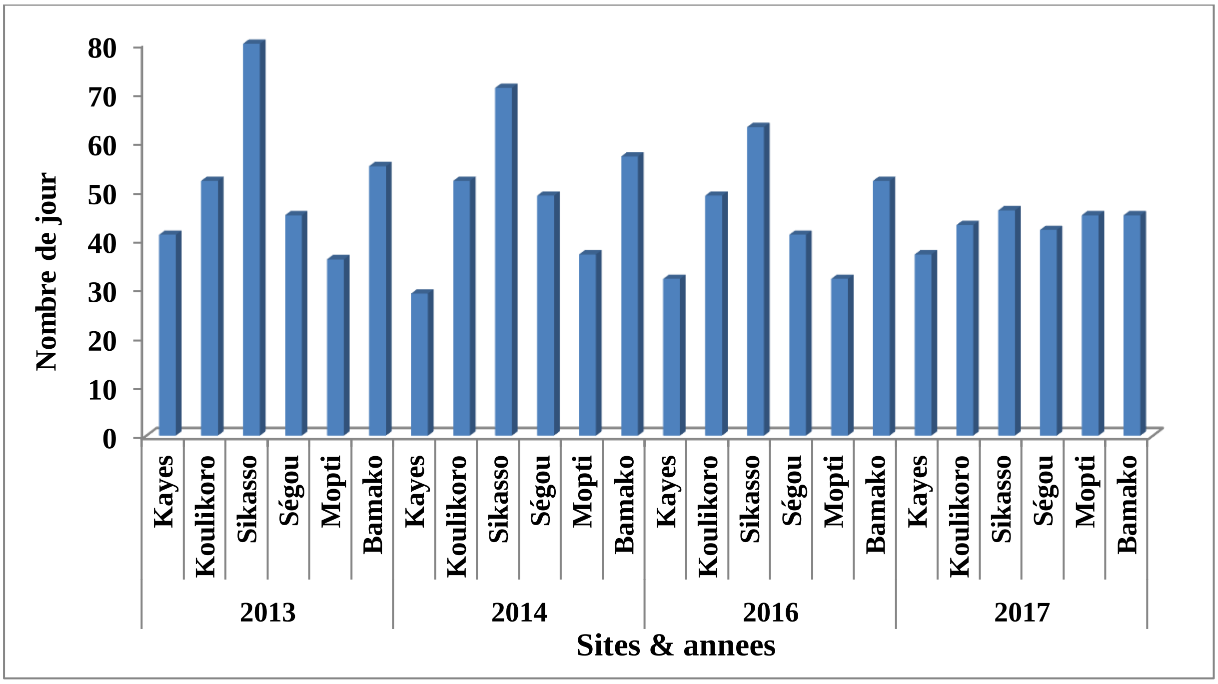

Figure 3 : Average number of rainy days of the research sites.

4.3. Effect of Fertilizer Formulations on Station Crops Across Regions

In the first year, enriched granular PNT formulations were tested on the different cereal crops (maize, millet, sorghum, rice (rainfed, lowland and irrigated), cotton and seeded legumes (peanut and cowpea). The statistical analysis of the yield data did not reveal any significant differences between the treatments for all the crops, and the yields did not vary significantly with the addition of sulfur and M4 bacteria to the trials in the first year (Table 4). The yields obtained by fertilizer formulation are very close to the grand averages for all the crops, explaining a great similarity between the PNT formulations compared to the popularized ones with coefficients of variation ranging from 9.15% to 19.32%. On the other hand, the statistical analysis showed significant differences between the different sites indicating a local effect for the formulations and the crops. Regarding Table 5, the statistical analysis showed significant differences between fertilizer formulations for sorghum and millet. For sorghum, the best yields were obtained by NPK fertilizer 15 15 15, 100 kg/ha with 1841 kg/ha and 35% NPK 100 kg/ha, NPKS 150 kg/ha, NPKSB 200 kg/ha with respectively 1612 kg/ha, 1650 kg/ha, 1676 kg/ha and a smallest significant difference (ppds) of 334.662 kg/ha. As for millet, 35% NPK at 100 kg/ha was different compared to other formulations with 2850 kg/ha and a ppds of 457 kg/ha with coefficients of variation of 4.65% to 16, 30% (Table 5). Another statistical difference was observed for the rest of the cultures, however significant differences were observed between the sites or localities. The equal behavior of these formulations with that of the popularized fertilizers (DAP, NPK) and their superiority to the PNT powder in the majority of the trials and On-farm tests was an indication of their good performance under the Malian conditions. In the second year of experimentation, as the effect of sulfur and that of the bacterium M4 were not noticeable were removed from the experiment. Thus enriched granular PNT formulations were tested as in the previous year to determine their effect on the same main crops in Mali. Statistical analysis of yield data (Table 6), showed significant differences between fertilizer formulations for maize, sorghum and irrigated rice. For maize, the best yields were obtained by the popular fertilizer NPK 15 15 15, 100 kg/ha, 35% NPK, 200 kg/ha, 35% P_2O_5 100 kg/ha, 35% P_2O_5 200 kg/ha with respectively 1907 kg/ha, 1812 kg/ha, 1799 kg/ha, 1773 kg/ha and a ppds of 243,201 kg/ha. As for sorghum, 35% NPK at 100 kg/ha made the difference compared to other formulations with 3381 kg/ha followed by 35% NPK 150 kg/ha with 3067 kg/ha and a ppds of 352.76 kg/ha. Regarding irrigated rice, 35% P_2O_5 200 kg/ha was different compared to other formulations with 6639 kg/ha followed by 35% P_2O_5 100 kg/ha 6442 kg/ha and 35% NPK 200 kg/ha 6392 kg/ha with coefficients of variation of 9.75% to 25.61% and a ppds of 817.8 kg/ha (Table 6). Another statistical difference was observed for the rest of the crops. Significant differences were observed between sites or localities (Table 6)

Table 4: Analysis of variance for crop yields (Kg/ha) across regions (year 1.1)

Treatments/Rates		Maize	Groundnut	Cowpea	Irrigated rice	Millet
NPK ou DAP	100 kg/ha	3243	846	1458	6110	1515
27% P_2O_5	100 kg/ha	2890	692	1355	6872	1440
27% P_2O_5	150 kg/ha	2902	1019	1312	6285	1360
27% P_2O_5	200 kg/ha	3124	1020	1414	6391	1430
27% P_2O_5 + sulfur	100 kg/ha	2879	880	1305	5878	1310
27% P_2O_5 + sulfur	150 kg/ha	2990	794	1392	5920	1375
27% P_2O_5 + sulfur	200 kg/ha	2696	1156	1437	6397	1425
27% P_2O_5 + bactery M4	100 kg/ha	2718	878	1227	6153	1470
27% P_2O_5 + bactery M4	150 kg/ha	2937	1103	1350	5898	1470
27% P_2O_5 + bactery M4	200 kg/ha	3261	1072	1521	5639	1450
PNT powder	300 kg/ha	928	631	1059	6547	1530
Great Average		2967	918	1349	6190	1434
Signification	Treatments	NS	NS	NS	NS	NS
	Replicates (sites)	**	**	**	+	+
CV%		16,42	19,32	9,15	12,53	9,41

*NS = not significant at the 5% threshold; CV = coefficient of variation; ** = highly significant; + = only one locality; ppds = smallest significant difference.*

Table 5: Analysis of variance for crop yields (Kg/ha) across regions (year 1.2)

Treatments/Rates		Sorghum	Millet	Rainfed rice	Lowland rice	Maize	Cotton	Irrigated rice
NPK ou DAP	100 kg/ha	1841 a	2350 b	2210	2639	2802	1748	6131
35%NPK 15-15-15	100 kg/ha	1522 abc	2295 b	2181	2227	4361	1384	5249
35%NPK 15-15-15	150 kg/ha	1612 ab	2000 b	2152	2397	4472	1604	4665
35%NPK 15-15-15	200 kg/ha	1650 ab	2150 b	2180	2441	3211	1285	5258
35%NPKS 15-15-15-1	100 kg/ha	1561 abc	2850 a	2357	2492	3810	1466	5456
35%NPKS 15-15-15-1	150 kg/ha	1542 abc	2225 b	2152	2521	3742	1564	5641
35%NPKS 15-15-15-1	200 kg/ha	1666 ab	2075 b	2181	2585	3765	1366	5002
35%NPKSB 15-15-15-1-0,2	100 kg/ha	1400 bcd	2100 b	2344	2374	4036	1501	5017
35%NPKSB 15-15-15-1-0,2	150 kg/ha	1248 cd	2300 b	2216	2807	3560	1473	5541
35%NPKSB 15-15-15-1-0,2	200 kg/ha	1676 ab	2400 ab	2284	2988	3628	1437	5615
PNT powder	300 kg/ha	1172 d	2300 b	1830	2358	3601	1281	4425
Great average		1525,939	2270	2189,818	2530,045	3639,409	1464,545	573,18
Signification	Treatments	S	S	NS	NS	NS	NS	NS
	Replicates (sites)	**	+	**	**	**	**	+
CV%		12,80	13,94	8,58	15,53	13,94	4,65	16,30
ppds		334,662	457	+	+	+	+	+

*NS = not significant at the 5% threshold; S = significant at the 5% threshold; CV = coefficient of variation; ** = highly significant; + = only one locality; ppds = smallest significant difference.*

Table 6: Analysis of variance for crop yields (Kg/ha) across regions (year 2)

Treatments		Maize	Sorghum	Irrigated rice	Rainfed rice	Lowland rice	ground -nut	Cowpea	Cotton	Millet	Wheat
NPKK, DAP	100 kg/ha	1907 a	3381 a	6387 abc	1837	1604	1578	1710	1755	1452	2051
27% P_2O_5	100 kg/ha	1643 bc	2936 bc	5720 bcd	1676	1844	1397	1700	1058	1273	1867
27% P_2O_5	150 kg/ha	1620 bc	2907 bc	5572 cd	1913	1729	1483	1556	1424	1482	2037
27% P_2O_5	200 kg/ha	1586 bc	2924 bc	5714 bcd	2018	1750	1322	1667	1179	1424	2625
35% P_2O_5	100 kg/ha	1799 ab	2674 c	6442 ab	1666	1761	1334	1659	1311	1304	2008
35% P_2O_5	150 kg/ha	1603 bc	2668 c	6118 abcd	1787	1719	1334	1547	1305	1439	2213
35% P_2O_5	200 kg/ha	1773 ab	2776 bc	6639 a	1820	1865	1405	1729	1274	1321	2552
35% NPK 15-15-15	100 kg/ha	1575 bc	2859 bc	5451 d	1956	1823	1358	1662	1304	1344	2274
35% NPK 15-15-15	150 kg/ha	1728 abc	3067 ab	5784 bcd	1983	2000	1393	1700	1365	1476	2046
35% NPK 15-15-15	200 kg/ha	1812 ab	2759 bc	6392 ab	1687	1969	1428	1766	1333	1354	2442
PNT powder	300 kg/ha	1488 c	2743 bc	5493 d	1641	1761	1274	1540	1223	1166	1952
Great average		1685	2881	5974	1817	1802	1391	1658	1328	1367	2188
Signification	Treatments	S	S	S	NS	NS	NS	NS	NS	NS	NS
	Replicates (sites)	**	**	**	**	+	**	**	+	**	+
CV%		15,39	10,56	11,80	11,53	15,0	10,20	9,75	23,75	13,68	25,61
ppds		243,201	352,76	817,8	+	+	+	+	+	+	+

*NS = not significant at the 5% threshold; S = significant at the 5% threshold; CV = coefficient of variation; ** = highly significant; + = only one locality;*
ppds = smallest significant difference.

The Statistical analysis of the On-Farm yield data (Table 7) showed significant differences between fertilizer formulations for sorghum. The best yields were obtained by the popularized NPK 15 15 15, 100 kg/ha, 35% NPK, 100 kg/ha, 35% P_2O_5 with respectively 1388 kg/ha and 1383 kg/ha; a smallest significant difference (ppds) of 127.41 kg/ha with coefficients of variation varying between 5% and 25.60%. Another statistical difference has been observed for other crops. But significant differences were observed between the different localities or extension services. The same is true for Table 8, which contains data collected on the legumes used (peanut and cowpea) with coefficients of variation of 8.95% and 9.14%.

Table 7: Analysis of variance for crop yields (cereals) (Kg/ha) at farm level across regions (year 3)

Treatments		Maize	Sorghum	Irrigated rice	Rainfed rice	Lowland rice	submer-ged rice	Cotton	Millet	Wheat
NPK, DAP, NPKSB		2757	1388 a	5427	2203	1808	2903	1415	2002	1830
35% NPK 100 kg/ha		-	1383 a	-	2203	-	-	-	1919	2140
35% NPK 150 kg/ha		2703	1239 b	5637	2185	1967	3451	-	2291	1790
35% NPK 200kg/ha		2789	1262 b	5795	2178	2208	3438	-	2221	1910
35% NPKSB 100kg/ha		-	-	-	-	-	-	1320	-	-
35% NPKSB 150 kg/ha		-	-	-	-	-	-	1384	-	-
35% NPK 200kg/ha		-	-	-	-	-	-	1435	-	-
Great average		2798	1319	5673	2192	2006	3235	1389	2108	1918
Signifi-cation	Treatments	NS	S	NS	NS	NS	NS	NS	NS	NS
	sites/localities	**	**	**	+	+	**	**	**	+
CV%		6,18	6,04	5,00	11,8	9,03	14,03	7,73	14,38	25,60
Ppds		-	127,41	-	-	-	-	-	-	-

*NS = not significant at the 5% threshold; S = significant at the 5% threshold; CV = coefficient of variation; ** = highly significant; + = only one locality; ppds = smallest significant difference.*

Table 8: Analysis of variance for crop yields (Grain legumes) (Kg/ha) at farm level across regions (year 3)

Treatments		Arachide	Niébé
DAP (NP 18-46) 43 kg/ha		957	924
27% P_2O_5 150 kg/ha		939	708
27% P_2O_5 200 kg/ha		958	635
35% P_2O_5 100 kg/ha		948	725
Great average		951	748
Signification	Treatments	NS	NS
	Sites/localities	**	**
CV%		8,95	9,14

*NS = not significant at the 5% threshold; CV = coefficient of variation; ** = highly significant;*
+ = only one locality

The last year of the technology development focused on On-Farm demonstrations of the effect of enriched granular PNT formulations in comparison with popular fertilizers. The obtained results not presented here revealed a similarity of the effect of the enriched PNT with that of the popularized fertilizers for all the main crops used of Mali namely: cereals: maize, millet, sorghum, rice (irrigated, rain-fed, lowland and submersion), cotton and grain legumes (peanut and cowpea). Results from the first and the second years of field testing and demonstration confirmed those of the two years of agricultural research stations.

5. Discussion

The equality between the behavior of the enriched PNT formulations and that of the popularized fertilizers from the first year of use is a strong signal of the advantage of the use of the enriched PNT in the Kayes region compared to its powdered form which effect was noticeable only the second year of its application. This phenomenon has been illustrated by the similar results obtained on sorghum, cowpea and groundnuts in the agronomic research stations and in pre-extension trials in the peasant environments. Authors like Hisinger, (1997); Chien, (1977); Lehr et al (1972); Pieri, (1989) and Perrott, (2003), indicated that the valuation of the PNT old formula would be necessary for direct application and wide adoption. In the Koulikoro area, significant differences were observed between enriched PNT and popular control fertilizers for maize, sorghum, rain-fed rice and cotton with a greater effect of the former on the lasts. The relatively good rainfall of the campaign could explain the satisfactory results of the region. They support the statements made by Bationo, (1990); FAO, (2004); IFDC-IER, (1982); Perrott, (2003) that the agronomic efficiency of the PNT is strongly related to the amount of rainfall. The good relative performance of the enriched PNT compared to the popular fertilizers is that most soils in the Sikasso region are clay-silty or sandy-loamy with a high water or moisture retention capacity. Its dissolution was prolonged in time; while the popularized fertilizers being 100% soluble are rapidly used entirety by the crops. This is consistent with the work of IER-FED, (1986); Samaké, (1987); Luxconsult SA, (1985); IER-FED, (1986); Traoré, (2012, 2014); Perrott, (2003) who indicated that the effect of the Tilemsi rock phosphate is highly dependent on rainfall and soil acidity levels (PH <5.2). The performance of the enriched PNT and popular fertilizer formulations found in the other regions cited in the first year of use was relatively low in the Segou region compared to the other regions of the country. Most of the Ségou soils are coarse sand, do not retain moisture for a long time and this has had a negative impact on the effect of fertilizers. Thus, the low observed performance of fertilizers tested on dry crops are explained by low rainfall such as the Ségou region (540 mm to 749 mm). This is in agreement with IFDC-IER (1982, 1989); IER-FED (1989). According to them, the rainfall regime is a determining factor of the effect of enriched PNT formulations on the crops. In the rice growing conditions of the Ségou and Mopti regions, the difference in performance of the enriched PNT effect, ie, low in rain-fed conditions and high in irrigated conditions was explained by the fact that the effect is highly dependent on soil humidity which itself depends on the amount of rainfall that has fallen or the permanence of the irrigation water. These results are supported by the work of SAFGRAD, (1985); Sanogo et al (1978); Truong et al (1993); Weil et al (1994) and Traore, (2010). They stipulated that since the PNT is composed essentially of anions, the rapid dispersion and absorption of phosphorus elements is strongly related to soil moisture conditions. The partial economic analysis taking into account the cost of the fertilizers used revealed a net average benefits for the enriched PNT greater than those of the control popularized fertilizers according to the crops: 705925 FCFA/ha against 478175 FCFA/ha for the control fertilizers with an average profit difference or economic gain in favor of the enriched PNT of 227750 FCFA/ha for irrigated crops (irrigated rice, submersion rice and lowland rice). 246,600 FCFA/ha for the enriched PNT against 184,900 FCFA/ha for the control fertilizers with an average difference in economic gain in favor of the enriched PNT of 61700 FCFA/ha for dry crops (maize, millet, sorghum). This was in line with the report of GREAT QUEST/Mali SA (2011) which showed that the large-scale use of enriched PNT is linked to its economic profitability and its competitiveness in the market.

6. Conclusion

Formulations based on granulated enriched PNT with 27% P_2O_5, 35% P_2O_5; NPK 15-15-15 and NPKSB 14-18-18-6-2 enriched to 35% P_2O_5 of GREAT QUEST/Mali SA, have been tested on different cereal crops (maize, millet, sorghum, rain-fed rice, lowland, irrigated and submerged rice), cotton and grain legumes (peanut and cowpea). The results of station experiments on the enriched granulated PNT of the 2013-2014 and 2014-2015 campaigns showed, from the first year of use, an equal behavior of these formulations to that of the popularized fertilizers (DAP, NPK and NPKSB) and their superiority compared to the PNT powder form in the majority of the trials. The encouraging results obtained on the research stations motivated the continuation of the experiments in the peasant environment. The results of the On-farm tests of the 2016-2017 and 2017-2018 cropping seasons confirmed those obtained at the research station with a similar effect of the enriched PNT to that of the popular control fertilizers. Partial comparative and economic analysis carried out on the agronomic results made it possible to highlight the economic profitability for each type of crop for the benefit of the producers. Given the observed performance, the enriched PNT product could be the solution to the large-scale use of the phosphate rock in Mali and in the sub-region with the following advantages: (1) the enriched PNT improves agricultural production considerably; (2) contains calcium, about 40%, which has a soil-letting power to fight against acidity, unlike the popularized fertilizers which acidify it with the excess of H + ions; (3) maintains moisture in the soil longer than conventional fertilizer, resulting in crops ripening with 75% of green leaves compared to conventional fertilizers where crops retain only 25%. This has the advantage of increasing the producers' resilience to the adverse effects of climate change; (4) loosens the soil by facilitating maintenance work; (5) simple formulations of enriched PNT (27% P_2O_5 and 35% P_2O_5) can be used in organic agriculture because do not contain chemicals; (6) It is better suited for crop rotation systems; (7) the posted price of the enriched PNT is half that of the popularized fertilizers making it a competitive product on the Malian market. The enriched PNT can be an effective way to enrich the soils with phosphorus, knowing that the soils of Mali and the sub-region have a proven deficiency in this element.

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