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Short-term effect of the distance between the point of application of phosphate fertilizers (CBKCa and TSP) and the crown of the plant on the evolution of the fractions and the phosphorus balance of a Lixisol

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The different fractions of phosphorus available in the short term were studied by the fractionation method. Soil samples (0-20 cm) were taken during 2021 and 2022 campaigns after the harvests in a test set up on the factorial design with four repetitions. The P sources (Calcined Burkina Phosphate enriched with calcium (CBKCa) and Triple Super Phosphate (TSP)) were applied to the main plots, and the subplots had three distances measured between the point of P fertilizer application and the plant crown (d0=0 d5=5 and d10=10 cm). The results showed that the fractions of inorganic P (Pi) (Pi-resin, Pi-$NaHCO_3$, Pi-NaOH, and Pi-HCl) increased over time, both for the different P sources and for the different supply distances. Regarding P sources, no significant difference was noted by the ANOVA for all the fractions, except that of P linked to Calcium (Pi-HCl). Whatever the year and the source of the P, the d5 led to a reduction in all the fractions of between 7% in Pi-HCl and 234% in Pi-NaOH, compared to the d0. In addition, d5 obtained P content in grains and straw significantly higher than those of samples from d0 and d10. These results will help improve agricultural production.

Key words: Soil acidity, Pi-HCl and Pi-NaOH fractions, Burkina Faso.

INTRODUCTION

In Burkina Faso, the soils are Lixisol dominated (39%). They are mainly deficient in phosphorus (P) and the assimilable portion of this element remains very low (Compaoré et al., 2003), making this element a limiting factor in plant production. In addition, the soils are generally acidic with high contents of iron and aluminium oxides and marked by the presence of soluble exchangeable ions (Fe^{2+}, Al^{3+}, Ca^{2+}, Mg^{2+}). Pallo and Thiombiano (1989) indicated that these soils had an available P rate of between 0.02 and 2.9 mg. kg^{-1} of soil. Another study conducted by Compaoré et al. (2001) showed, via the isotope exchange method, that the

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average concentrations of phosphate ions in the soil solution were close to 0.07 mg PL^{-1}. However, these same authors indicated that values greater than 0.2 mg PL^{-1} must be reached so that P does not constitute a limiting factor in the growth and development of the plant. This low availability of P in the soil, combined with the low financial capacity of small producers to invest in fertilizers, considerably limits agricultural productivity. To deal with this situation, effective local phosphate fertilizers using the natural phosphates available in the country have been put in place.

Unfortunately, suitable methods of applying these have not been defined. However, according to Siemens et al. (2004) and Ilg et al. (2005), inadequate application of phosphate fertilizers could reduce soil fertility through the mobilization of organic colloids. Indeed, according to Azzaori et al. (1994) and et Wang and Chu (2015), after application, the phosphate fertilizer is transformed into progressively less labile forms (Ca8-P, Al-P, and Fe-P) then finally to less labile P such as apatite (Ca10-P) and occluded-P (OP), due to its very high reactivity with soil colloids. Additionally, a series of studies have indicated that inorganic phosphorus (Pi), existing in various forms, can form complexes with iron, aluminium, and calcium in soils and become unavailable for uptake by plants (Dossa et al., 2008; Khan and Joergensen, 2009; Gérard, 2016), and in this case, the availability of phosphorus for plants will depend in particular on the pH of the sediments and the redox potential (Lamontagne, 2009).

Considering the very low mobility of P in the soil, increasing the availability of P for the benefit of plants must necessarily involve a strategy of supplying phosphate fertilizers. This strategy must on the one hand take into account the distance between the point of supply and the surface explored by the root system of the crops and on the other hand, it must make it possible to reduce the fixation of P by chemical precipitation and specific adsorption. For this purpose, the localized supply in strips following three (03) distances between the point of supply of phosphate fertilizers and the crown of the plant has been identified as an effective strategy for increasing the availability of P.

Furthermore, although the study of the dynamics of P fractions in tropical soils over the long term is well documented (Bandaogo et al., 2020), few studies have been carried out on the labile forms (P-resin, Pi-$NaHCO_3$) in the short term and to a lesser extent Pi-NaOH. However, these fractions constitute the forms most available to the plant in the short term (Cross and Schlesinger, 1995) and correspond to the Pi adsorbed by the exchangeable soluble ions (Fe^{2+}, Al^{3+}, Ca^{2+}, and Mg^{2+}); hence, the need to evaluate the dynamics of these fractions following a band application of phosphate fertilizer.

The objective of this study is to evaluate the effect of the supply distances of two sources of phosphate fertilizer with different solubilities on the P fractions in a Lixisol in Burkina Faso.

MATERIALS AND METHODS

Study zone

The test was installed on a Lixisol (IUSS Working Group WRB, 2014) at the Saria Agricultural Research Station, located at 309 m altitude, 12° 15′ 57″ North latitude and 2° 08′ 47″ of longitude west of the equator. Annual precipitation was 757 and 1165 mm with a unimodal pattern, respectively for the 2021 and 2022 seasons. The chemical characteristics of the 0-20 cm layer indicate an acidic soil (pH water = 3.64), with a low content of organic matter (OM) (0.45%). The available P content is 6.16 mg kg^{-1}.

Soil sampling and analysis

The soil and plant samples used in this study were taken in 2021 and 2022 from a test implemented in 2021 and renewed in 2022. The test was conducted using a split-plot experimental design with four repetitions. The P sources (CBKCa and TSP) were applied to the main plots, and the distance between the point of application and the plant collar with three modalities (d0=0 cm; d5=5 cm, and d10=10 cm) was assigned to subplots. The sampling concerned the 0-20 cm layer. They were carried out at five points corresponding to five pockets distributed on the two diagonals in each elementary plot. At each sampling point, the soil sample was taken at the point of application of phosphate fertilizers. Then, a composite sample was produced from all the samples from each elementary plot.

Chemical analysis of soil, plants, and grains

The pH water was measured by the electrometric method using an electronic pH meter. The current standard defines a ratio of 1/2.5 (mass of land per volume of water) (AFNOR, 1981). Total carbon content was determined using the method of Walkley and Black (1934). Organic matter consists essentially of carbon, oxygen, and hydrogen. In this organic matter, the carbon rate is estimated at 58%. The organic matter content is determined from the organic carbon content, using the multiplier coefficient of 1.724.

Exchangeable bases and cation exchange capacity were determined by the silver thiourea centrifugation method (Metson, 1956). The procedure is based on the extraction of soil samples with a solution of silver thiourea [Ag $(H_2NCSNH_2)^{+2}$)] at 0.01 M. The affinity of (AgTU) for negative soil particles is high enough to have complete saturation even if the soil contains enough other salts. Available P was determined according to the Bray I method (Bray and Kurtz, 1945). Phosphorus is extracted with a mixed solution of ammonium fluoride (0.03M) and hydrochloric acid (0.025M). This solution allows the extraction of acid-soluble P, a large fraction of the P linked to calcium, a part of the phosphorus linked to aluminium and iron. Ammonium fluoride dissolves iron and aluminium phosphates by forming complexes with these metals in an acidic environment.

Total P was evaluated after mineralization by the KJELDAHL method (Hillebrand et al., 1953). The plant or soil samples are subjected to mineralization with a solution that is a mixture of sulfuric acid (H_2SO_4) of Selenium (Se) and Salicylic Acid ($C_7H_6O_3$), in the presence of peroxide (H_2O_2). Selenium is used as a catalyst. After this mineralization, the aqueous solution is mixed with active carbon and then filtered. Total P is determined using a Continuous Flow Spectrophotometer (Auto-analyzer).

Phosphorus fractionation

The procedure of Hedley et al. (1982) was used to sequentially determine soil inorganic P fractions. For this purpose, four grams (4

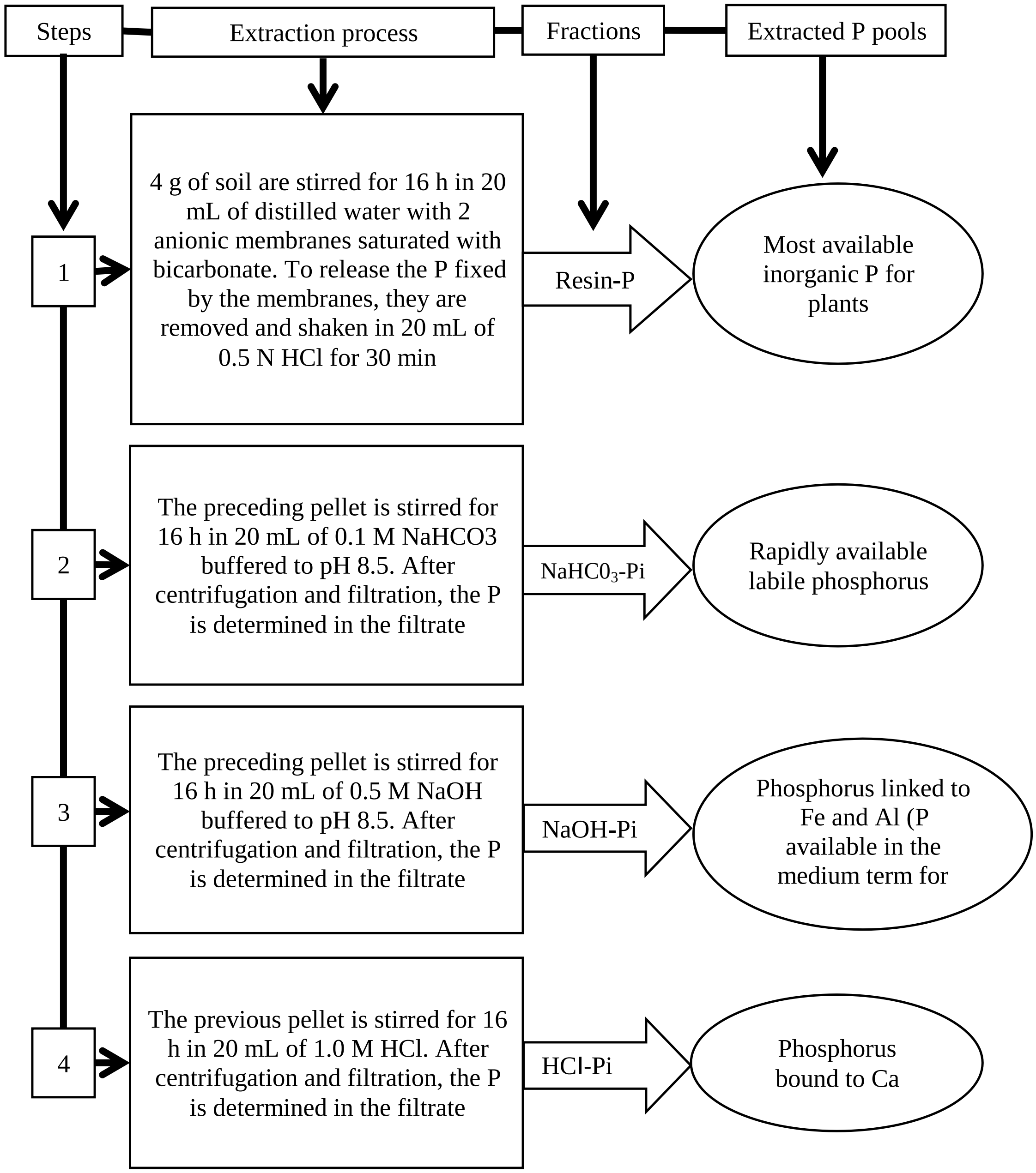

Figure 1. Phosphorus fractionation (Hedley et al., 1982).

g) of soil were extracted sequentially in the order described in Figure 1. The use of anion exchange resin required regeneration. This consisted of placing the batch of resin in a large clean 100 mL Meyer flask of 0.5 M $NaHCO_3$ for 30 min, stirring from time to time. Repeat and wash twice with distilled water and store in the final rinse water until use. The phosphorus content of the extract was measured using a manual colorimeter (Cecil 3021) at 880 nm according to the method of Murphy and Riley (1962).

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) with GenStat software version 12.1. Means were separated using the Student-Newman-Keuls test ($p < 0.05$) when the differences were significant.

RESULTS

Initial soil phosphorus status

The main phosphorus fractions from the initial samples in 2021 and 2022 are reported in Table 1. In 2021, the fractions ranged from 0.8 (P-HCl) to 3.8 mg.kg^{-1} (Pi-

Table 1. The main phosphorus fractions from the initial samples in 2021 and 2022.

Phosphorus fractions (mg/kg)	2021	2022
P-Résine	2.15	1.1
Pi-$NaHCO_3$	3.8	5
Pi-NaOH	0.8	0.6
P-HCl	5.35	1.7

Table 2. Soil chemical parameters for 2021 and 2022.

Factors	Treatments	pH water		P assimilable		MO		It $^{2+}$		Mg $^{2+}$		CEC	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Source P	CBKCa	3.96	5.10	5.99^{a}	17.9^{b}	1.083	0.379	1.09	1.03	0.34	0.12	2.42	6.49
	TSP	3.92	4.96	7.66^{b}	10.7^{a}	1.077	0.361	1.04	0.80	0.31	0.14	2.16	6.64
	Probability	0.853	0.190	0.037	0.032	0.951	0.845	0.672	0.267	0.609	0.726	0.651	0.780
	Significance	NS	NS	S	S	NS	NS	NS	NS	NS	NS	NS	NS
Input distance	d10	3.85	5.017	7.06	16.6	1.018	0.364	1.04	0.96	0.32	0.11	2.66	6.51
	d5	4.01	5.117	7.06	13.3	1.082	0.371	1.09	0.98	0.35	0.14	2.30	6.57
	d0	3.960	4.950	6.36	12.9	1.140	0.375	1.06	0.80	0.31	0.14	1.91	6.61
	Probability	0.847	0.476	0.74	0.66	0.515	0.996	0.955	0.743	0.776	0.838	0.547	0.990
	Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction	Source P×Input distances	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

MO: Organic Matter; CEC: Cation Exchange Capacity; Ca2+: Calcium ion; Mg2+: Magnesium ion; P: Phosphorus; S: significant; NS: not significant; S: significant; d0, d5, and d10 correspond respectively to the series of distances of 0, 5 and 10 cm between the point of application of phosphate fertilizers and the collar of the plant.

$NaHCO_3$). In 2022, these fractions varied from 0.6 (P-HCl) to 5 mg.kg^{-1} (Pi-$NaHCO_3$). With the exception of Pi-$NaHCO_3$, a decrease in the various phosphorus fractions was observed.

Effect of P source and distance between the point of application of phosphate fertilizers and the plant crown on soil chemical properties

The main chemical characteristics of soils likely to influence phosphate dynamics are recorded in Table 2. There was no significant interaction between the different P sources. And the different distances between the point of supply of these and the crown of the plant for all the chemical parameters ($p > 0.05$). Soil pH was generally acidic for all treatments and in both years. Both in 2021 and 2022, the pH practically did not vary depending on the source of P. It was 3.92 for TSP and 3.96 for CBKCa in 2021 and 4.96 for TSP and 5.12 for CBKCa in 2022. Between 2021 and 2022, soil acidity decreased by almost 29 and 27% due to the use of CBKCa and TSP respectively (Table 2). Regarding the distance between the point of application of the P sources and the plant collar, treatment d5 (5 cm distance) obtained the highest value whatever the year. Independently of the year, the sources of phosphorus on the one hand, and the different distances of phosphate fertilizers application on the other hand had no statistically significant effect ($p > 0.05$) on the chemical parameters, except assimilable phosphorus ($p = 0.03$). In 2021, regarding the contribution of P sources, the TSP made it possible to record the highest value of assimilable phosphorus (7.66%) compared to CBKCa.

On the other hand, in 2022, the highest value of assimilable phosphorus (17.9%) was observed by the CBKCa. Between 2021 and 2022, the TSP led to an increase of 39.69% in assimilable phosphorus. In the same period, this increase was estimated at more than 198% for CBKCa (Table 2). However, concerning the different distances between the point of application of phosphate fertilizers and the crown of the plant, no significant difference was observed between the different treatments whatever the year. The organic matter (OM) contents, over the two years of production, are higher on the CBKCa plot. Furthermore, in general, OM contents are low. In addition, from 2021 to 2022, the plot experienced a drop in its OM content. This reduction is

Table 3. Phosphorus fractions according to treatments.

Factors	Treatments	P-resin ($mg.kg^{-1}$)		Pi-$NaHCO_3$ ($mg.kg^{-1}$)		Pi-NaOH ($mg.kg^{-1}$)		Pi-HCl ($mg.kg^{-1}$)	
		2021	2022	2021	2022	2021	2022	2021	2022
Source	CBKCa	2.45	4.50	2.48	3.05	0.139^{a}	0.543^{a-}	3.56	5.83^{b}
	TSP	2.71	3.33	2.77	3.13	0.544^{b}	0.933^{b-}	4.16	3.21^{a}
	Probability	0.396	0.249	0.458	0.645	0.03	0.01	0.571	0.033
	Meaning	NS	NS	NS	NS	S	S	NS	S
Input distance	d0	3.47^{b}	5.24^{b}	3.34^{b}	7.032^{b}	0.683^{b}	1.22^{b}	4.26	5.33
	d5	2.04^{a}	2.01^{a}	1.90^{a}	2.105^{a}	0.217^{a}	0.537^{a}	2.89	4.96
	d10	2.22^{a}	4.48^{ab}	2.64^{ab}	3.142^{a}	0.575^{b}	1.058^{ab}	3.54	5.23
	Probability	0.004	0.049	0.035	<.001	0.002	0.046	0.062	0.012
	Meaning	HS	S	S	HRT	HS	S	NS	NS
Interaction	Source×Input distance	NS	NS	NS	NS	NS	NS	NS	NS

S: Significant; NS: not significant; HS: highly significant; HRT: very highly significant. d0, d5, and d10 correspond respectively to the series of distances of 0, 5 and 10 cm between the point of application of phosphate fertilizers and the collar of the plant.

estimated at 65 and 67%, respectively for CBKCa and TSP (Table 2). It is the same for the contents of calcium (Ca^{2+}), magnesium (Mg^{2+}), the sum of exchangeable bases, and the cation exchange capacity (CEC).

Effect of phosphate fertilizers and the distance between the point of application of phosphate fertilizers and the plant crown on P fractions

The effects of the two P sources and the series of differences between the point of application of these fertilizers and the crown of the plant on the P fractions are presented in Table 3. No significant interaction was observed between the two factors. In 2021, regardless of the fraction, TSP recorded the highest values compared to those of CBKCa. On the other hand, in 2022, the opposite effect was observed. Except for the Pi-NaOH fraction in 2021 and 2022 and the Pi-HCl fraction in 2022, no significant difference was observed between the effects of the two P sources whatever the fraction and the year considered.

Concerning the different distances between the point of application of phosphate fertilizers and the crown of the plant, the different fractions of P were significantly influenced. The resin-P fraction varied from 2.04 $mg.kg^{-1}$ in d5 (supply of phosphate fertilizer at 5 cm from the crown) to 3.47 $mg.kg^{-1}$ in d0 (supply of phosphate fertilizer at the crown) in 2021. In 2022, this fraction varied from 2.01 to 10.8 $mg.kg^{-1}$ in d5 and d0, respectively. In 2021, the analysis of variance showed that d5 and d10 constitute a homogeneous group. On the other hand, a highly significant difference (p=0.004) was observed between d0 and this group. Concerning 2022, the analyses indicated that d0 and d10 on the one hand, and d5 and d10 on the other hand are statistically identical. However, d0 and d5 show a significant difference (p=0.049).

Concerning the $NaHCO_3$-Pi fraction, in 2021, the d0 treatment obtained the highest content (3.34 $mg.kg^{-1}$). It is followed by treatment d10 with a content of 2.64 $mg.kg^{-1}$. The lowest content (1.90 mg kg^{-1}) was obtained with treatment d5. Thus, d5 led to a drop in the $NaHCO_3$ -P content of almost 76% compared to d0. This reduction is of the order of 39% compared to d10. In 2022, the same ranking order was recorded with values of 7.03, 3.14 and 2.11 $mg.kg^{-1}$ respectively for d0, d10, and d5. At this level, the drop in content caused by d5 is of the order of 233 and 49% compared to d0 and d10. The ANOVA noted a significant response (p=0.035) in 2021 and a very highly significant response (p<0.001) in 2022, between the different distances of application of phosphate fertilizers.

In 2021, the contents of the NaOH-Pi fraction varied between 0.217 mg kg^{-1} (d5) and 0.683 mg kg^{-1} (d0); while they varied between 0.537 mg kg^{-1} (d5) and 1.22 mg kg^{-1} (d0) in 2022. Whatever the year, the d5 treatment recorded the NaOH-Pi content as weaker. Thus, the use of the d5 treatment led to drops in content of around 215 and 165% in 2021 compared to d0 and d10. In 2022, this drop was estimated at 127 and 49% compared to d0 and d10. The analysis of variance noted a highly significant (P = 0.002) and significant (P = 0.046) difference at the 5% level, in 2021 and 2022 respectively.

As for the HCl -Pi fraction, the treatment d0 with contents of 4.26 mg. kg^{-1} in 2021 and 5.33 $mg.kg^{-1}$ in 2022 were recorded as the highest values. It is followed by treatment d10 with contents of 3.54 and 5.23 $mg.kg^{-1}$ in 2021 and 2022, respectively. The lowest contents were obtained with treatment d5. These contents are of the

Table 4. P contents in crop grains and straw in fractions of treatments.

Factors	Treatments	Grain (mg P.kg^{-1})		Straw (mg P.kg^{-1})	
		2021	2022	2021	2022
Source	CBKCa	1891	2414	613	504
	TSP	1958	1982	645	439
	Probability	0.769	0.151	0.856	0.890
	Meaning	NS	NS	NS	NS
Input distance	d0	1423^{b}	1448^{b}	504^{b}	425^{b}
	d5	2568^{a}	3158^{a}	884^{a}	641^{a}
	d10	1782^{b}	1988^{b}	487^{b}	388^{b}
	Probability	<.001	<.001	0.044	0.005
	Meaning	HRT	HRT	S	HS
Interaction	Source×Input distance	NS	NS	NS	NS

S: Significant; NS: not significant; HS: highly significant; HRT: very highly significant. d0, d5 and d10 correspond respectively to the series of distances of 0, 5, and 10 cm between the point of application of phosphate fertilizers and the collar of the plant.

Table 5. Correlation coefficients between soil properties and the different inorganic fractions of phosphorus.

Correlation coefficient	P-Resin (mg.kg^{-1})				Pi-$NaHCO_3$ (mg.kg^{-1})				Pi-NaOH (mg.kg^{-1})			
	2021		2022		2021		2022		2021		2022	
pH water	-0.16	P>0.05	-0.24	P>0.05	-0.45	P>0.05	-0.41	P>0.05	0.60	P<0.01	0.08	P>0.05
P assimilable	0.49	P<0.05	0.52	P<0.05	0.36	P>0.05	0.28	P>0.05	0.14	P>0.05	0.24	P>0.05
MO	0.19	P>0.05	-0.002	P>0.05	0.15	P>0.05	0.29	P>0.05	0.29	P>0.05	0.25	P>0.05

P = phosphorus, Pt=total phosphorus, MO=material P=phosphorus, Pi=inorganic phosphorus.

order of 2.89 mg.kg^{-1} in 2021 and 4.96 mg.kg^{-1} in 2022. Thus, reductions in the contents of the HCl-Pi fraction due to d5 of 47 and 22% in 2021 and 7 and 5% in 2022, respectively compared to d0 and d10, were obtained. The ANOVA, independently of the year, revealed no statistically significant difference between the different distances of application of phosphate fertilizers at the 5% threshold.

Effect of phosphate fertilizers and distances between the point of application of phosphate fertilizers and the crown of the plant on P export

Table 4 presents the effect of treatments on P export depending on the treatments. Analysis of this table reveals that the P content in millet grains and straw was not significantly affected by the different types of phosphate fertilizers. However, it was significantly to very highly significantly affect by the different distances between the point of application of phosphate fertilizers and the crown of the plant. The highest P contents were recorded by treatment d5, corresponding to the distance of 5 cm between the point of application of phosphate fertilizers and the crown of the plant, both in the grains and in the straw, regardless of the year of production (2021 and 2022). Concerning the P content at grain level, treatment d5 is followed by treatment d10 and treatment d0 recorded the lowest contents. On the other hand, when we consider this content at the straw level, treatment d5 is followed by treatment d0. Analysis of variance indicated that treatments d0 and d10 constitute a statistically homogeneous group. On the other hand, this homogeneous group differs statistically ($P<0.05$) from treatment d5 at the 5% threshold.

Relationship between soil properties and the different inorganic fractions of phosphorus

Table 5 shows the correlation coefficients between soil properties and the different inorganic fractions of phosphorus. Both in 2021 and 2022, all relationships were non-significant for the Pi-$NaHCO_3$ fraction. Concerning the P-Resin and Pi-NaOH fractions in 2021, the relationships were also non-significant except the following: P-resin with assimilable phosphorus and Pi-NaOH with assimilable phosphorus and organic matter.

In 2022, only assimilable phosphorus had a significant relationship with P-resin. Concerning Pi-NaOH, no significant relationship was recorded. The relationship between Pass and P-resin was significant both in 2021 (r = 0.49; P< 0.05) and in 2022 (r = 0.52; P< 0.05).

DISCUSSION

The study of the effects of two P sources (TSP and CBKCa) subjected to a series of three distances between the band supply point of the phosphorus sources and the crown of the millet plants showed that the phosphorus sources induced a significant effect on the content of assimilable P both in 2021 and in 2022. These results could be explained by the transformation process undergone by BP to result in CBKCa. Indeed, this transformation by calcination followed by calcium enrichment would have made it possible to significantly improve the quantity of phosphorus soluble in citric acid contained in the phosphate ore, corroborating the work of Nakamura et al. (2019).

Concerning organic matter (OM), the results revealed no significant difference whatever the study factor considered. Furthermore, they indicated that the OM contents of the study soil decreased between 2021 and 2022 to below a critical threshold, estimated at 1% (Bationo et al., 1998). This result could be explained by the lack of organic matter supply during the two years of production. This would have led to a drop in the OM content of the study soil. Especially since the high-temperature conditions and the alternation of humidification-drying, a typical characteristic of the tropical climate, favor the mineralization of organic matter (Nacro, 1997). In addition, they are generally acidic with high contents of iron and aluminium oxides and marked by the presence of soluble exchangeable ions (Fe^{2+}, Al^{3+}, Ca^{2+}, and Mg^{2+}) (Kwabiah et al., 2003; Ebbisa, 2022), having a phosphorus-fixing power, greater than that of clays. This situation could be the cause of low phosphorus availability through fixation of phosphorus provided by fertilizers. Indeed, the organic anions released during the decomposition of organic matter compete for the same binding sites as phosphorus (exchange of ligands) and complex metal ions (Ca, Al, and Fe) involved in immobilization phosphorus (Faucon et al., 2015). This low availability of phosphorus could limit the effectiveness of use of nitrogen and potassium mineral fertilizers.

Regarding the evaluation of soil acidity, water pH was measured. The analysis of these data revealed no significant difference between the treatments either for the different sources of phosphorus or for the series of three distances between the point of application of these fertilizers and the crown of the plant. However, a slight increase was observed in both 2021 and 2022. These results could be explained by the solubilization process of the phosphate fertilizer (CBKCa) provided, and corroborate those of Nakamura et al. (2019). These authors showed that the process of solubilization of phosphate fertilizers was accompanied by an increase in soil pH. The results also showed that neither the sources of phosphorus nor the different distances between the point of supply of these sources and the crown of the plant had a significant effect on the content of Mg^{2+}, Ca^{2+} and on the cation exchange capacity. However, these results generally indicated that the study soil recorded low levels of base cations (Ca and Mg), thus reflecting lower levels of cation exchange capacity.

The different fractions of inorganic phosphorus (Pi), corresponding to the phosphorus available to plants in the short term, were also studied. The data showed that with the exception of Pi-NaOH for both campaigns and Pi-HCl in 2022, no significant difference was observed between the two phosphorus sources for all inorganic phosphorus fractions, and this, whatever the year of production. For the Pi-NaOH fraction, representing the content of phosphorus fixed on Fe/Al in the soil, the TSP recorded the highest content, corroborating the work of Walker and Syers (1976). These authors showed that part of the available phosphorus from soluble fertilizers once applied to the soil, can be easily fixed by soil Fe/Al compared to slow-release phosphate fertilizers. Regarding the fraction of phosphorus fixed to Ca (Pi-HCl), CBKCa recorded the highest content. This predominance of Pi-HCl in soils receiving CBKCa compared to those receiving TSP could be explained on the one hand by the composition of the CBKCa which during its transformation process was enriched in calcium. On the other hand, the persistence of CBKCa in raw form in the plots having received CBKCa, especially since it is defined as being a phosphate fertilizer with slow release of phosphorus. Hence, the impact on pH; this experienced a more marked increase in the second campaign.

The results indicated that whatever the year of production, the three distances between the point of supply of the P sources and the crown of the plant induced a statistically significant effect on all the fractions, except the Pi- HCl. From observations of the effect of the three distances between the point of application of phosphate fertilizers and the crown of the plant (d0; d5 and d10) on the different inorganic fractions of P, it appears that treatment d5 recorded the highest levels but was lower compared to other treatments (d0 and d10). In addition, the results of chemical analysis showed that the different distances between the point of application of phosphate fertilizers and the crown of the plant induced a significant effect on the P contents in grains and straw, with an abundance of P in the samples from treatment d5. These results could be explained by the efficiency of P use by the millet plant in this treatment. Thus, the abundance of the different fractions of Pi observed with treatments d0 and d10 cannot be explained by a better availability of P for the culture compared to treatment d5, but rather by inefficiency in the use of the available P which is seen adsorbing by the iron and aluminium contained in the soil. Indeed, for the d0 treatment, the sources of phosphorus were brought to an area where the roots, while developing, move away from the P. Unfortunately, the roots do not reach that of d10. These observations confirm the results obtained in the literature (Hedley et al., 1995; Siemens et al., 2004; Ilg et al., 2005). Indeed, Hedley et al. (1995) showed that the placement of slow-release phosphate fertilizers in the rooting zone of crops made it possible to reduce the proportion of P fixed in the soil and improve the efficiency of P use by crops. This result shows the synergy between phosphorus sources and the distance of application of these sources in improving the bioavailability of phosphorus in the soil.

The results of the present study indicated that a significant relationship was observed between assimilable phosphorus and P-resin both in 2021 (r = 0.49; P < 0.05) and in 2022 (r = 0 .52; P<0.01). Indeed, both methods effectively measure the availability of phosphorus; so it makes sense that there is a relationship between the two. However, the Bray I method (P-assimilable) allows more phosphorus to be extracted than that of the anion resin (P-resin). In 2021, the relationship between water pH and Pi-NaOH (r = 0.60; P < 0.01) was significant. This relationship is entirely logical, and it corroborates the results in the literature (Furihata et al., 1992; Schvartz et al., 2005). Indeed, Pi-NaOH corresponds to Fe and Al phosphates, and many researchers have established that iron and aluminium compounds are largely responsible for the fixation of phosphorus in acidic soils. However, Kwabiah et al. (2003) showed that the soils of the study area have high levels of iron and aluminium oxides. In addition, the analysis results showed that the water pH of the study soils was less than 5, therefore acidic. Consequently, all the conditions are in place for the establishment of such a relationship.

Conclusion

The study revealed that regardless of the source of phosphorus, the distance from the points of application of phosphate fertilizers to the crown of the plant did not have a significant effect on the chemical parameters measured, whatever the year of production. Likewise, for the source of phosphorus, except for assimilable phosphorus, no difference was observed between the treatments. However, a significant drop in organic matter was observed across all treatments regardless of the factor considered. It also revealed that the different phosphorus sources used did not affect the inorganic phosphorus fractions. Furthermore, the application of phosphate fertilizers following the series of three distances between the point of supply of the P sources and the crown of the plant showed that treatment d5 corresponded to a gap of 5 cm between the point of supply and the collar of the millet plant, recorded for all the fractions, the lowest content compared to the contribution at the collar (d0) and 10 cm from the collar (d10). This indicates efficiency in the use of phosphorus by this strategy of supplying phosphate fertilizers, especially since these are fractions more or less available in the short term for the plants. Through a mechanized system for supplying phosphate fertilizers, producers could considerably improve their production through efficient use of P.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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