Residual Effect of Phosphate Amendments on Agronomic Parameters of Rainfed Rice in Three Agroecological Zones of Côte d'Ivoire

Abstract

A study was conducted in Côte d'Ivoire to assess the after-effect of phosphate amendments on rice yield and soil properties. Eight types of amendments, composed of Moroccan phosphate rock (PRM) and triple superphosphate were tested in three agroecological zones over three consecutive years of cultivation. The results of the study showed that the application of phosphate amendments led to a significant improvement in rice grain yield in all the agroecological zones. Grain yield was ranged from 1.7 to 4.5 t/ha, compared to 0.8 to 1 t/ha in the control. Treatments with a higher proportion of PRM showed the best results. These results suggest that the input of natural phosphate rock can significantly improve rice yield in the studied agroecological zones in Côte d'Ivoire.

Key words : phosphate amendment, Moroccan Phosphate Rock, triple superphosphate, yield

1. Introduction

In many tropical countries in Africa, particularly in Côte d'Ivoire, most agricultural soils face a major challenge: the lack of soluble phosphorus, mainly due to increasing soil acidification, thus threatening their productivity and sustainability (Agegnehu *et al*., 2021). This acidification has harmful consequences on agricultural production, especially on vital crops like rice, maize, and cocoa, which play an essential role in the country's economy (Kotchi *et al*., 2010; Soro *et al*., 2015). It leads to a decrease in the availability of nutrients, particularly phosphorus, as well as a decline in productivity and greater vulnerability to diseases (Gnahoua *et al*., 2023; Kone *et al*., 2010).

This is the case for soils of rain-fed rice cultivation in many regions of Côte d'Ivoire, which are also facing soil acidification due to agricultural practices such as deforestation, monoculture, and excessive use of fertilizers (Kouadio *et al*., 2018; Koné *et al*., 2010). This acidification can lead to a decrease in the availability of essential nutrients for rice growth, including phosphorus, which can negatively affect agricultural yield.

In response to these challenges, various innovative and environmental friendly strategies have been implemented to improve soil fertility in rain-fed rice cultivation, such as the use of organic and mineral amendments. In this context, phosphate amendments based on natural phosphate rock have been proposed as solutions to improve agricultural yield (Reddy *et al*., 2002; Xiao *et al*., 2011; Carpenter and Bennett, 2011). However, their effectiveness is often hindered by the complexity of soil characteristics (Husson *et al*., 2022), as the solubility of natural phosphate rock in the soil is closely related to specific soil properties, according to Smalberger *et al*. (2010). Therefore, it becomes crucial to study the efficiency of phosphate amendments in different type of soils.

This study aims to evaluate the agronomic effectiveness of different phosphate amendments in three contrasting zones (Man, Gagnoa, and Bouaké). Thus, it seeks to assess the long-term effect of phosphate amendments after three years of cultivation without additional inputs on the agronomic parameters of upland rain-field rice.

2. Material and methods

2.1 Description of Experimental Sites

Three departments in Côte d'Ivoire: Bouaké, Gagnoa, and Man, were selected for the study based on specific pedo-climatic and agronomic criteria. Bouaké (6°41'37"N, 5°01'49"W) is characterized by a sub-equatorial climate and features Ferralsol and Fluvisol soils with a sandy-clay texture and concentrated organic matter at the surface (Koné *et al.,* 2023). Gagnoa (6°07'54"N, 5°57'02"W), with its tropical climate, has Dystric Ferralsol soils that are conducive to rice cultivation (Bongoua-Devisme, 2009). Man (7°24'45"N, 7°33'13"W) is located in a Guinean forest climate zone and has soils such as Plinthic Ferralsol and Plinthic Cambisol, which affect soil cultivability (Kotchi *et al*., 2010).

2.2 Rice Variety

The rice variety IDSA 10, also known as Fafa, was provided by the National Center for Agronomic Research (CNRA) in Man. Resulting from a cross between IRAT 112 and Iguape Cateto, it is suited to uplands and slopes and has a short growth cycle of 105 days. Its potential grain yield is 4.8 t/ha. However, in agricultural practice in Côte d'Ivoire, the average harvest is 2.5 t/ha, which can vary depending on the agroecology. This variety is widely adopted in the country.

2.3 Fertilizers and Rock Phosphate

During the experiment, chemical fertilizers were used as conventional sources of nitrogen (N), phosphorus (P), and potassium (K). The phosphate rock from Morocco (PRM) was provided by OCP-Africa (Office Chérifien des Phosphates). Its chemical composition is detailed in Table 1. Triple Superphosphate (TSP), also supplied by OCP-Africa, contains 45% P_2O_5. These two phosphate amendments were applied at a total rate of 90 kg P_2O_5/ha, equivalent to 300 kg/ha of TSP and/or RP, at the first cropping cycle before sowing. Other chemical fertilizers, such as NPK 15/15/15 and Urea 46% N, were used in this study. The description of the treatments is summarized in Table 2.

Table 1. Chemical composition of phosphate rock in Morocco

Chemical elements	P_2O_5	CO_2	SO_3	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	F	H_2O
Content (%)	30	6,44	1,29	6,64	49,54	1,16	0,2	0,41	2,21	2,13

Table 2: Composition of treatments and doses of fertilizing elements applied

Treatments	Doses of fertilizers applied (kg/ha)					Quantity of fertilizing elements added (kg/ha) by different treatments		
	PRM	TSP	NPK	Urea	Total quantity of fertilizer	N	P	K
T0a	0	0	0	0	0	0	0	0
T0	0	0	200	100	200 NPK + 100 Urea	76	13.2	24.9
T1	300	0	200	100	300 RPM + 200 NPK + 100 Urea	76	52.8	24.9
T2	270	30	200	100	270 RPM + 30 TSP + 200 NPK + 100 Urea	76	52.8	24.9
T3	240	60	200	100	240 RPM + 60 TSP + 200 NPK + 100 Urea	76	52.8	24.9
T4	120	180	200	100	180 RPM + 120 TSP + 200 NPK + 100 Urea	76	52.8	24.9
T5	60	240	200	100	60 RPM + 240 TSP + 200 NPK + 100 Urea	76	52.8	24.9
T6	0	100	200	100	300 TSP + 200 NPK + 100 Urea	76	52.8	24.9

2.4 Experimental Setup

In each locality, the experiment was conducted on six distinct plots, each with a usable area of 200 m², subdivided into eight micro-plots of 25 m² each (8 m × 3.13 m), separated by a 1.5 m alley. Each micro-plot corresponded to a specific treatment, while each plot, treated as a separate block, was considered a repetition of the experiment. A total of eight treatments were applied per block on each plot. The treatments consisted of eight different phosphate amendments, resulting from the combination of Moroccan Phosphate Rock (PRM) and Triple Superphosphate (TSP):

- absolute Control Treatment without NPK (T0a)
- Control Treatment with NPK (T0)

- 100% PRM and 0% TSP with NPK (T1)
- 90% PRM and 10% TSP with NPK (T2)
- 80% PRM and 20% TSP with NPK (T3)
- 40% PRM and 60% TSP with NPK (T4)
- 20% PRM and 80% TSP with NPK (T5)
- 0% PRM and 100% TSP with NPK (T6)

These treatments were designed to assess the effectiveness of different proportions of PRM and TSP in combination with NPK on rice yield.

2.5 Experimental Design and Implementation

The experimental setup used was a multi-location randomized complete block design (RCBD), with a single application of treatments in the first cycle. According to the agricultural calendar of each study locality, seeds were directly sown at a rate of four seeds per hole. After germination, thinning was carried out to leave two plants per hole before tillering. Urea 46% N was applied at a rate of 100 kg/ha, with 50 kg/ha applied at tillering and 50 kg/ha at panicle initiation. To avoid competition between the rice and weeds, manual weeding was performed as needed. No insecticides or fungicides were applied to the plots.

This methodology allowed for the study of the impact of phosphate fertilizers over three distinct cropping cycles: cycle 1 (2020), cycle 2 (2021), and cycle 3 (2022). Each cycle provided a temporal perspective to evaluate the short-term and long-term effects of the treatments on yields.

2.6 Data Collection

To determine straw yield (SY) per square meter, the biomass (leaves, straw from panicles, and tillers) from each yield square was air-dried at rice maturity. Grain yield (GY) was determined after air-drying the grains and then drying them in an oven at 65°C for 72 hours. The grain yield (GY) was calculated by adjusting the grain weight to 14% moisture content using the method employed by Koné *et al*. (2010):

$$\text{GY}\ (14\%) = \frac{\text{P1}\ (100-\text{h1})}{100-14} \quad (1)$$

- $P1$ is the weight of the grains
- $h1$ is the initial moisture content

The Agronomic Efficiency Index (AEI) was calculated as the ratio of the grain yield in year n+1 to the grain yield in year n as described below:

$$\text{IEA} = \frac{\text{GY}_{\text{n+1}}}{\text{GY}_{\text{n}}} \times 100 \qquad (2)$$

The profitability of the treatments was evaluated using the formula:

Economic Profitability=Revenues−Total Cost

Where:

- "Total Cost" represents the sum of all expenses incurred for the treatment, including the costs of inputs, labor, and equipment.
- Total Cost = (cost of input1 * quantity of input1) + (cost of input2 * quantity of input2)
- "Revenues" represent the income generated by the treatment, which can be determined by factors such as yields, sales, or any other type of financial gain.

2.7 Analysis and Statistical Treatment of Data

Statistical models were developed using the lm function from the agricolae package in R software version 4.3.2 (R Core Team, 2023), with its RStudio interface (Posit team, 2023). The data are presented as mean ± standard deviation. Statistical differences were considered significant for $p<0.05$. The agronomic data were subjected to a logarithmic transformation to ensure homoscedasticity. If the assumptions of normality were satisfied, one-way and multifactorial analyses of variance, as well as Student-Newman-Keuls (SNK) tests, were used to assess differences between different treatments in each locality.

3. Results

3.1 Soil Characteristics Before Experimentation

The characterization of soils from the three studied localities shows that they have a sandy texture with 49.45% to 58.5% sand content and a high total phosphorus content (Man: 180.3 mg/kg; Gagnoa: 188.21 mg/kg; Bouaké: 106.7 mg/kg) regardless of the locality. The soils in Man are more acidic (pH = 4.52) than those in Gagnoa (pH = 5.81) and Bouaké (pH = 6.25) (Table 3). The available phosphorus content is lower in Man and Gagnoa, with 7.61 g/kg and 8.36 g/kg, respectively, compared to Bouaké (21 g/kg). The levels of K^+ (0.45 to 1.32 mmol+/kg), Ca^{2+} (29.7 to 36.4 mmol$^+$/kg), and Al^{3+} (3.12 to 6.2 mmol$^+$/kg) are higher in Gagnoa and Man than in Bouaké, which has 2.5 mmol+/kg K^+, 22.15 mmol+/kg Ca^{2+}, and 0.75

mmol+/kg Al^{3+}. The cation exchange capacity (CEC) of the soil in Man (55.6 $mmol^+/kg$) and Gagnoa (52.8 $mmol^+/kg$) is higher than that of Bouaké (32.1 $mmol^+/kg$). The soils in Man and Gagnoa are richer in organic carbon (Corg) (14.3 to 16.6 g/kg dry soil), nitrogen (N) (120 to 150 g/kg dry soil), and organic matter (24 to 28 g/kg dry soil) than those in Bouaké, which have 55 g/kg dry soil Corg, 100 g/kg dry soil N, and 9.4 g/kg dry soil OM.

Table 3. Physico-chemical characteristics of soils in the 0 - 20 cm stratum before experimentation

Parameters	**Man**	**Gagnoa**	**Bouaké**
Clay (%)	27,22	24,43	17,5
Silt (%)	23,33	20,33	24
Sand (%)	49,45	55,24	58,5
pHwater	5,52	6,01	6,25
pH_{KCl}	4,5	5,6	5,9
P total ($mg.kg^{-1}$ sol sec)	180,3	188,21	106,7
P assi ($mg.kg^{-1}$ sol sec)	7,61	7,36	21
C organic ($g.kg^{-1}$ sol sec)	14,3	16,6	15,5
N total ($g.kg^{-1}$ sol sec)	1,20	1,50	1,00
MO ($g.kg^{-1}$ sol sec)	24,73	28,71	26,66
C/N	11,92	11,07	15,50
K^+ ($mmol^+.kg^{-1}$)	2,78	2,85	2,5
Na^+ ($mmol^+.kg^{-1}$)	0,45	1,32	0,4
Ca^{++} ($mmol^+.kg^{-1}$)	29,67	36,4	22,15
Mg^{++} ($mmol^+.kg^{-1}$)	5,25	9,48	6,6
Al^{+++} ($mmol^+.kg^{-1}$)	6,20	3,12	0,75
CEC ($mmol^+.kg^{-1}$)	49,11	54,35	21,49

3.2 Evolution of rice agronomic parameters after three crop cycles under different phosphate amendments

3.2.1 Rice Grain and Straw Yield

The evolution of rice grain yield (GY) (Table 4) and straw yield (SY) (Table 5) over the three crop cycles showed a significant decrease ($p < 0.0001$) from cycle 1 to cycle 3 in all studied zones under control treatments (T0, T0a) and under treatments low in Moroccan Phosphate Rock (PRM), i.e., treatments T5 and T6. However, under treatments rich in PRM (T1, T2, T3, and T4), there was a significant increase in GY and SY from cycle 1 to cycle 3 in all studied zones (Tables 4 and 5).

The GY under treatments T1, T2, T3, and T4 ranged from 3.66 t/ha to 4.71 t/ha at the third cycle compared to 1.87 t/ha to 3.43 t/ha at the first cycle in Man, from 2.17 t/ha to 3.18 t/ha at the third cycle compared to 1.95 t/ha to 3.09 t/ha at the first cycle in Gagnoa, and from 2.04 t/ha to 2.61 t/ha at the third cycle compared to 1.38 t/ha to 1.67 t/ha at the first cycle in Bouaké (Table 4).

The SY under treatments T1, T2, T3, and T4 varied from 4.76 t/ha to 5.92 t/ha at the third cycle compared to 3.02 t/ha to 4.54 t/ha at the first cycle in Man, from 3.03 t/ha to 3.96 t/ha at the third cycle compared to 3.14 t/ha to 4.74 t/ha at the first cycle in Gagnoa, and from 2.7 t/ha to 3.41 t/ha at the third cycle compared to 1.99 t/ha to 2.51 t/ha at the first cycle in Bouaké (Table 5).

The average GY obtained under treatments in the three studied localities show GY averages ranging from 2.67 t/ha to 3.57 t/ha at the third cycle compared to 1.77 t/ha to 2.62 t/ha at the first cycle (Table 6), regardless of the locality. Furthermore, our results indicate significantly better average GY after the three crop cycles, particularly in Man under treatments rich in PRM (T1, T2, T3, and T4) regardless of the crop cycle (Table 6).

Table 4. Evolution of rice grain yield (GY) over three cycles in Man, Gagnoa and Bouaké under different treatments (T0a: no fertilizer; control T0 : 0%PRM+0%TSP+NPK; T1 : 100%RPM+0%TSP+NPK; T2 : 90%PRM+10%TSP+NPK; T3 : 80%PRM+20%TSP+NPK; T4 : 40%PRM+60%TSP+NPK ; T5 : 20%PRM+80%TSP+NPK; T6 : 0%PRM+100%TSP+NPK)

Treatments	GY (t/ha) - MAN			GY(t/ha) - GAGNOA			GY (t/ha) - BOUAKE		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
T0a	$0,82^{f}\pm0,1$	$0,66^{d}\pm0,1$	$0,4^{d}\pm0,1$	$0,88^{f}\pm0,1$	$0,5^{e}\pm0,1$	$0,44^{e}\pm0,1$	$0,68^{f}\pm0,1$	$0,58^{e}\pm0,1$	$0,39^{e}\pm0,1$
T0	$1,1^{e}\pm0,2$	$0,98^{d}\pm0,1$	$0,75^{cd}\pm0,1$	$1,36^{e}\pm0,2$	$0,86^{d}\pm0,3$	$0,68^{d}\pm0,1$	$1,17^{e}\pm0,2$	$0,77^{d}\pm0,1$	$0,59^{d}\pm0,1$
T1	$1,87^{d}\pm0,3$	$2,69^{b}\pm0,4$	$3,79^{b}\pm0,5$	$2,06^{c}\pm0,3$	$1,95^{b}\pm0,4$	$2,17^{b}\pm0,3$	$1,38^{d}\pm0,2$	$1,59^{b}\pm0,2$	$2,04^{b}\pm0,3$
T2	$2,00^{c}\pm0,3$	$2,70^{b}\pm0,4$	$3,66^{b}\pm0,5$	$1,95^{d}\pm0,3$	$1,96^{b}\pm0,3$	$2,3^{b}\pm0,3$	$1,39^{d}\pm0,2$	$1,85^{a}\pm0,2$	$2,07^{b}\pm0,3$
T3	$3,43^{a}\pm0,5$	$4,02^{a}\pm0,6$	$4,71^{a}\pm0,6$	$2,76^{b}\pm0,4$	$2,74^{a}\pm0,4$	$3,18^{a}\pm0,4$	$1,67^{c}\pm0,2$	$1,84^{a}\pm0,1$	$2,81^{a}\pm0,4$
T4	$2,6^{b}\pm0,4$	$3,6^{ab}\pm0,5$	$4,42^{ab}\pm0,6$	$3,09^{a}\pm0,4$	$2,48^{ba}\pm0,3$	$2,79^{a}\pm0,4$	$1,61^{c}\pm0,2$	$1,79^{ba}\pm0,2$	$2,07^{b}\pm0,1$
T5	$2,6^{b}\pm0,4$	$1,66^{c}\pm0,2$	$1,13^{c}\pm0,2$	$2,69^{b}\pm0,4$	$1,71^{c}\pm0,2$	$1,61^{c}\pm0,2$	$2,14^{b}\pm0,3$	$1,36^{c}\pm0,2$	$0,92^{c}\pm0,1$
T6	$3,06^{ab}\pm0,4$	$1,39^{c}\pm0,2$	$0,97^{cd}\pm0,1$	$3,04^{a}\pm0,4$	$1,6^{c}\pm0,2$	$1,34^{c}\pm0,2$	$2,36^{a}\pm0,3$	$1,31^{c}\pm0,2$	$0,94^{c}\pm0,1$
Mean	2,18	2,21	2,48	2,23	1,73	1,81	1,55	1,38	1,48
CV (%)	19,79	19,11	17,64	28,93	49,27	55,62	10,97	9,76	8,85
ppds	0,4	0,39	0,41	0,64	0,85	1,01	0,19	0,15	0,15
Pr > F	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001

*Data in the same column, followed by the same letter, are not significantly different according to the Newman-Keuls test p<0.05. *** very highly significant at p<0.05; ** highly significant at p<0.05; * significant at p<0.05.*

Table 5. Evolution of rice straw yield (SY) over three cycles in Man, Gagnoa and Bouaké under different treatments (T0a: no fertilizer; control T0 : 0%PRM+0%TSP+NPK; T1 : 100%RPM+0%TSP+NPK; T2 : 90%PRM+10%TSP+NPK; T3 : 80%PRM+20%TSP+NPK; T4 : 40%PRM+60%TSP+NPK ; T5 : 20%PRM+80%TSP+NPK; T6 : 0%PRM+100%TSP+NPK)

Treatments	SY (t/ha) - MAN			SY (t/ha) - GAGNOA			SY (t/ha) - BOUAKE		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
T0a	1,35^{f}±0,2	1,03^{d}±0,1	0,6^{d}±0,1	1,82^{d}±0,3	1,09^{d}±0,2	0,75^{d}±0,1	1,24^{e}±0,2	1,18^{e}±0,2	1,01^{d}±0,1
T0	2,04^{e}±0,3	1,51^{d}±0,2	1,07^{cd}±0,2	2,42^{c}±0,3	2,47^{c}±0,3	1,68^{c}±0,2	2,11^{d}±0,3	1,84^{d}±0,3	1,42^{c}±0,2
T1	3,02^{d}±0,4	3,51^{b}±0,5	4,76^{b}±0,7	3,05^{cb}±0,4	3,14^{b}±0,4	3,2^{b}±0,4	1,99^{d}±0,3	2,3^{bc}±0,3	2,70^{b}±0,4
T2	3,45^{cd}±0,6	3,79^{b}±0,5	4,81^{b}±0,7	3,03^{cb}±0,4	3,15^{b}±0,4	3,44^{b}±0,4	2,06^{d}±0,3	2,63^{a}±0,4	2,85^{b}±0,4
T3	4,54^{a}±0,6	4,98^{a}±0,7	5,92^{a}±0,8	3,96^{ba}±0,6	4,03^{a}±0,6	4,34^{a}±0,5	2,13^{d}±0,3	2,63^{a}±0,4	3,42^{a}±0,5
T4	3,86^{bc}±0,5	4,67^{a}±0,6	5,43^{ab}±0,7	3,36^{b}±0,7	3,63^{ba}±0,5	4,74^{a}±0,5	2,51^{c}±0,3	2,48^{ba}±0,3	3,01^{b}±0,4
T5	3,69^{c}±0,5	2,55^{c}±0,4	1,35^{c}±0,2	3,88^{b}±0,5	2,65^{c}±0,4	1,98^{c}±0,2	2,89^{b}±0,4	2,16^{c}±0,3	1,65^{c}±0,2
T6	4,23^{ab}±0,6	2,08^{c}±0,3	0,94^{cd}±0,1	4,63^{a}±0,6	2,73^{c}±0,4	1,78^{c}±0,2	3,26^{a}±0,5	2,22^{c}±0,3	1,74^{c}±0,2
Mean	3,27	3,02	3,11	3,26	2,86	2,73	2,27	2,18	2,23
CV (%)	15,79	17,65	24,12	27,66	36,8	56,93	9,26	7,66	12,27
ppds	0,48	0,5	0,7	0,97	1,06	1,41	0,24	0,19	0,31
Pr > F	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	0,0003	<0,0001	<0,0001	<0,0001

*Data in the same column, followed by the same letter, are not significantly different according to the Newman-Keuls test p<0.05. *** very highly significant at p<0.05; ** highly significant at p<0.05; * significant at p<0.05.*

Table 6: Effect of treatments on rice grain yields according to crop cycles (C1, C2 and C3) regardless of the locality studied. Treatments: T0a: no fertilizer; control T0 : 0%PRM+0%TSP+NPK; T1 : 100%RPM+0%TSP+NPK; T2 : 90%PRM+10%TSP+NPK; T3 : 80%PRM+20%TSP+NPK; T4 : 40%PRM+60%TSP+NPK ; T5 : 20%PRM+80%TSP+NPK; T6 : 0%PRM+100%TSP+NPK).

CV : coefficient de variance.

	T0a	T0	T1	T2	T3	T4	T5	T6	Mean	CV	Pr(>F)
C1	0,79aC	1,21aC	1,77bB	1,78bB	2,62bA	2,43aA	2,47aA	2,82aA	1.99	25.03	< 2,2x10^{-16}
C2	0,58bF	0,87bEF	2,08bBC	2,16bB	2,87abA	2,62aAB	1,58bCD	1,43bDE	1.77	31.08	< 2,2x10^{-16}
C3	0,41cD	0,67cCD	2,67aB	2,68aB	3,57aA	3,09aAB	1,22cC	1,08cCD	1.92	35.98	< 2,2x10^{-16}
Mean	0,59	0,92	2,17	2,21	3,02	2,72	1,76	1,78	-	-	-
CV	17,69	17,11	29,85	26,63	31,2	33,28	19,71	19,69	-	-	-
Pr(>F)	3,93x10^{-14}	2,70x10^{-13}	0,0005	0,0001	0,011	0,0887	1,86E-14	< 2,2x10^{-16}	-	-	-

In the same column, means with the same lower-case letters are not significantly different according to the Student Newman-Keuls test at the 5% threshold.

In the same line, means affected by the same upper-case alphabetical letters are not significantly different according to the Student Newman-Keuls test at the 5% threshold.

3.2.2 Agronomic Efficiency Index (AEI)

The Agronomic Efficiency Index (AEI) of the applied treatments shows a highly significant effect ($P < 0.0001$) in Man and Bouaké, unlike in Gagnoa (Table 7). However, the AEI of treatments rich in PRM (T1, T2, T3, and T4) is higher than those of treatments rich in TSP (T5 and T6) and those of controls (T0 and T0a) regardless of the locality. There is no significant difference between the AEI of plots amended with treatments rich in TSP (T5, T6) and those of control treatments (T0a, T0), but with lower AEI under T5 and T6. Furthermore, there is an increase in AEI from cycle 2 to cycle 3 in all three agroecological zones of treatments rich in PRM, with values ranging from 117% to 146% in Man, from 111% to 120% in Gagnoa, and from 112% to 153% in Bouaké. There is a decrease in AEI from treatments rich in TSP from cycle 2 to cycle 3, compared to the C2/C1 ratio (Table 7).

Table 7 : Agronomic Efficiency Index (AEI, %) multi-cycle of phosphate amendments on upland rice RDG (T0a: no fertilizer; control T0 : 0%PRM+0%TSP+NPK; T1 : 100%RPM+0%TSP+NPK; T2 : 90%PRM+10%TSP+NPK; T3 : 80%PRM+20%TSP+NPK; T4 : 40%PRM+60%TSP+NPK ; T5 : 20%PRM+80%TSP+NPK; T6 : 0%PRM+100%TSP+NPK).

Treatments	**Man (Cambisol Plintic)**		**Gagnoa (Ferrasol Dystric)**		**Bouaké (Ferralsol)**	
	C2/C1	**C3/C2**	**C2/C1**	**C3/C2**	**C2/C1**	**C3/C2**
T0a	$52,63^{d}$	$87,32^{dc}$	$60,18^{bc}$	$100,78^{ba}$	$85,90^{c}$	$67,34^{e}$
T0	$73,31^{c}$	$89,16^{c}$	$66,74^{bc}$	$78,77^{b}$	$66,84^{d}$	$76,29^{d}$
T1	$140,59^{a}$	$145,69^{a}$	$111,48^{a}$	$111,51^{ba}$	$115,79^{b}$	$128,43^{b}$
T2	$136,29^{a}$	$137,71^{ba}$	$110,63^{a}$	$119,66^{a}$	$132,96^{a}$	$112,15^{c}$
T3	$118,53^{b}$	$117,38^{b}$	$96,89^{ba}$	$118,05^{ba}$	$112,48^{b}$	$152,80^{a}$
T4	$119,71^{b}$	$145,35^{a}$	$83,23^{bac}$	$112,5^{ba}$	$110,45^{b}$	$116,96^{c}$
T5	$64,71^{dc}$	$65,03^{ed}$	$66,34^{bc}$	$97,39^{ba}$	$69,42^{d}$	$68,21^{e}$
T6	$69,58^{c}$	$45,23^{e}$	$52,15^{c}$	$90,98^{ba}$	$57,29^{d}$	$71,67^{ed}$
Mean	96,92	104,1	80,95	103,7	93,14	99,23
CV (%)	16,36	22,9	52,4	39,22	9,45	5,48
ppds	14,94	22,45	42,43	40,74	10,27	6,34
Pr > F	$<0,0001^{***}$	$<0,0001^{***}$	$0,033^{*}$	$0,44^{ns}$	$<0,0001^{***}$	$<0,0001^{***}$

Data in the same column, followed by the same letter, are not significantly different according to the Newman-Keuls test p<0.05.

**** very highly significant at p<0.05; ** highly significant at p<0.05; * significant at p<0.05.*

3.2.3 Economic Profitability of Applied Treatments

The analysis of Table 8 highlights distinct trends among treatments and crop cycles of rainfed rice. The doses of treatments T3 (240 kg/ha PRM and 60 kg/ha TSP) and T4 (120 kg/ha PRM and 180 kg/ha TSP) stand out with consistently higher profitability across all cycles and regardless of the locality, suggesting their strategic potential to maximize profits regardless of the stage of the cycle. The doses of treatments T1 (300 kg/ha PRM) and T2 (270 kg/ha PRM and 30 kg/ha TSP) may not be economically viable in the short term, while those of T3 and T4 offer more consistent profitability in the long term. Thus, optimizing the profitability of rice cultivation in Bouaké, Gagnoa, and Man requires a nuanced approach, taking into account the doses, yields, and specific costs of each treatment across all cycles.

Table 8 : Economic profitability (CFA) of treatments in Bouaké (A), Gagnoa (B), Man (C)A

Treat	Total cost			Grain yield t ha^{-1}			Profit CFA ha^{-1}			Economic profitability		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
T1	40500	0	0	1,38	1,59	2,04	345000	397500	510000	304500	397500	510000
T2	45045	0	0	1,39	1,84	2,07	347500	460000	517500	302455	460000	517500
T3	49590	0	0	1,67	1,84	2,81	417500	460000	702500	367910	460000	702500
T4	67770	0	0	1,61	1,79	2,07	402500	447500	517500	334730	447500	517500
T5	76860	0	0	2,14	1,36	0,92	535000	340000	230000	458140	340000	230000
T6	85950	0	0	2,36	1,31	0,94	590000	327500	235000	504050	327500	235000

B

Treat	Total cost			Grain yield t ha^{-1}			Profit CFA ha^{-1}			Economic profitability		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
T1	40500	0	0	2,06	1,95	2,17	515000	487500	542500	474500	487500	542500
T2	45045	0	0	1,95	1,96	2,3	487500	490000	575000	442455	490000	575000
T3	49590	0	0	2,76	2,74	3,18	690000	685000	795000	640410	685000	795000
T4	67770	0	0	3,09	2,48	2,79	772500	620000	697500	704730	620000	697500
T5	76860	0	0	2,69	1,71	1,61	672500	427500	402500	595640	427500	402500
T6	85950	0	0	3,04	1,6	1,34	760000	400000	335000	674050	400000	335000

C

Treat	Total cost			Grain yield t ha^{-1}			Profit CFA ha^{-1}			Economic profitability		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
T1	40500	0	0	1,87	2,69	3,79	467500	672500	947500	427000	672500	947500
T2	45045	0	0	2,0	2,69	3,66	500000	672500	915000	454955	672500	915000
T3	49590	0	0	3,43	4,02	4,71	857500	1005000	1177500	807910	1005000	1177500
T4	67770	0	0	2,60	3,6	4,42	650000	900000	1105000	582230	900000	1105000
T5	76860	0	0	2,59	1,66	1,13	647500	415000	282500	570640	415000	282500
T6	85950	0	0	3,06	1,39	0,97	765000	347500	242500	679050	347500	242500

4. Discussion

4.1 Effect of Soil Parameters on the Agronomic Efficiency of Phosphate Amendments Applied

The characterization of soils in the studied areas revealed that the soils of Man (Dystropept Cambisol) and Gagnoa (Plinthic Ferralsol) are richer in clay (more than 20%), organic carbon (Corg) with 14 to 16 g/kg, calcium (29 to 36 mmol+/kg), aluminum (3 to 6 mmol+/kg) than those of Bouaké. The soils of Man and Gagnoa are also poor in assimilable P, have a higher C/N ratio, and higher CEC. Furthermore, the characterization of soil pH in the rice fields of the studied area showed that the pH of the soils in different plots of Man varies from 4 to 5.1 with an average of 4.6, which is very strongly acidic, and those of Gagnoa vary from 4.3 to 5.7 with an average of 5.2, which is strongly acidic (Bassole et al., 2023). On the other hand, in Bouaké, the pH of the soils in the plots varies from 5.9 to 6.8 with an average of 6.4 and reveals that they are weakly acidic to neutral. This strong soil acidity in Man compared to Gagnoa and Bouaké could also result from the nature of the soil type, as demonstrated by Nishigak *et al.,*(2020) who showed that Cambisols are more acidic than Ferralsols in Madagascar. Our results also indicate that the potential acidity is higher in the soils of Man (Dystropept Cambisol) compared to that of Gagnoa (Plinthic Ferralsol) and Bouaké (Ferralsol) where the soils are more sandy, probably due to the intensity of soil weathering. The lower potential acidity in Bouaké could thus justify the higher content of assimilable P (21 g/kg dry soil) analyzed in this locality. This higher acidity in both localities (Gagnoa and Man) would favor a good dissolution of phosphate amendments based on Moroccan phosphate rock and triple superphosphate as suggested in various studies that have observed rapid dissolution of phosphate rocks when soil pH is acidic (pH <5.5); poor in phosphorus and rich in organic matter (FAO, 2004). Indeed, acidic pH soils enhance the agronomic efficiency of phosphate rocks (PR) as demonstrated by the works of Koné *et al.*, (2010; 2011 and 2014) and Kotchi *et al.*, (2018). Since the application of phosphate rocks to acidic soils allows the release of hydrogen ions that promote the dissolution of phosphate rock, and consequently the increase in the form of P assimilated by plants (Begum *et al.*, 2004; FAO, 2004; Wahid, 2016).

Furthermore, the higher organic carbon content for the soils of Man and Gagnoa than those of Bouaké (2.47%; 2.87% and 0.95%, respectively) could contribute to the rapid dissolution of phosphate amendments as suggested by Chaibou (2013); Aziable *et al.*, (2014), Kpan (2019). Moreover, Kotchi *et al.,* (2018) demonstrated that the decomposition of organic matter leads to a decrease in soil pH through the production of humic acids that will in turn enhance the dissolution of phosphate rock and the solubilization of P. Since the soils of Man and Gagnoa are more acidic than those of Bouaké, and their percentages of OM are higher than in Bouaké, they will therefore favor a better dissolution of RPM and increase the agronomic efficiency of phosphate amendments applied compared to those of Bouaké. The higher values of organic carbon (Corg) in the soils of Man and Gagnoa compared to those of Bouaké would thus be a consequence of their acidic pH.

4.2 Backward Effect of Phosphate Amendments on Rice Yield

The assessment of the backward effect of phosphate amendments, formulated based on Moroccan phosphate rock (RPM) combined or not with triple superphosphate (TSP) in different proportions, on the agronomic parameters of rainfed rice first revealed an increase in plant height, number of tillers, and number of panicles compared to the control treatment, as demonstrated by Abbasi *et al*., (2015) in a study conducted with Phosphate Rock (PR), Single Superphosphate (SSP), and Di-Ammonium Phosphate (DAP). Furthermore, the application of phosphate amendments significantly increased straw yield (SY) and grain yield (GY) compared to the control T0 during the cropping cycles, consistent with the findings of Koné *et al*., (2010) who obtained similar results using phosphate rock (PR) of different origins and TSP on rainfed rice. Sossa (2012) made the same observation with different doses of TSP combined with K on SY and GY. A significant increase in agronomic parameters (height, number of tillers and panicles, SY, and GY) of rice, up to three cropping cycles after its application in all agroecological zones (Man, Gagnoa, and Bouaké), was observed when the phosphate amendment (AP) contained more than 50% of RPM (T1, T2, T3, and T4). This gradual increase in agronomic parameters of rice under amended soils receiving treatments rich in PRM (T1, T2, T3, T4) compared to treatments rich in TSP (T5, T6) could stem from the nature of the amendments used. Indeed, in the first year of treatment application, a higher yield (GY and SY) was observed for soils amended with TSP (T5 and T6) compared to soils amended by PRM (T1, T2, T3, and T4). However, a gradual decrease in yield under TSP-rich treatments (T5 and T6) and an increase in GY and SY under soils amended by PRM (T1, T2, T3, and T4) were observed from the second year of cultivation onwards, probably because plants directly utilize the available P in soluble fertilizer (TSP) in the first year of cultivation unlike phosphate rock, which dissolves more slowly (Sanogo *et al*., 2020). These results are consistent with those of Koné *et al*., (2010) who observed increased yield under treatments composed of natural phosphate rock of various origins compared to TSP under upland rice in the semi-mountainous forest zone of Côte d'Ivoire under tropical climates, and those of Kotchi *et al.*, 2010 who tested the responses of different rice varieties to different increasing doses of phosphate rock and TSP.

The highest higher rate of agronomic efficiency index (AEI) of the applied treatments were observed for soils amended by treatments rich in PRM (T1, T2, T3, and T4) with AEI > 100%, compared to the non-amended soil and soils amended by treatments rich in TSP (T5, T6). These results reflect a more significant effect of PRM years after its application as already indicated in various studies (FAO, 2004; Wopereis *et al*., 2004; Useni *et al.*, 2012; Sanogo *et al*., 2020) which have indicated that the application of phosphate rocks generates residual effects in the years following their application.

However, AEI varies depending on the study area. Under Cambisols (Man), i.e., when soils are strongly acidic, amended soils particularly amended by treatments T1, T2, T3, and T4 have a higher AEI than moderately acidic Plinthic Ferralsols (Gagnoa) and weakly acidic Ferralsol (Bouaké). Soils receiving more than 40% of PRM remain those with more effective AEI over the 03 cycles of rainfed rice cultivation compared to other treatments, probably due to the slow dissolution of RPM and the slow release of phosphorus content in the treatments.

5. Conclusion

The application of 300 kg/ha of Moroccan phosphate rock (PRM) and/or triple superphosphate (TSP), equivalent to 90 kg/ha of P_2O_5, on rainfed rice soils in different locations not only improved yield but also reduced the deficit in phosphorus and promoted the export of nitrogen (N), phosphorus (P), and potassium (K) by rice plants on highly acidic soils (Man) to moderately acidic soils (Gagnoa) and even slightly acidic soils (Bouaké). Phosphate amendments containing more than 40% Moroccan phosphate rock (PRM) resulted in a better response in terms of rice grain yield (GY) and straw yield (SY) and soil parameters (pH, N, P, K content) after three successive cropping cycles compared to treatments rich in TSP, regardless of the agroecological zone. Our results therefore indicate a better residual effect of phosphate amendments when they are rich in Moroccan phosphate rock (T1, T2, T3, T4). After three cropping cycles, the combination T3, i.e., 80% PRM and 20% TSP, is the best combination regardless of the agroecological zone, with a relative yield increase ranging from 398% in Man, 262% in Gagnoa, and 184% in Bouaké, compared to the control T0.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

Abbasi M.K., Musa N., Manzoor M., 2015. Mineralization of soluble P fertilizers and insoluble rock phosphate in response to phosphate-solubilizing bacteria and poultry manure and their effect on the growth and P utilization efficiency of chilli (Capsicum annuum L.). *Biogeosciences*, 12(15), pp. 4607–4619. https://doi.org/10.5194/bg-12-4607-2015

Aziable E., Sanonka T., Kokou S., Magnoudéwa B.B., Kokou D., Koffi K.A., … Gnon B., 2014. Study of the availability of assimilable phosphorus from urban waste composts in two different soils. 10(6), 156–167.

Agegnehu G., Amede T., Erkossa T., Yirga C., Henry C., Tyler R., Sileshi G.W., 2021. Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science, 71(9): 852-869. https://doi.org/10.1080/09064710.2021.1954239

Bassole Z., Yanogo I.P., Idani F.T., 2023. Characterization of leached tropical ferriginous soils and tropical eutrophic brown soils for agricultural use in the Goundi-Djoro lowland (Burkina Faso). I.J. Biol. Chem. Sci. 17(January), 247–266. https://doi.org/https://dx.doi.org/10.4314/ijbcs.v17i1.18

Begum B.A., Kim E., Biswas S.K., Hopke P.K.., 2004. Investigation of sources of atmospheric aerosol at urban and semi-urban areas in Bangladesh. ATM. Envi., 38(19), 3025–3038. https://doi.org/10.1016/j.atmosenv.2004.02.042

Bongoua-Devisme A.J. 2009. Implications des communautés bactériennes ferri-réductrices et des paramètres environnementaux dans le fonctionnement et la qualité des sols de rizières (Thaïlande et Côte d'Ivoire). Thèse de doctorat en Science des sols. Université Henri Poincaré - Nancy 1, 2009. Français. ⟨NNT : 2009NAN10071⟩. ⟨tel-01748391⟩

Carpenter S. R., Bennett E. M. 2011. Reconsideration of the planetary boundary for phosphorus. Approx. Res. Let. 6:12.

Chaibou Z., 2012. Effet du phospho-compost sur la production de mil (Pennisetum glaucum : cas de la commune urbaine de Niamey. Mémoire de Master, Niamey, Niger. p28.

FAO. 2004. Use of natural phosphates for sustainable agriculture. http://www.fao.org/3/y5053f/y5053f00.htm#Contents, consulted online October 4, 2022.

Gnahoua, J. B. G., Ouattara, M. L. M. S., Coulibali, Z., Diomandé, L. B., Soro, Y. R. (2023). Integrated Soil Fertility Management: A Promising Pathway for Sustainable Intensification of Smallholder Cotton Farming Systems in Côte d'Ivoire. Asian Journal of Research in Crop Science, 8(1): 51-58. DOI: 10.9734/ajrcs/2023/v8i1157

Husson O., Tano, B. F., Saito, K. 2022. Designing low-input upland rice-based cropping systems with conservation agriculture for climate change adaptation: A six-year experiment in M'Bé, Bouaké, Côte d'Ivoire. 277(March). https://doi.org/doi.org/10.1016/j.fcr.2021.108418

Koné, B., Bongoua-Devisme, A.J., Hien, M. P., Coulibaly, K. D., Koné, A., 2023. Combined Effect of Morocco Rock Phosphate and Chemical Fertilizer in Low-Land Rice Production in Guinea Savanna Zone of Côte D'Ivoire: Replenishment of Degraded Fluvisol for Boosting Rice Production. Journal of Waste Management & Recycling Technology, 1(3): 2-7.

Koné B., and Konan-Kan K., 2014. Rice Grain Yield Gap and Yield Declining as Affected by Different Phosphorus Fertilizers in Acid Soil Over Successive Cropping Seasons. 40–53.

Koné B, Sylvester O, Diatta S, Somado E, Valere K, Sahrawat KL. 2011. Response of interspecific and sativa upland rices to mali phosphate rock and soluble phosphate fertilizer. Arch. Agro. Soil Sci., 57(4), 421–434. DOI: https://doi.org/10.1080/03650340903563382

Koné B., Ettien J.B., Amadji G.L., Diatta S., Camara M., 2010. Effects of phosphate fertilizers of different origins on rainfed rice production on acidic soils in semi-mountainous forest areas in tropical climates Case of hyperdystric ferralsols under fallows in Ivory Coast. 22(1), pp. 55–63.

Kouadio, E. N., Koffi, E. K., Julien, K. B., Messsoum, G. F., Brou, K., & N'guessan, D. B. (2018). Diagnostic de l'état de fertilité des ols sous culture Cotonnière dans les Principaux Bassins de Production de Côte d'Ivoire. European Scientific Journal, ESJ, 14(33), 221. https://doi.org/10.19044/esj.2018.v14n33p221

Kotchi V., Yao-Kouamé A., Diatta S., 2010. Response of five varieties of rice to the addition of natural phosphate from Tilemsi (Mali) on the acidic soils of the humid forest region of Man (Côte d'Ivoire). pp. 1895–1905.

Kotchi V., Charlotte T.D., Faustin S. D., 2018. Influence of the Use of Spent Mushroom Substrates of Pleurotus Eous var. on the Availability of Phosphorus in Acid Soils of Humid Forest Regions of Côte d'Ivoire. 3(4), 256–261.

Kpan W.H., 2019. Efficiency of a bacterial isolate on the solubilization of phosphate amendments (PA) in acidic soils: case of a rice plot on the Man plateau (Western Ivory Coast). Master memory. UFR of Earth Sciences and Mining Resources at Felix Houphouët Boigny University. Abidjan. pp. 48-50.

Nishigaki T., Ikazaki K., Tsujimoto Y., Andriamananjara A., Rakotoson T. Razafimbelo T. 2020. Soil survey of the east coast and the central highlands indicates need to update Madagascar soil map, Soil Science and Plant Nutrition, DOI: 10.1080/00380768.2020.1769452

Reddy M.S., Kumar S., Babita K., 2002. Biosolubilization of poorly soluble rock phosphates by Aspergillus tubingensis and Aspergillus niger. Bior. Tech.,84, pp. 187-189.

Sanogo S., Paul A.K., Zoumana K., Mameri C., 2020. Evaluation of the effect of doses of nitrogen and phosphorus on agromorphological parameters and rice yield: case of the

Djoukèmin variety in a lowland bottom of the Gagnoa region Evaluation of the effect of nitrogen and phosphorus doses on. 1, 8–16.

Smalberger S.A., Chien S.H., Singh U., Henao J., 2010. Relative agronomic effectiveness of phosphate rock compared with triple superphosphate for initial canola, wheat, or ryegrass, and residual wheat in two acid soils. Soil Sci., 175(1): pp. 36-43.

Soro D, Ayolié K, Zro F.G.B, Yao F.Y.H.K., 2015. Impact of organic fertilization on maize (*Zea mays* L.) production in a ferralitic soil of centre-west Côte d'Ivoire. *Journal of Experimental Biology and Agricultural Sciences* 3 (6), 556-565.

Sossa Elvire Line, 2012. Back effect of fertilization and cowpea (vigna unguiculata) harvest residues on lowland rice production in a rice-market gardening cultivation system. Doctoral thesis. Faculty of Agricultural Sciences (FSA) / Doctoral School of Agricultural Sciences, University of Abomey-Calavi (UAC).

Useni S.Y, Baboy L.L, Nyembo K.L, Mpundu M.M., 2012. Effects of combined inputs of biowaste and inorganic fertilizers on the yield of three varieties of Zea mays L. grown in the Lubumbashi region. J. Ap. Biosci., 54: 3935-3943.

Wahid Fazli, 2016. Rock phosphate solubility as influenced by phosphate solubilizing bacteria and arbuscular mycorrhiza fungi and its effect on growth, yield and phosphorus uptake of crops. Thèse de doctorat : University of Agriculture, Peshawar. http://prr.hec.gov.pv/jspui/handle/123456789//7455

Wopereis W.C.S., Defoer T., Idinoba P., Diack S., Dugué M. J., 2004. Participatory learning and action research (APRA) curriculum for the integrated management of lowland rice cultivation (GIR) in sub-Africa -Saharan. Technical manual, 122 p.

Xiao C.Q., Chi R.A, Li W.S, Zheng Y., 2011. Biosolubilization of phosphorus from rock phosphate by moderately thermophilic and mesophilic bacteria. Miner. Eng., 24:956-958.

Mishra, U. S., Singh, D., Bais , B. S., Mishra , A., Singh, O. K., & Gupta, A. (2023). Effect of Phosphorous and Vermicompost on Growth Characterstics and Yield of Chickpea (Cicer aretinum L.). International Journal of Plant & Soil Science, 35(9), 58–64. https://doi.org/10.9734/ijpss/2023/v35i92904

N. Onwonga, R., J. Lelei, J., & K. Macharia, J. (2013). Comparative Effects of Soil Amendments on Phosphorus Use and Agronomic Efficiencies of Two Maize Hybrids in Acidic Soils of Molo County, Kenya. Journal of Experimental Agriculture International, 3(4), 939–958. https://doi.org/10.9734/AJEA/2013/4380

Chien SH, Prochnow LI, Tu S, Snyder CS. Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: an update review. Nutrient Cycling in Agroecosystems. 2011 Mar;89(2):229-55.