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Residual Effects of Phosphate Amendments on Rainfed Rice (*Oryza sativa* L.) Nutrition and Soil Properties in Three Agroecological Zones of Côte d'Ivoire

Affi Jeanne Bongoua-Devisme[1]*, Wondouet Hippolyte Kpan[1], Pla Kouassi Adou[1], Franck Michaël Lemonou Bahan[2], Konan-Kan Hippolith Kouadio[1], Anselme Kan Louis Koko[2]

[1]Département de Pédologie et Agriculture Durable, UFR STRM, Université FHB, Abidjan, Côte d'Ivoire
[2]Centre National de Recherche Agronomique-CNRA de Man, Man, Côte d'Ivoire
[3]Office Chérifiens des Phosphates (OCP), Abidjan, Côte d'Ivoire
Email: *affi.bongoua64@ufhb.edu.ci, *bongoua_jeanne@yahoo.fr

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Abstract

A study was conducted in Côte d'Ivoire to assess the after-effect of phosphate amendments on rice yields 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. This study revealed that the application of Moroccan phosphate rock (PRM) and/or triple superphosphate (TSP) did not significantly affect soil cation exchange capacity (CEC) and organic carbon (Corg) content. However, there was a negative residual effect of PRM-rich treatments on soil pH and K and N content, but the impact varies depending on the characteristics of the soils studied. Furthermore, nutrient losses, notably nitrogen from −17.5 to −267.7 kg/ha and potassium (−0.1 to 0.7 kg/ha), were observed in all treatments. Only phosphorus showed a positive balance of +49.56 to +52 kg/ha in PRM-rich treatments. Treatment T3, composed of 80% RPM and 20% TSP, was the most effective in all zones, with a relative increase in grain yields of over 100% compared to the control. These results suggest that the input of natural phosphate rock can significantly improve rice yields and soil properties in the studied agroecological zones in Côte d'Ivoire.

Keywords

Phosphate Amendment, Moroccan Phosphate Rock, Triple Superphosphate, Yield, After-Effect, Nutrition, Crop Balance, Cote d'Ivoire

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 [1]. 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 [2] [3]. It leads to a decrease in the availability of nutrients, particularly phosphorus, as well as a decline in productivity and greater vulnerability to diseases [4] [5]. This is the case for soils used for 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 [5] [6]. This acidification can lead to a decrease in the availability of essential nutrients for rice growth, including phosphorus, which can negatively affect agricultural yields.

In response to these challenges, various innovative and environmentally 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 yields [7]-[9]. However, their effectiveness is often hindered by the complexity of soil characteristics [10], as the solubility of natural phosphate rock in the soil is closely related to specific soil properties, according to [11]. Therefore, it becomes crucial to study the efficiency of phosphate amendments in different types of soils.

This study aimed to evaluate the agronomic effectiveness of different phosphate amendments in three contrasting zones (Man, Gagnoa, and Bouaké). Thus, it sought to 1) assess the long-term effect of phosphate amendments after three years of cultivation without additional inputs on upland rain-fed rice nutrition and on soil properties, and 2) study the interactions between phosphate amendments and soil parameters to better define optimal agricultural practices suited to each soil type to maximize agricultural yields while minimizing environmental impacts.

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 [12]. Gagnoa (6˚07'54"N, 5˚57'02"W), with its tropical climate, has Dystric Ferralsol soils that are conducive to rice cultivation [13]. 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 [2]. These soils exhibit variations in clay content, organic matter, pH, and exchangeable bases with depth, influencing the dispersion and durability of organic matter, which has a low concentration of exchangeable bases.

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), with its chemical composition is detailed in the works of [14]. Triple Superphosphate (TSP), also supplied by OCP-Africa, contains 45% P_2O_5. These two phosphate amendments were applied at a dose of 90 kg P_2O_5 ha^{-1} or 300 kg TSP or PR per hectare, 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 1**.

Table 1. 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	300	200	100	300 TSP + 200 NPK + 100 Urea	76	52.8	24.9

2.4. Soil Characterization of Study Plots

Before the experiment was established, soil samples (0 - 30 cm) were collected from each plot and combined to form a composite sample for each locality. These composite samples were used to evaluate various parameters, such as organic matter (OM), total nitrogen (N), pH, available phosphorus (available P), exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+, K^+), and cation exchange capacity (CEC). The methods of analysis included:

- Organic Matter (OM): Walkley and Black method;
- Total Nitrogen (N): Kjeldahl method;
- pH: Electrometric method;
- Available Phosphorus (available P): Bray I method;
- Exchangeable Calcium (Ca^{2+}) and Magnesium (Mg^{2+}): Atomic absorption spectrometry;
- Exchangeable Sodium (Na^+) and Potassium (K^+): Flame emission spectrometry;
- Cation Exchange Capacity (CEC): Extraction with a silver thiourea solution;
- These analyses provided a comprehensive understanding of the soil properties in each locality, helping to tailor the phosphate amendment strategies for optimal effectiveness.

2.5. 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 soil fertility and rice yield.

2.6. 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) on rice production, mineral nutrition and soil properties. Each cycle provided a temporal perspective to evaluate the short-term and long-term effects of the treatments on yields and soil characteristics.

2.7. Data Collection

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 [15].

The total export of nutrients (N, P, and K) was determined by chemical analysis of the straw and rice grain samples.

2.8. Soil Properties

After each harvest, soil samples (0 - 20 cm) were collected from various points within each micro-plot and combined to form composite samples. These composite samples were used to evaluate various parameters, such as organic matter (OM), total nitrogen (N), pH, available phosphorus (available P), exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), and cation exchange capacity (CEC).

2.9. 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 [16], with its RStudio interface. 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.

To study the interaction of soil parameters with treatments, a non-metric multidimensional scaling (NMDS) analysis was performed. NMDS is a relevant method for graphically representing relationships between soil properties using the "Vegan" package in R software (Clarke, 1993). This method allows us to overcome the normality assumption of the data and to understand the spatial distribution of variables in relation to response variables and across cycles. The graphical representation of Shepard's plot showed the distances of the ordination plotted against community dissimilarities, and the fit is scored as a monotonic step line. The low dispersion around the line suggests that dissimilarities of origin are well preserved, which can be explained by the large number of dimensions chosen.

The structuring of properties was first analyzed. A heatmap was generated to observe the existing correlation between environmental parameters (chemical and physical) explaining the observed gradients on the axes of the NMDS conducted on soil properties, as well as the residual effect of treatment from cycle 1 on the two subsequent cycles.

3. Results

3.1. Soil Characteristics before Experimentation

The characterization of soils from the three studied localities showed 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 were more acidic (pH = 4.52) than those in Gagnoa (pH = 5.81) and Bouaké (pH = 6.25) (**Table 2**). The available phosphorus content was 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 had 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 soils in Man (55.6 $mmol^+/kg$) and Gagnoa (52.8 $mmol^+/kg$) was higher than that of Bouaké (32.1 $mmol^+/kg$). The soils in Man and Gagnoa was 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 had 55 g/kg dry soil Corg, 100 g/kg dry soil N, and 9.4 g/kg dry soil OM.

Table 2. Physico-chemical characteristics of soils in the 0 - 20 cm stratum before experimentation.

Parameters	Man	Gagnoa	Bouaké	Critical values	References
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	6.2 - 6.8	Adeoye and Agboola, 1985
pH_{KCl}	4.5	5.6	5.9		Adeoye and Agboola, 1985
P total ($mg \cdot kg^{-1}$ dry soil)	180.3	188.21	106.7	10.9 - 21.4	Bai et al., (2013)
P assi ($mg \cdot kg^{-1}$ sol sec)	7.61	7.36	21	10 - 16	Bai et al., (2013)
C organic ($g \cdot kg^{-1}$ dry soil)	14.3	16.6	15.5	3.5 - 11	Moges and Holden (2008)
N total ($g \cdot kg^{-1}$ sol sec)	1.20	1.50	1.00	25 - 50	Moges and Holden (2008)
MO ($g \cdot kg^{-1}$ sol dry soil)	24.73	28.71	26.66	40 - 100	Moges and Holden (2008)
C/N	11.92	11.07	15.50		
K^+ ($mmol^+ \cdot kg^{-1}$)	2.78	2.85	2.5	0.2 - 0.5	Moges and Holden (2008)
Na^+ ($mmol^+ \cdot kg^{-1}$)	0.45	1.32	0.4	>2.61	
Ca^{++} ($mmol^+ \cdot kg^{-1}$)	29.67	36.4	22.15	1- 50	Moges and Holden (2008)
Mg^{++} ($mmol^+ \cdot kg^{-1}$)	5.25	9.48	6.6	1 - 2.5	Moges and Holden (2008)
Al^{+++} ($mmol^+ \cdot kg^{-1}$)	6.20	3.12	0.75		Zhao et al., (2022)
CEC ($mmol^+ \cdot kg^{-1}$)	49.11	54.35	21.49	120 - 170	Moges and Holden (2008)

3.2. Mineral Exportation

Overall, regardless of the studied location, applied treatments, and crop cycles, the average quantities of phosphorus (P) (ranging from 0.67 to 0.83 kg/ha P) and potassium (K) (ranging from 12 to 13.3 kg/ha K) exported by rice productions (straw and grains) are low compared to nitrogen, with values ranging from 86.5 to 95.5 kg/ha N (**Table 3**). Compared to the control treatments (T0a and T0), the application of Moroccan phosphate rock (RPM) and/or Triple Superphosphate (TSP) in the amended treatments significantly increased the quantities of nitrogen, phosphorus, and potassium exported by rice productions (straw and grains), with nitrogen exports ranging from 102.4 kg/ha N to 190.4 kg/ha N, phosphorus exports ranging from 0.71 kg/ha P to 1.34 kg/ha P, and potassium exports ranging from 14.6 kg/ha K to 26.1 kg/ha K, regardless of the location (**Table 3**). However, the quantification of phosphorus taken up by the plant indicated that 60% to 81% of the phosphorus taken up by the plant comes from the phosphate amendment (PA) for soils that received an amendment rich in Moroccan phosphate rock (RPM), *i.e.*, under treatments T1, T2, T3, and T4, and 30% to 37% of the phosphorus taken up by the plant comes from the PA for soils that received PA rich in Triple Superphosphate (TSP), *i.e.*, under treatments T5, T6, compared to the control T0a. Similarly, the quantification of nitrogen and potassium in this study indicates that 70% to 80% of N and 53% to 83% of K taken up by the plant come from the PA for soils with PA rich in Moroccan phosphate rock (RPM), *i.e.*, under treatments T1, T2, T3, and T4, and 27% to 54% of N and 27% to 45% of K for soils with PA rich in Triple Superphosphate (TSP), *i.e.*, under treatments T5, T6, compared to the control T0a. Additionally, the quantities of nitrogen, phosphorus, and potassium exported by rice productions (straw and grains) decrease from one cycle to another under non-amended treatments (T0, T0a), decreasing from 38.98 kg/ha N, 0.3 kg/ha P, and 4.81 kg/ha K in cycle 1 to 24.3 kg/ha N, 0.24 kg/ha P, and 3.3 kg/ha K in cycle 2 (**Table 3**). This same decrease in the quantities of N, P, and K exported by rice straw and grain productions is observed under treatments rich in TSP (T5 and T6), decreasing from 54.75 kg/ha N, 0.49 kg/ha P, and 7.78 kg/ha K in cycle 1 to 38.74 kg/ha N, 0.26 kg/ha P, and 4.03 kg/ha K in cycle 2 (**Table 3**), regardless of the location, representing a decrease of 19 to 57% in nitrogen, 16 to 46% in phosphorus, and 10 to 48% in potassium compared to cycle 2. Conversely, under treatments amended by RPM, the quantities of N, P, and K exported by rice straw and grain productions in the third crop cycle increase by 5% to 60% in nitrogen, 12% to 54% in phosphorus, and 11% to 56% in potassium compared to cycle 2.

Comparing the studied locations, the quantities of nitrogen, phosphorus, and potassium exported by productions after the two harvests are higher in Man, with an average of 182.07 kg/ha N, 1.5 kg/ha P, and 25.43 kg/ha K, followed by Gagnoa with an average of 148.09 kg/ha N, 1.33 kg/ha P, and 20.04 kg/ha K, and Bouaké with an average of 107 kg/ha N, 1.08 kg/ha P, and 17.3 kg/ha K (**Table 3**). Nitrogen, phosphorus, and potassium exports in the third crop cycle increased by 10.4%, 24.6%, and 9.9% in Man, respectively, and by 13.02%, 7.01%, and 4.8% in Bouaké, respectively, in rice productions (straw and grains) compared to the second crop cycle. Treatments receiving phosphate fertilizers had higher nutrient export rates compared to the control T0. However, treatments T3 and T4 had a greater influence on the export of all three nutrients (N, P, K) by rice straw and grain productions (**Table 3**), with export increases ranging from 80% to 87% for nitrogen, 64% to 82% for phosphorus, and 59% to 83% for potassium compared to the control T0, regardless of the agroecological zone (**Table 3**).

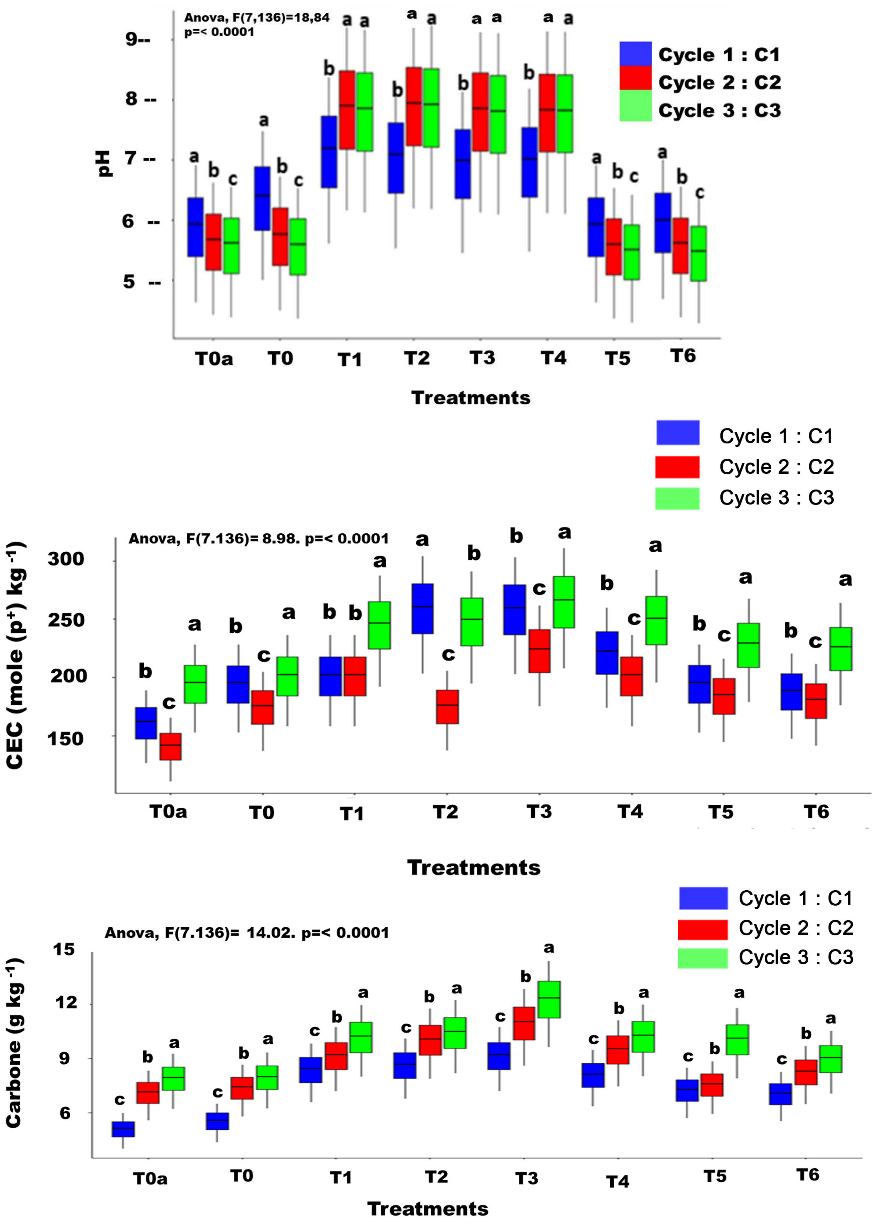
Table 3. Changes in nitrogen (N), phosphorus (P) and potassium (K) content in rice straw and grains biomass after the second and third harvests in Man, Gagnoa and Bouaké under different treatments (T0a: no fertilizer; control T0: 0%PRM + 0%TSP + NPK; T1: 100%RPM + 0%TSP + NPK; T2: 90%PRM + 10%TSP + NPK; T3: 80%PRM + 20%TSP + NPK; T4: 40%PRM + 60%TSP + NPK; T5: 20%PRM + 80%TSP + NPK; T6: 0%PRM + 100%TSP + NPK).

Treatment	Rice straw and grains biomas (kg/ha)-MAN						Rice straw and grains biomas (kg/ha)-GAGNOA						Rice straw and grains biomas (kg/ha)-BOUAKE					
	Cycle 2			Cycle 3			Cycle 2			Cycle 3			Cycle 2			Cycle 3		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
T0a	25.76^{h}	0.20^{h}	2.99^{h}	12.54^{h}	0.11^{h}	1.74^{h}	22.88^{h}	0.10^{h}	2.55^{h}	15.81^{h}	0.08^{h}	1.95^{h}	20.28^{h}	0.10^{h}	3.51^{h}	14.75^{h}	0.05^{h}	2.49^{h}
T0	38.98^{g}	0.3^{g}	4.81^{g}	24.28^{g}	0.25^{g}	3.27^{g}	48.45^{g}	0.25^{g}	5.292^{g}	31.79^{g}	0.17^{g}	3.88^{g}	30.5^{g}	0.18^{g}	5.63^{g}	22.59^{g}	0.11^{g}	4.09^{g}
T1	102.4^{d}	0.71^{d}	15.3^{c}	143.8^{d}	1.09^{d}	20.2^{c}	82.71^{d}	0.68^{d}	10.59^{d}	91.77^{c}	0.87^{d}	14.0^{d}	56.35^{d}	0.66^{d}	9.16^{d}	76.39^{c}	0.82^{d}	11.7^{d}
T2	106.5^{c}	0.81^{c}	14.6^{d}	147.5^{c}	1.12^{c}	20.02^{d}	83.87^{c}	0.7^{c}	10.91^{c}	88.59^{d}	1^{c}	14.1^{c}	65.62^{c}	0.67^{c}	10.9^{b}	75.94^{d}	0.85^{c}	12.2^{c}
T3	153.29^{a}	1.34^{a}	21.31^{a}	190.4^{a}	1.9^{a}	26.13^{a}	120.47^{a}	1.19^{a}	15.41^{a}	134.0^{a}	1.53^{a}	19.89^{b}	67.83^{a}	0.97^{a}	11.38^{a}	108.84^{a}	1.26^{a}	16.29^{a}
T4	143.75^{b}	1.07^{b}	20.77^{b}	178.3^{b}	1.61^{b}	25.83^{b}	98.62^{b}	1.04^{b}	12.75^{b}	129.4^{b}	1.5^{b}	19.93^{a}	64^{b}	0.85^{b}	10.87^{c}	84.28^{b}	0.96^{b}	12.79^{b}
T5	67.08^{e}	0.46^{f}	9.38^{e}	28.55^{f}	0.36^{e}	5.3^{e}	68.13^{e}	0.48^{e}	8.17^{e}	46.5^{f}	0.4^{e}	7.29^{e}	48.91^{e}	0.41^{e}	8.05^{e}	35.61^{f}	0.23^{e}	5.67^{e}
T6	54.75^{f}	0.49^{e}	7.78^{f}	38.74^{e}	0.26^{f}	4.03^{f}	67.28^{f}	0.43^{f}	7.66^{f}	54.48^{e}	0.28^{f}	5.98^{f}	48.19^{f}	0.34^{f}	7.95^{f}	35.68^{e}	0.19^{f}	5.43^{f}
Mean	86.56	0.67	12.11	95.51	0.83	13.31	74.05	0.608	9.16	74.04	0.72	10.87	50.21	0.52	8.43	56.76	0.55	8.83
CV (%)	26.12	154.2	20.41	6.36	6.13	0.71	21.37	159.33	22.07	4.03	29.76	1.48	38.61	88.66	14.62	10.35	7.35	4.37
Ppds	10.41	0.26	0.53	12.08	0.28	0.29	21.83	0.14	2.621	4.58	0.028	0.037	3.82	0.11	0.47	24.52	0.29	3.43
Pr > F	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***

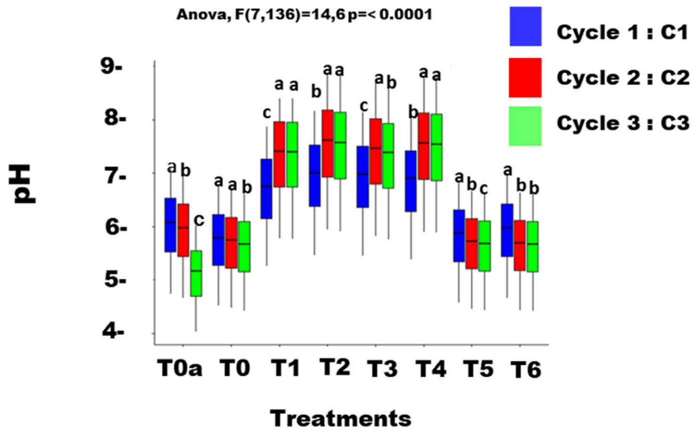
Data in the same column. followed by the same letter. are not significantly different according to the Newman-Keuls test $p < 0.05$. *** very highly significant at $p < 0.05$; ** highly significant at $p < 0.05$; * significant at $p < 0.05$.

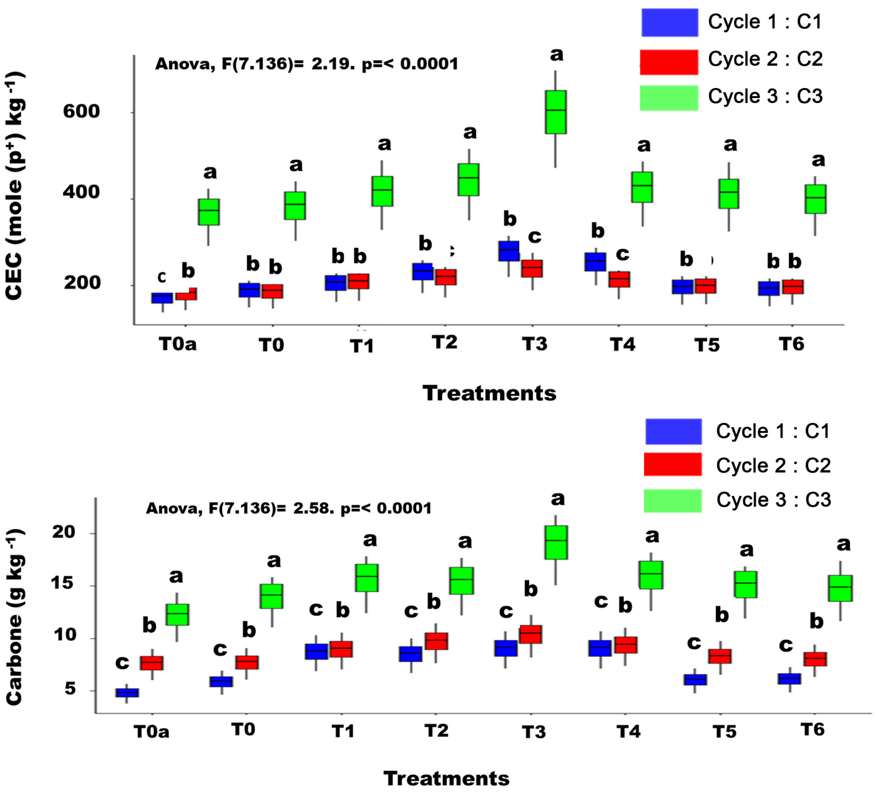
3.3. Effects of Treatments on Soil Properties

The ANOVA analysis was conducted among sample groups, following the amendments applied in trials during the 1st cycle (C1), highlights notable multivariate differences and their medium and long-term implications on the C2 and C3 crop cycles. The results indicate significant divergences among each of the eight treatments across the three cycles. Treatments T1, T2, T3, and T4 applied stand out for their significant effect on soil variables. The results of the analysis of variance for the linear model of response variables (pH, phosphorus, CEC, organic carbon, nitrogen, and potassium) indicate significant effects of the different factors (gradient of amendments applied, *i.e.*, treatments). Significant values derived from the analysis of soil response variable concentrations and pH units are presented in **Figures 1-3**. The post-hoc analysis (pairwise t-tests with Tukey correction at a 5% threshold) applied, allowed for distinguishing specific differences among the groups.

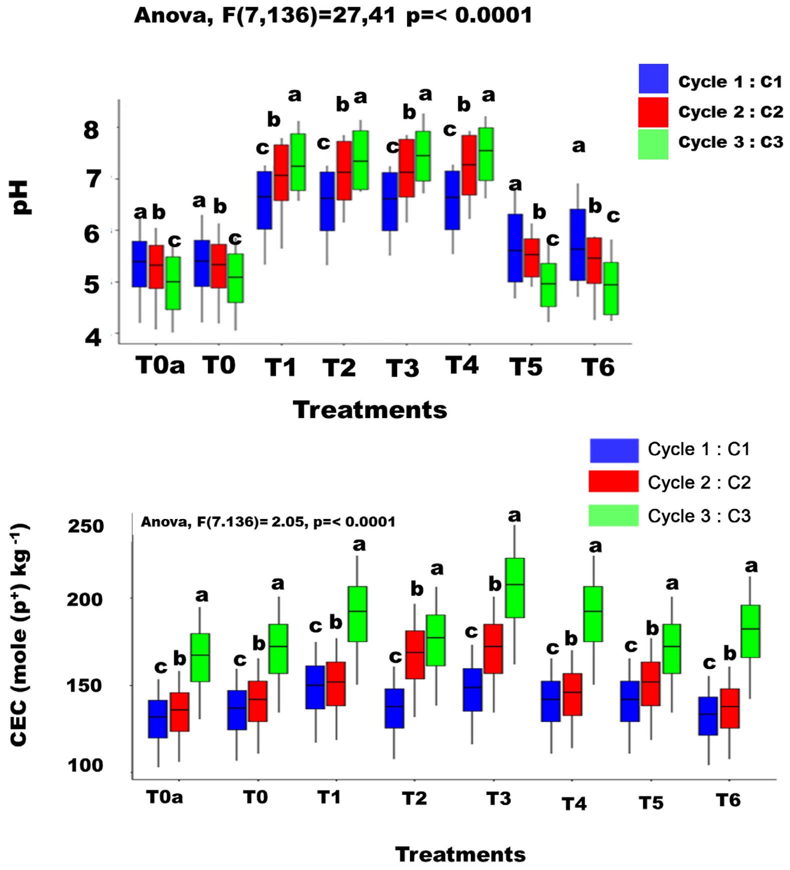

Anova, F(7,136)=18,84
p=< 0.0001
pH
9--
8 --
7 --
6 --
5 --
Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments
Anova, F(7.136)= 8.98. p=< 0.0001
CEC (mole (p⁺) kg⁻¹)
300
250
200
150
Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments
Anova, F(7.136)= 14.02. p=< 0.0001
Carbone (g kg⁻¹)
15
12
9
6
Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments

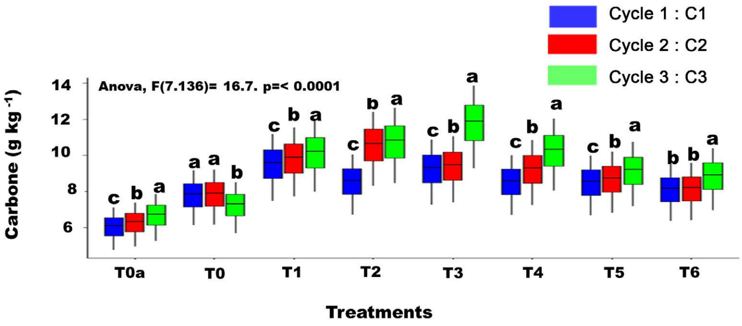
(a)


Anova, F(7,136)=14,6 p=< 0.0001
pH
9-
8-
7-
6-
5-
4-
Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments


Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
Anova, F(7.136)= 2.19. p=< 0.0001
CEC (mole (p⁺) kg⁻¹)
600
400
200
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments
Anova, F(7.136)= 2.58. p=< 0.0001
Carbone (g kg⁻¹)
20
15
10
5
Treatments

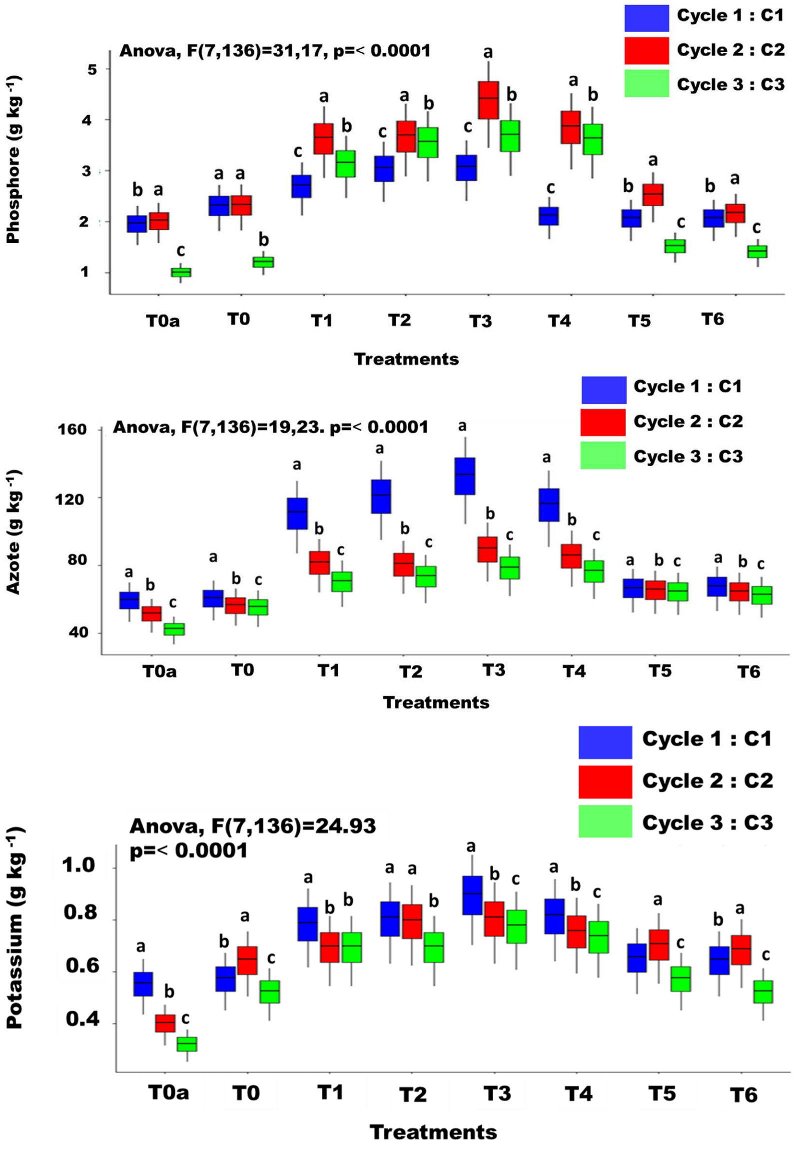
(b)


Anova, F(7,136)=27,41 p=< 0.0001
Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
pH
8
7
6
5
4
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments
Anova, F(7.136)= 2.05, p=< 0.0001
CEC (mole (p⁺) kg⁻¹)
250
200
150
100
Treatments

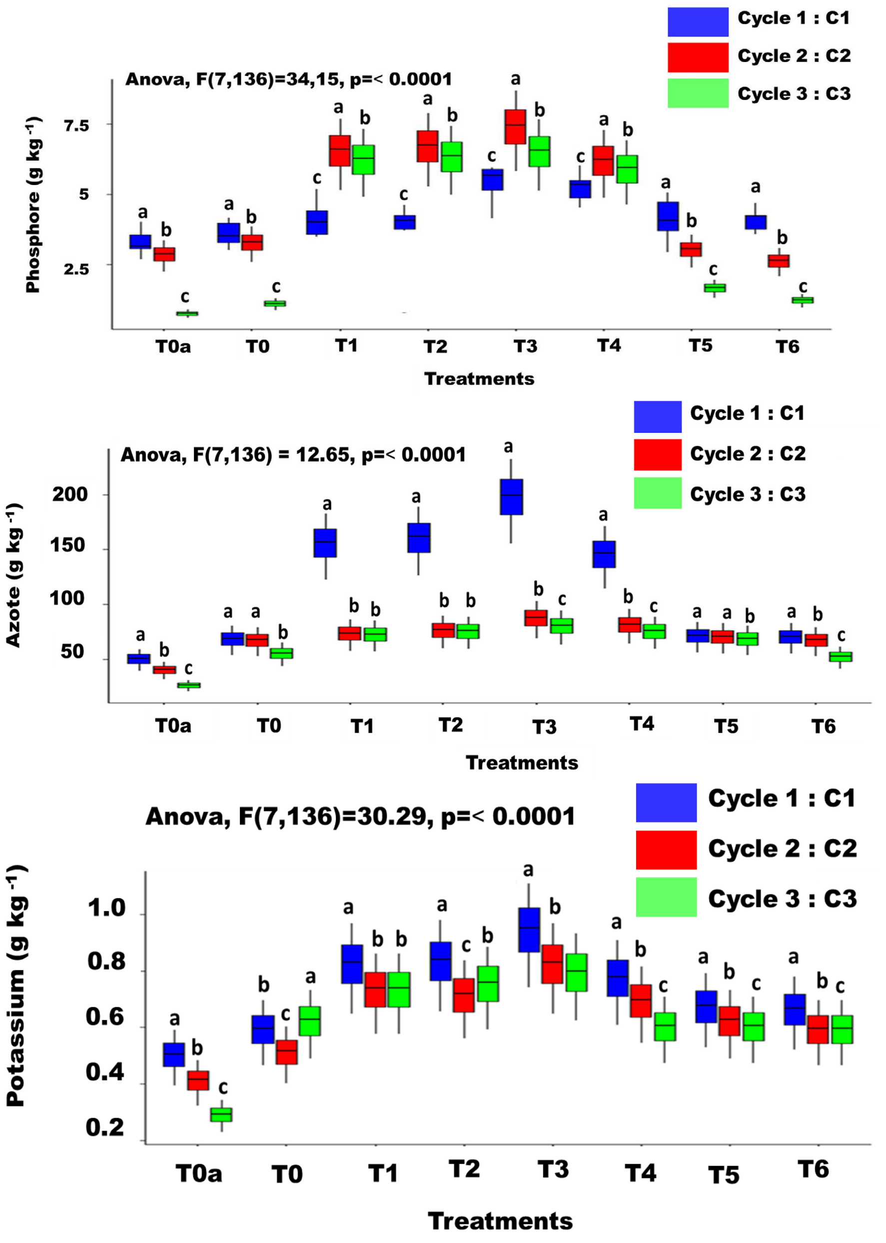


(c)

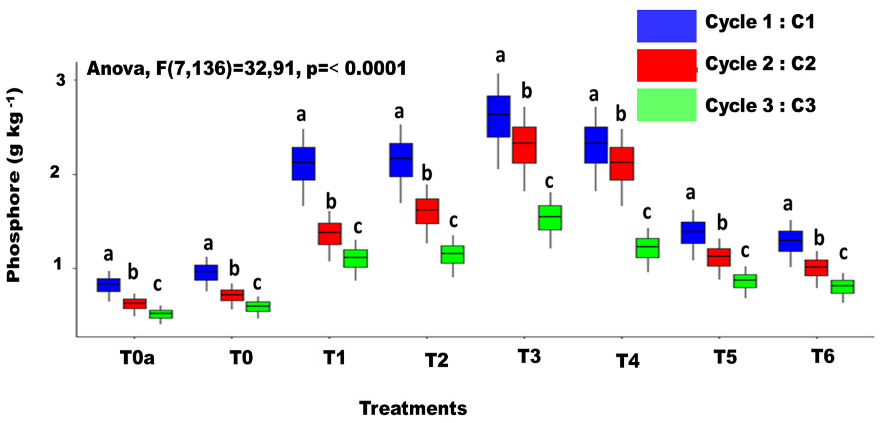
Figure 1. Boxes Plot showing the long-term implications of phosphate amendments on soil parameters (pH, CEC, organic carbon) under each treatment according to rainfed rice growing cycles. (a) Bouaké, (b) Gagnoa and (c) Man. The horizontal line inside each box represents the mean.

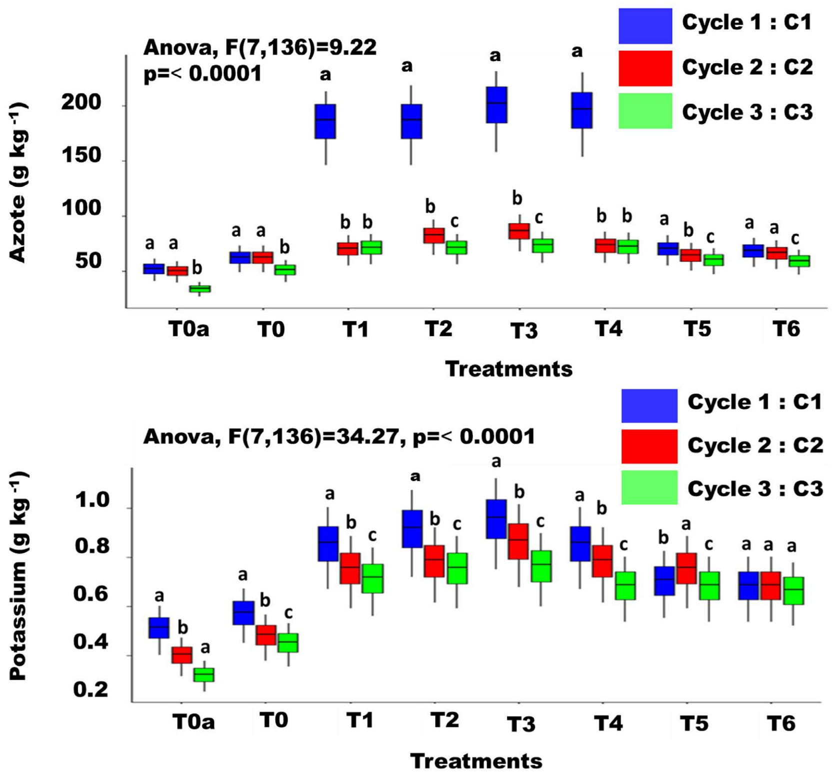


(a)


Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
Anova, F(7,136)=34,15, p=< 0.0001
Phosphore (g kg -1)
7.5
5
2.5
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments
Anova, F(7,136) = 12.65, p=< 0.0001
Azote (g kg -1)
200
150
100
50
Anova, F(7,136)=30.29, p=< 0.0001
Potassium (g kg -1)
1.0
0.8
0.6
0.4
0.2

(b)


Cycle 1 : C1
Cycle 2 : C2
Cycle 3 : C3
Anova, F(7,136)=32,91, p=< 0.0001
Phosphore (g kg -1)
3
2
1
T0a
T0
T1
T2
T3
T4
T5
T6
Treatments



(c)

Figure 2. Boxes Plot showing the long-term implications of phosphate amendments on soil parameters (content of Potassium (K), Nitrogen (N), Phosphorus (P)) under each treatment according to rainfed rice growing cycles. (a) Bouaké, (b) Gagnoa and (c) Man. The horizontal line inside each box represents the mean.

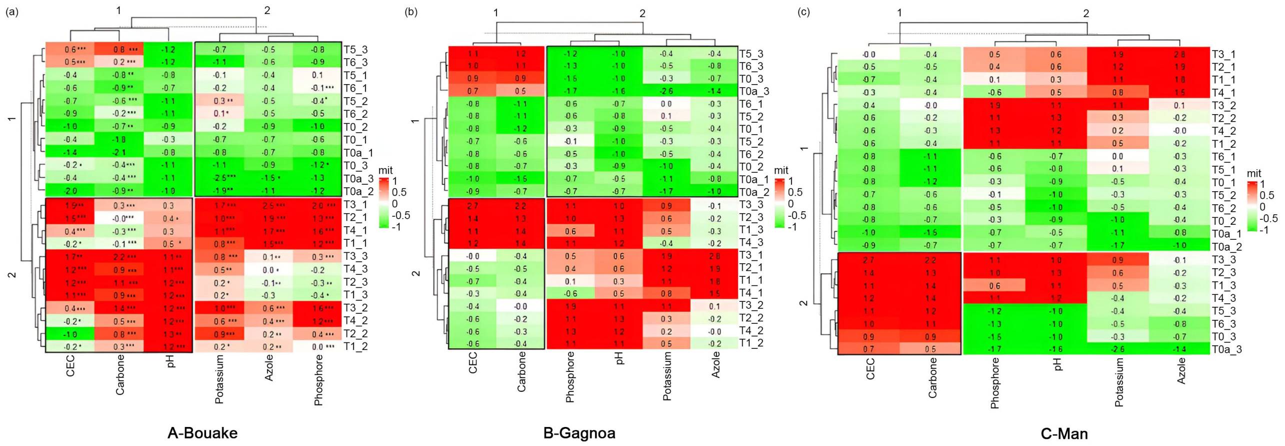


Figure 3. Exploring spatial and temporal variations in soil nutrients for precise soil fertility management in Bouaké (a), Gagnoa (b) and Man (c). Treatments: T0a, T0, T1, T2, T3, T4, T5, T6. Cycle 1 (−1), cycle 2 (−2), cycle 3 (−3). In the graph, high values are in red and low values in yellow. Treatments with positive values (T3, T4, T1, and T2) indicate an increase in the levels of certain nutrients or soil properties following amendment. Treatments with negative values (T0a, T0, T5 and T6) could indicate a decrease in the levels of certain nutrients or soil properties, or a negative impact on the soil.

pH: Overall, regardless of the agroecological zone (locality), soil type (ferralsol, cambisol), and crop cycle, an increase in soil pH from the 1st cycle to the 3rd cycle was observed for plots subjected to treatments T1, T2, T3, and T4, ranging from 5.52 to 7.15 in Man, from 6.01 to 7.5 in Gagnoa, and from 6.25 to 7.9 in Bouaké, compared to those under control treatments (T0, T0a) and treatments enriched with triple superphosphate (TSP) like T5 and T6 (**Figure 1**). However, for plots subjected to treatments T5 and T6, a decrease in soil pH from the 1st crop cycle to the 3rd cycle is observed regardless of the locality, decreasing from pH 5.42 to 5.34 in Man, from 5.9 to 5.6 in Gagnoa, and from 5.93 to 5.42 in Bouaké (**Figure 1**).

Figure 1 indicates significant distinctions observed between plots subjected respectively to treatments T1, T2, T3, and T4 and those receiving doses T0a, T0, T5, and T6 regardless of the locality or soil type. These observations indicate that the residual effect of phosphate amendments (PA) appeared more pronounced when the PA is rich in Moroccan phosphate rock (PRM), regardless of the soil type of the locality, as revealed by the results of bifactorial analysis of variance with F (7, 136) = 18.84, $p < 0.0001$ (**Figure 1**). These results suggested that treatments T1, T2, T3, T4 have a lasting beneficial effect on soil pH in Bouaké, Gagnoa, and Man, unlike treatments T5 and T6 and also controls (T0a, T0) where the beneficial effect was less and short-term (**Figure 1**).

CEC, Corg: The values of cation exchange capacity (CEC) and soil organic carbon content (Corg) showed an increase in CEC and a decrease in soil Corg content after each crop cycle regardless of the treatment applied (**Figure 1**). There was no significant difference between amended and non-amended soils. The application of RPM and/or TSP did not appear to affect the CEC and Corg of the studied soils. For cation exchange capacity (CEC), the trend to maintain a consistently higher CEC in the soil ($p < 0.0001$) was not observed in Man regardless of the applied treatments; however, a more pronounced lasting beneficial effect was observed in Bouaké and Gagnoa under treatments T1, T2, T3, and T4 than under T5 and T6 (**Figure 1**), as revealed by the results of bifactorial analysis of variance, with statistics F (7, 136) = 8.98, $p < 0.0001$; F (7, 136) = 2.19, $p = 0.039$, and F (7, 136) = 2.05, $p = 0.053$, in Bouaké, Gagnoa, and Man, respectively.

The results indicated that the amendments applied sustainably maintain the soil carbon content in all studied locations (**Figure 1**), suggesting a lasting beneficial effect on soil Corg stock, as revealed by the results of bifactorial analysis of variance, with statistics F (7, 136) = 14.02, $p < 0.0001$; F (7, 136) = 2.58, $p = 0.016$, and F (7, 136) = 16.7, $p < 0.0001$, in Bouaké, Gagnoa, and Man, respectively.

Nitrogen, Phosphorus, Potassium Content: Soil nitrogen levels in the three localities are higher under amended treatments rich in Moroccan phosphate rock (T1, T2, T3, T4) with average values ranging from 185 to 200 g/kg N in Man, from 145 to 197 g/kg N in Gagnoa, and from 110 to 132 g/kg N in Bouaké, compared to treatments rich in TSP (T5 and T6) with average values ranging from 66 to 71 g/kg N, and control treatments (T0, T0a) with average values ranging from 50 to 68 g/kg N after the first crop cycle (**Figure 2**). Two distinct groups were observed in **Figure 2**: regardless of the agroecological zone (locality), soil type (ferralsol, cambisol), and crop cycle, an increase in soil nitrogen content was noted for plots subjected respectively to treatments T1, T2, T3, and T4 in the 1st cycle. However, from the 2nd cycle to the 3rd cycle, a decrease in soil nitrogen content is observed under treatments T1, T2, T3, and T4, decreasing on average from 200 to 70 g/kg N in Man, from 197 to 73 g/kg N in Gagnoa, and from 132 to 81 g/kg N in Bouaké. For plots subjected respectively to treatments T5, and T6, a decrease in content from the 1st cycle to the 3rd cycle is noted, decreasing on average from 120 to 66 g/kg N in Man, from 150 to 67 g/kg N in Gagnoa, and from 100 to 64 g/kg N in Bouaké (**Figure 2**). These observations indicate that the residual effect of phosphate amendments (PA) appeared to be less pronounced in amended soils, regardless of the soil type of the locality, as revealed by the results of bifactorial analysis of variance, with F (7, 136) = 19.23, $p < 0.0001$; F (7, 136) = 12.65, $p < 0.0001$, and F (7, 136) = 9.22, $p < 0.0001$, in Bouaké, Gagnoa, and Man, respectively (**Figure 2**). As for the P and K content of the soils, regardless of the locality of the plots, an increase in the P and K content of the plots' soils is observed from cycle 1 to cycle 2, but these concentrations were significantly higher for soils receiving phosphate amendments rich in RPM (T1, T2, T3, T4) with average values ranging from 4.1 to 7.3 g/kg P and from 0.68 to 0.95 g/kg K in Man, from 2.1 to 4.36 g/kg P and from 0.6 to 0.94 g/kg K in Gagnoa, and from 1.1 to 2.6 g/kg P and from 0.69 to 0.89 g/kg K in Bouaké compared to soils receiving amendments rich in TSP (T5, T6) and untreated control soils (T0, T0a) (**Figure 2**). However, the results indicated a progressive decrease in soil P and K content from the 2nd crop cycle to the 3rd cycle. The trend to maintain consistently higher concentrations of phosphorus (P) in the soil ($p < 0.0001$) was not observed in Man regardless of the applied treatments; however, a more pronounced lasting beneficial effect was observed in Bouaké and Gagnoa under treatments T1, T2, T3, and T4 than under T5 and T6 (**Figure 2**), as revealed by the results of bifactorial analysis of variance, with statistics F (7, 137) = 31.17, $p < 0.0001$; F (7, 136) = 34.17, $p < 0.0001$, and F (7, 136) = 32.91, $p < 0.0001$, in Bouaké, Gagnoa, and Man, respectively. For potassium, our results indicate that the amendments applied do not maintain the soil K level sustainably in the studied localities (**Figure 2**), suggesting no lasting beneficial effect on the soil K content, as revealed by the results of bifactorial analysis of variance, with statistics F (7, 136) = 24.93, $p < 0.0001$; F (7, 136) = 30.29, $p < 0.0001$, and F (7, 136) = 34.27, $p < 0.0001$, in Bouaké, Gagnoa, and Man, respectively.

3.4. Correlation between Soil Parameters of the Localities and the Amendments Applied

The evaluation of interactions between soil properties of the studied localities and the applied treatments was conducted through a heatmap analysis. This analysis revealed two distinct main groups, regardless of the locality or soil type, based on observed correlations, whether negative or positive, with soil properties. The first set relates to treatments T1, T2, T3, and T4, while the second set encompasses the doses represented by treatments T0a, T0, T5, and T6. However, characteristic distinctions of treatments on soil properties of each locality were revealed (**Figure 3**).

In the locality of Bouaké (ferralsol), an opposition between soil acidity (expressed by pH, cation exchange capacity (CEC), and carbon) and the soil's nutrient retention capacity (nitrogen, phosphorus, and potassium) was observed. Strongly positive and significant correlations were identified, especially between pH, carbon, and treatments T1 to T4 in the 2nd and 3rd cycles (**Figure 3(a)**), as indicated by the high and positive values in red for treatments T1, T2, T3, and T4. However, our results indicate that CEC is significantly positively correlated with treatments T1, T2, T3, and T4 only in the 3rd cycle. These observations suggest an overall positive impact of amendments T1, T2, T3, and T4 on soil acidity parameters. Additionally, strongly positive and significant correlations were observed between the phosphorus, nitrogen, and potassium (N-P-K) content of soils and treatments T1, T2, T3, and T4 during the 1st and 2nd cycles (**Figure 3(a)**). However, in the 3rd cycle, negative correlations were observed between nitrogen and potassium content, suggesting a decrease in their concentrations due to the amendments provided compared to the reference of the 1st cycle. Overall, the results obtained at the Bouaké site highlight that the residual effect of treatments T1 to T4 leads to an improvement in soil acidity and nutrient retention capacity during the 2nd and 3rd crop cycles (**Figure 3(a)**). However, for doses represented by treatments T0a, T0, T5, and T6, regardless of the crop cycle, negative and significant correlations were observed between soil acidity (expressed by pH, CEC, and carbon) and the soil's nutrient retention capacity (nitrogen, phosphorus, and potassium) and treatments T0a, T0, T5, and T6, reflecting a decrease in soil acidity and nutrient retention capacity (N, P, K) and thus a low residual effect of the treatments.

In the locality of Gagnoa (Ferralsol Distryc), the presence of two distinct groups was also observed: one characterized by treatments T1, T2, T3, and T4, and the other by treatments T0a, T0, T5, and T6. On this site, there is an opposition between the pole represented by cation exchange capacity (CEC) and soil organic carbon content (Corg) and the one represented by pH and soil nutrient retention capacity (nitrogen, phosphorus, and potassium). Strongly positive and significant correlations were identified, especially between CEC and soil carbon content, and treatments T1 to T4 in the 3rd cycle (**Figure 3(b)**), as indicated by the high and positive values in red for treatments T1, T2, T3, and T4. However, the results indicated that in the 1st and 2nd cycles, there was no significant effect of treatments T1, T2, T3, and T4 on CEC and soil Corg content, as negative correlations are observed (**Figure 3(b)**). Regarding pH and soil phosphorus concentration, strongly positive and significant correlations are observed between these parameters and treatments T1, T2, T3, and T4 in the 2nd and 3rd cycles, suggesting a positive residual effect of treatments on pH and phosphorus. For the retention capacity of nutrients such as N and K, strongly positive and significant correlations are observed only in the 1st cycle. These observations suggest an overall positive impact of amendments T1, T2, T3, and T4 on parameters such as pH, CEC, Corg content, and phosphorus from the 2nd cycle onwards, but more pronounced in the 3rd cycle. However, a negative residual effect of treatments T1, T2, T3, and T4 on soil potassium and nitrogen content was observed from the 2nd cycle onwards (**Figure 3(b)**).

In Man (**Figure 3(c)**), the presence of two distinct groups was noted: one characterized by the 1st and 2nd cycles, and the other by the 3rd cycle. There was also an opposition between the pole represented by cation exchange capacity (CEC) and soil organic carbon content (Corg) and the one represented by pH, soil nitrogen (N), potassium (K), and phosphorus (P) levels. Negative and significant correlations were identified between CEC, soil organic carbon level (Corg) following the application of all amendments in the 1st and 2nd cycles, indicating a decrease in CEC and Corg of the soils. However, from the 3rd cycle onwards, strongly positive and significant correlations were noted between CEC, soil organic carbon level (Corg), and all applied treatments, but more pronounced under treatments T1, T2, T3, and T4, suggesting an increase in CEC and Corg under the latter.

Furthermore, the results indicate strongly positive and significant correlations between pH, phosphorus (P), and treatments T1, T2, T3, and T4 during the 2nd and 3rd cycles of cultivation (**Figure 3(c)**). Conversely, strongly negative correlations were noted between pH, phosphorus (P), and treatments T5 and T6 during the 2nd and 3rd cycles of cultivation (**Figure 3(c)**). These observations suggest a residual effect, on soil pH and phosphorus level, positive under treatments T1, T2, T3, and T4, and negative under treatments T5 and T6, from the 2nd cycle onwards.

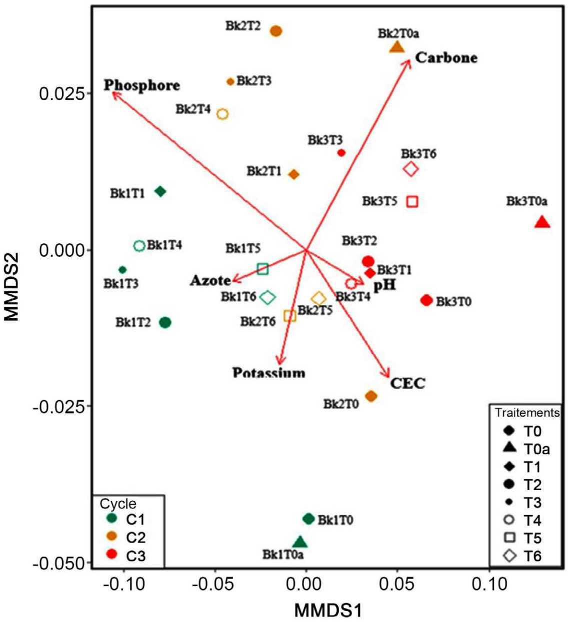
For soil nitrogen (N) and potassium (K) concentrations, positive correlations between N, K, and treatments T1, T2, T3, and T4 are observed in the 1st cycle. However, from the 2nd cycle onwards, a negative residual effect on N and K is observed under all treatments.

Overall, the results obtained at the Man site highlight that the residual effect of treatments T1 to T4 led to an improvement in soil pH, CEC, Corg, and P from the 2nd cycle of cultivation onwards. However, for N and K, a positive residual effect is observed only in the 1st cycle but becomes negative from the 2nd cycle onwards under all treatments (**Figure 3(c)**).

3.5. Residual Effects of Treatments on Soil Parameters over Three Crop Cycles

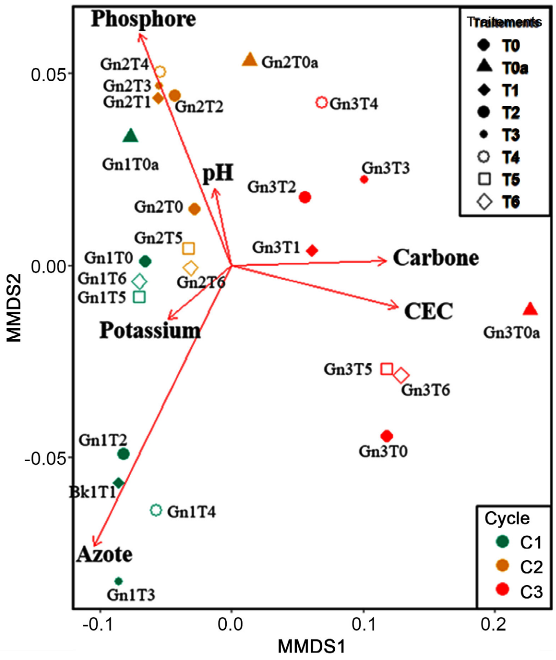
In-depth analysis using Non-Metric Multidimensional Scaling (NMDS) of soil parameters (nitrogen, phosphorus, potassium, CEC, and carbon) in plots subjected to different treatments over three crop cycles revealed significant differences in soil properties among different treatment groups for all sites studied in Bouaké, Gagnoa, and Man. It was evident that the cycles separate well along the environmental gradient of amendment application (**Figures 4-6**). These results underscore the distinct impact of amendment application in the 1st cycle on site parameters after two successive crops.

In Bouaké (**Figure 4**), NMDS analysis indicates that in the 1st cycle, all applied amendments closely affect nitrogen concentration in plots (with a statistical value of 0.438, $p = 0.0001$), but more pronounced under treatments T1, T2, T3, and T4. Conversely, in the 2nd cycle, positive correlations were observed between phosphorus level, soil pH, and treatments T1, T2, T3, and T4, and between soil potassium level and treatments T5 and T6. In the 3rd cycle, correlations between pH, soil carbon content, and applied amendments were observed, reflecting the profound impact of fertilization practices and crop management on soil parameters in Bouaké.



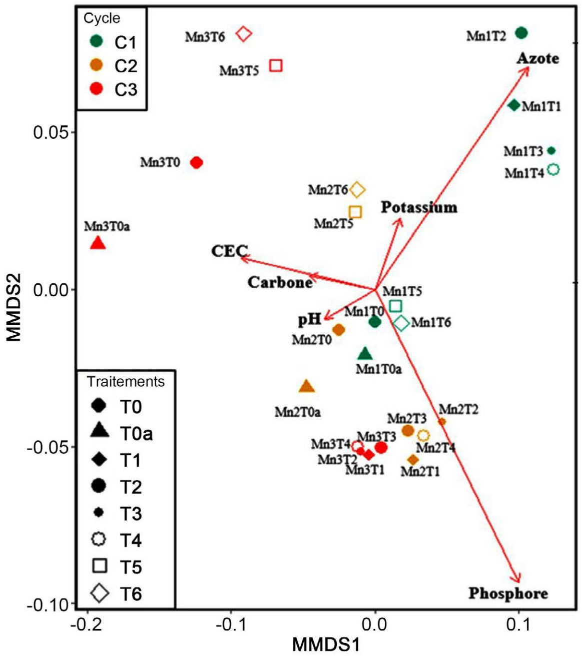
Variables indicators		
	statistic	Pr > F
Groups C1		
Nitrogen	0.438	0.0001
Group C1+C2		
Phosphorus	0.413	0.0001
Potassium	0.280	0.0001
Groups C1+C3		
CEC	0.395	0.0001
Groups C2+ C3		
Carbon	0.413	0.0001

Figure 4. Non-metric multidimensional positioning (NDMS) performed on soil properties of Bouaké (Bk) plots. Assemblages sampled in cycle 1 (Bk1) are in green, those sampled in cycles 2 (Bk2) and 3 (Bk3) are in orange and red, respectively.



Variables indicators		
	statistic	Pr>F
Groups C1		
Nitrogen	0.546	0.0001
Potassium	0.267	0.0032
Group C2		
Phosphorus	0.322	0.0003
Groups C3		
CEC	0.867	0.0001
Carbon	0.845	0.0001

Figure 5. Non-metric multidimensional positioning (NDMS) performed on soil property assemblages sampled at the Gagnoa (Gn) site. Assemblages sampled in cycle 1 (Gn1) are in green, those sampled in cycles 2 (Gn2) and 3 (Gn3) are in orange and red, respectively.



Variables indicators		
	statistic	Pr>F
Groups C1		
Nitrogen	0.583	0.0001
Potassium	0.250	0.0066
Group C2		
Phosphorus	0.202	0.0413
Groups C3		
CEC	0.594	0.0001
Carbon	0.220	0.0212

Figure 6. Non-metric multidimensional positioning (NDMS) performed on soil property assemblages sampled at the Man (Mn) site. Assemblages sampled in cycle 1 (Mn1) are in green, those sampled in cycles 2 (Mn2) and 3 (Mn3) are in orange and red, respectively.

In Gagnoa (**Figure 5**), NMDS analysis indicates that in the 1st cycle, treatments T1, T2, T3, and T4 closely affect nitrogen concentration in plots (Statistic = 0.546, p-value = 0.0001), and treatments T5 and T5 affect potassium concentration in plots (Statistic = 0.267, p-value = 0.0032). However, in the 2nd cycle, positive correlations were observed between phosphorus level (Statistic = 0.322, p-value = 0.0003), soil pH, and treatments T1, T2, T3, and T4. In the 3rd cycle, correlations between CEC and treatments T0, T5, T6, and between soil carbon content and applied amendments T1, T2, T3, and T4 were observed, highlighting the differentiated effect of management practices on the availability of essential nutrients in this region.

Conversely, in Man (**Figure 6**), NMDS analysis indicated that in the 1st cycle, treatments T1, T2, T3, and T4 closely affected nitrogen (Statistic = 0.583, p-value = 0.0001) and potassium (Statistic = 0.250, p-value = 0.0066) concentrations in plots. However, in the 2nd cycle, positive correlations are observed between phosphorus level (Statistic = 0.322, p-value = 0.0003), soil pH, and treatments T1, T2, T3, and T4. In the 3rd cycle, correlations between CEC, soil carbon content, and applied amendments were observed.

3.6. Cultural Balance

Considering the mineral elements brought to the soil by phosphate amendments on one hand, and on the other hand, the exports through rice straw and grains, in Man, the cultural balance for nitrogen is negative for amended soils (−17.5 to −267.7 kg/ha N) and for the untreated control soil with (−38 kg/ha N) (**Table 4**), but this deficit was more pronounced for soils receiving amendments rich in Moroccan phosphate rock (PRM) with −170 to −267.7 kg/ha N than those rich in triple superphosphate (TSP) with −17.5 to −19.6 kg/ha N (**Table 4**). The phosphorus balance was positive for all amended soils (+49.56 to +52 kg/ha P) and negative for the untreated control soil with (−0.3 kg/ha P) (**Table 4**). The potassium balance was negative for soils receiving PRM amendments with −9.7 to −22.5 kg/ha K and for the untreated control soil with −4.7 kg/ha K, but positive for soils receiving TSP amendments (+10 to +13.1 kg/ha K). In Man, PRM inputs did not reduce the deficit in N and K of the soils but rather accentuated it. However, TSP inputs mitigated the deficit in N but reduced that of K. However, the deficit in P of the soils was reduced by PRM and/or TSP.

Table 4. Crop balance of mineral elements (N. P. K) after three crop cycles in the three localities. (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).

Locality	Mineral elements	Balance sheet components	Treatments							
			T0a	T0	T1	T2	T3	T4	T5	T6
MAN	Nitrogen (N) (kg/ha)	Inputs from treatments	0	76	76	76	76	76	76	76
		Total exports by production	38.3	63.26	246.19	253.98	343.69	322.06	95.63	93.49
		Nitrogen balance	**−38**	**12.74**	**−170.19**	**−177.98**	**−267.69**	**−246.06**	**−19.6**	**−17.49**
	Phosphorus (P) (kg/ha)	Inputs from treatments	0	13.2	52.8	52.8	52.8	52.8	52.8	52.8
		Total exports by production	0.31	0.545	1.8	1.93	3.24	2.68	0.82	0.75
		Phosphorus balance	**−0.3**	**12.66**	**51**	**50.87**	**49.56**	**50.12**	**51.98**	**52.05**
	Potassium (K) (kg/ha)	Inputs from treatments	0	24.9	24.9	24.9	24.9	24.9	24.9	24.9
		Total exports by production	4.73	8.08	35.48	34.62	47.44	46.6	14.68	11.81
		Potassium balance	**−4.7**	**16.82**	**−10.58**	**−9.72**	**−22.54**	**−21.7**	**10.22**	**13.09**
GAGNOA	Nitrogen (N) (kg/ha)	Inputs from treatments	0	76	76	76	76	76	76	76
		Total exports by production	38.69	80.238	174.48	172.46	254.5	228	114.63	121.76
		Nitrogen balance	**−39**	**−4.238**	**−98.48**	**−96.46**	**−178.5**	**−152**	**−38.6**	**−45.76**
	Phosphorus (P) (kg/ha)	Inputs from treatments	0	13.2	52.8	52.8	52.8	52.8	52.8	52.8
		Total exports by production	0.185	0.418	1.55	1.7	2.72	2.54	0.88	0.71
		Phosphorus balance	**−0.2**	**12.78**	**51.25**	**51.1**	**50.08**	**50.26**	**51.92**	**52.09**
	Potassium (K) (kg/ha)	Inputs from treatments	0	24.9	24.9	24.9	24.9	24.9	24.9	24.9
		Total exports by production	4.5	9.172	25.57	25.004	35.3	32.68	15.46	13.64
		Potassium balance	**−4.5**	**15.72**	**−0.67**	**−0.104**	**−10.4**	**−7.78**	**9.44**	**11.26**
BOUAKE	Nitrogen (N) (kg/ha)	Inputs from treatments	0	76	76	76	76	76	76	76
		Total exports by production	35.03	53.15	132.74	141.56	176.67	148.28	84.52	83.87
		Nitrogen balance	**−35**	**22.85**	**−56.74**	**−65.56**	**−100.67**	**−72.28**	**−8.52**	**−7.87**
	Phosphorus (P) (kg/ha)	Inputs from treatments	0	13.2	52.8	52.8	52.8	52.8	52.8	52.8
		Total exports by production	0.146	0.295	1.48	1.52	2.23	1.81	0.64	0.53
		Phosphorus balance	−0.1	12.91	51.32	51.28	50.57	50.99	52.16	52.27
	Potassium (K) (kg/ha)	Inputs from treatments	0	24.9	24.9	24.9	24.9	24.9	24.9	24.9
		Total exports by production	6	9.72	20.87	23.02	23.67	23.66	13.72	13.38
		Potassium balance	**−6**	**15.18**	**4.03**	**1.88**	**1.23**	**1.24**	**11.18**	**11.52**

In Gagnoa, the application of PRM and/or TSP did not reduce the deficit in soil N (−38.6 to −178.5 kg/ha N), compared to the untreated control soil (−39 kg/ha N). However, this deficit was accentuated for soils receiving PRM-rich phosphate amendments (−98.5 to −178.5 kg/ha N) than for soils receiving TSP-rich phosphate amendments (−38.6 to −45.76 kg/ha N). The deficit in P for amended soils was reduced for soils amended by PRM and/or TSP (+50 to +52 kg/ha P), compared to the unamended soil (−0.2 kg/ha P). The potassium balance was negative for untreated control soils (−4.5 kg/ha K) and for soils receiving PRM-rich amendments (−0.1 to 0.7 kg/ha K). But it was positive for soils receiving TSP-rich amendments (+9.44 to +11.3 kg/ha K), compared to untreated control soils (−4.5 kg/ha K) (**Table 4**).

As for Bouaké, the presence of PRM and/or TSP in the soils did not reduce the deficit in soil N for amended soils (−7 to −100.7 kg/ha N), but rather reduced that of P (+50 to +52 kg/ha P) and K (+1.23 to +11.52 kg/ha K), compared to the untreated control soil (−35 kg/ha N; −0.1 kg/ha P; −6 kg/ha K).

Inputs of 300 kg/ha of PRM and/or TSP helped to reduce the deficit in soil phosphorus but also accentuated that of nitrogen regardless of the locality and soil parameters. However, for potassium, in soils with moderately to highly acidic pH like those of Man and Gagnoa, the presence of 300 kg/ha of PRM and/or TSP could not improve the deficit in K. On the other hand, in weakly acidic soils (Bouaké), the addition of PRM and/or TSP resulted in a positive potassium balance.

4. Discussion

4.1. Effect of Amendments on Mineral Nutrition (N, P, K) of Rice Plant

The rice plant requires several essential nutrients for high yield. These nutrients include 8 elements, some of which were required in relatively large quantities [17]. These are nitrogen, phosphorus, and potassium, which are called major elements. The effect of phosphate amendments on the mineral nutrition of the rice plant indicated a greater increase in nitrogen exports by rice straw and grains in amended soils than those of P and K, as well as an accentuation of the deficit in soil nitrogen despite the nitrogen (N) supplied in the form of urea at a rate of 100 kg/ha. The results showed that the application of P amendment increases N uptake and promoted to the rice grain as demonstrated [18] which have noted a high N uptake by rice plant when P fertilizer was added in the N-insufficient environments. The positive impact of phosphorus (P) fertilizer on rice grain yield, and N, P and K uptake by rice plant were supported by the past finding that P fertilizer promoted nutrient uptake by plant [19]-[22]. It appears that 300 kg/ha of PRM (Moroccan phosphate rock) and/or TSP, equivalent to 90 kg/ha of P_2O_5, were sufficient for P nutrition of rice plant and increase nitrogen and potassium uptake by rice plant. According to [23], the application of phosphorus fertilizer will result in a greater uptake of nitrogen by the plant and consequently increase straw and grain yields. The result showed that the application of PRM and/or TSP to acidic soils positively influenced the absorption of nitrogen and potassium by the plant, as already revealed in various studies affirming a close relationship between nitrogen absorption and phosphorus accumulation [23]-[25]. This study suggests that the addition of phosphate amendments based on RPM and/or TSP to soils promoted strong nitrogen and potassium uptake by the rice plant, indicating a direct interaction between these three elements. However, the quantification of phosphorus taken up by the plant indicated that more than 50% of the phosphorus taken up by the plant comes from the phosphate amendment (AP) for soils receiving an amendment rich in Moroccan phosphate rock (PRM), *i.e.*, under treatments T1, T2, T3, and T4, and 30% to 37% of the phosphorus taken up by the plant comes from the AP for soils receiving AP rich in Triple Superphosphate (TSP), *i.e.*, under treatments T5, T6. These results corroborate those of [26], which show that 50% to 80% of the phosphorus taken up by the plant could come from insoluble P in the soil, *i.e.*, from the release of P forms complexed with Fe or Al in the soil solution; either by reducing acidity or by the action of rhizospheric microorganisms of the plant which can increase the concentration of phosphate ions in the medium through mineralization of carbon compounds. Similarly, the quantification of nitrogen and potassium in this study revealed that 50% to 80% of N and 20% to 80% of K taken up by the plant comes directly from the phosphate amendment (AP) applied to the soil, with a higher uptake when the AP is rich in Moroccan phosphate rock (PRM), *i.e.*, under treatments T1, T2, T3, and T4 with over 70% for N and over 50% for K, compared to AP rich in Triple Superphosphate (TSP) with 27% to 52% for N and 27% to 45% for K. These results indicated a positive effect of AP on nitrogen and potassium nutrition, suggesting, as [20] [27] did, a close relationship between nitrogen and potassium nutrition by rice plant and the availability of P in the environment. Other studies conducted in 2021 by [28] had highlighted the existence of interactions between nitrogen and phosphorus that improve P absorption and thus the vegetative development of rice plants.

Furthermore, the best nutrient exports (P, N, and K) in rice straw and grains were observed when the phosphate amendment contains 40% to 80% RPM and 20% to 60% TSP.

4.2. Effect of Treatments on Soil Properties

Regardless of the study area, the results indicated an increase in soil pH for soils that received an amendment rich in Moroccan phosphate rock (PRM) after each cropping cycle, *i.e.*, under treatments T1, T2, T3, and T4, compared to control treatments (T0, T0a) and treatments T5 and T6 where pH decreases. Notably, there was a gradual increase in pH from cycle 1 to cycle 3 under soils receiving a phosphate amendment (AP) containing 40% to 100% PRM. This trend is likely related to the residual effects of PRM, which dissolves slowly, as demonstrated by [29]. They noted that increased soil pH leads to decreased dissolution of PRM, as evidenced by the rise in exchangeable calcium. The increase in pH could also have been attributed to the high calcium content in PRM (49.54%), which acted as a liming agent by binding to the clay-humic complex of soils and reducing the concentration of H+ ions in the soil solution. [30] similarly observed that phosphate rock (PR) enhanced soil pH and increased the availability of phosphorus (P) by replacing aluminum and iron oxides in the soil, thereby releasing phosphate ions into the soil solution. This mechanism likely explained the observed reduction in P deficit and the higher yields of rice straw and grain under these treatments. The study also showed that Moroccan rock phosphate, as a phosphorus fertilizer, significantly improved soil acidity attributes, such as exchangeable acidity [31]. In contrast, the application of P fertilizer as Triple Superphosphate (TSP) decreased soil pH. This decrease could be due to the high solubility of TSP, which rapidly releases nutrients or precipitates with aluminum and iron oxides in the soil, thereby increasing the concentration of H^+ ions and acidifying the environment. [32] suggest that the low pH of TSP itself may contribute to this effect. However, this finding contrasts with [33], who reported no effect of TSP on soil acidity in pasture soils in New Zealand. It appeared that the change in soil pH based on the type of phosphorus fertilizer used could be attributed to the chemical form and solubility of the phosphorus in the fertilizers. Triple superphosphate contains phosphorus in the form of soluble inorganic phosphates, such as monocalcium phosphate, which can be readily dissolved and utilized by plants [34]. In contrast, the phosphorus in natural rock phosphate is mainly in the form of insoluble calcium phosphates, which are less available to plants and require specific soil conditions or treatments, such as acidulation, to become soluble [35].

This change in soil pH could also have influenced the availability of phosphorus fractions for plants and the various forms of phosphorus in the soil, including those associated with aluminum and oxides. This observation aligns with [36], who noted a remobilization of the phosphorus-aluminum fraction following changes in pH. Consequently, the absence of a phosphorus deficit in both amended and non-amended soils after three successive cropping cycles could be attributed to the phosphorus content and its forms in the soil.

Additionally, the results indicated a decrease in soil nitrogen (N) and potassium (K) content, and an increase in soil phosphorus (P) content after the application of phosphate fertilizers (phosphate rock and/or triple superphosphate) in the studied soils following the second cropping cycle, compared to non-amended soils. This decrease in soil N and K content may be attributed to the high uptake of these nutrients by rice.

The data showed that P fertilizers increased nitrogen and potassium content in rice straw and grains. This substantial uptake by rice could explain the lower N and K content in the soil, as numerous studies have affirmed that fertilizer application significantly affects soil nutrient availability, thereby altering its chemical properties [20] [37]-[39].

According to various authors, rice cultivation is highly nutrient-intensive, leading to a considerable depletion of soil mineral elements [28] [40] [41]. This nutrient depletion could account for the observed decrease in soil N and K content after the first cropping cycle and the significant removal of these elements in rice straw and grains. The increase in soil P content following P fertilization could be linked to the native soil P content and the forms of soil P, which fertilization enhanced, improving P availability in the soil and its uptake by rice plants, as demonstrated by [42].

Regardless of soil type in each locality, evaluating the interactions between soil properties and the treatments applied revealed two distinct main groups based on the nature of the phosphorus (P) fertilizers used (*i.e.*, phosphate amendments rich in either rock phosphate or triple superphosphate). However, these interactions varied according to soil type. The data indicated that in ferralsols (Bouaké and Gagnoa), phosphate amendments rich in rock phosphate generally had a positive impact on soil acidity parameters (measured by pH, cation exchange capacity (CEC), and carbon content) and a negative correlation with soil nutrient element contents (N, P, K). In Cambisols (Man), positive and significant correlations were observed between P, pH, CEC, soil carbon content, and P treatments, while strongly negative and significant correlations were noted between soil nitrogen and potassium contents and the applied phosphate amendments. These findings suggest that the residual effect of rock phosphate improved soil acidity and nutrient retention capacity, as supported by [20] [43] [44]. However, when phosphate amendments were rich in triple superphosphate, strongly negative and significant correlations were observed between soil parameters (P, pH, CEC, soil carbon, P, and K content) and the applied treatments, suggesting a lack of lasting beneficial effects on nitrogen levels across all localities. These observations indicate that such treatments are unlikely to have a sustained positive impact on soil nitrogen and potassium levels, particularly in Bouaké, Gagnoa, and Man, and to a lesser extent on soil phosphorus levels in Bouaké and Gagnoa.

These results highlight the importance of considering regional specificities in the development of sustainable agricultural management practices. They underscore the need for a contextualized approach, taking into account the specific characteristics of each site to maximize soil fertility and agricultural productivity while ensuring the long-term sustainability of agricultural management practices.

This study revealed that the application of Moroccan phosphate rock (PRM) and/or triple superphosphate (TSP) does not seem to significantly affect the CEC and Corg of the studied soils, probably due to the action of indigenous soil bacteria which, during their activities, not only release organic carbon (Corg) into the soil, thus impacting the absorbing complex and cation exchange capacity (CEC) of soils, as demonstrated in the works of [45] on the effect of compost and RP combination on organic matter and absorbing complex of a ferralsol.

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 yields 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.

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Authors' Contributions

Affi Jeanne BONGOUA-DEVISME, Wondouet Hippolyte KPAN, Brahima KONE, and Kouassi Pla ADOU contributed to the fieldwork, design, writing, and formatting of the article. Konan-Kan Hippolyte KOUADIO and Franck Michael Lemounou BAHAN supervised all stages of this work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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