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Calcium-Magnesium Ca/Mg Ratios and Their Agronomic Implications for the Optimization of Phosphate Fertilization in Rainfed Rice Farming on Acidic Ferralsol in the Forest Zone of Ivory Coast

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Abstract

This study is a contribution to improving rice productivity on acidic plateau soils of the tropical rainforest zone. It is based on taking into account the cationic balances of the soil in order to optimize the phosphorus (P) nutrition of rice on these acidic soils, where this nutrient constitutes a limiting factor for agricultural production. Three (3) pot trials were conducted in Adiopodoumé in the forested south of Côte d'Ivoire. The interactive effects of calcium carbonate (0, 25, 50 and 75 kg Ca ha^{-1}) and magnesium sulfate (0, 25, 50 and 75 kg Mg ha^{-1}) were evaluated on the response of NERICA 5 rice at doses 0, 25, 50 and 75 kg P ha^{-1} of natural phosphate from Togo, applied only once at the start of the experiment. Additional fertilizers of nitrogen (N) (100 kg N ha^{-1}) and potassium (K) (50 kg KCl ha^{-1}) were added to each of the tests in a split-plot device. The test results revealed a paddy production potential of approximately 3 to 5 t·ha^{-1} for NERICA 5 on an acidic soil, under the effect of the interaction of P, Ca and Mg. The quadratic response of rice yield to the doses of these fertilizers would be more dependent on their balance, itself influenced by Ca nutrition. For the sustainability and maintenance of rice production in agro-ecology studied, it was recommended doses of 38 kg Ca ha^{-1}, 34 kg Mg ha^{-1} in a Ca/Mg ratio (1/1) with intakes of 41 kg P ha^{-1}, overall in a ratio 1/1/1 (P/Ca/Mg) more favorable to the availability of free iron considered a guiding element of mineral nutrition. Thus, these promising results should be confirmed in a real environment for better management of the fertilization of rice cultivated on acidic plateau soils in Côte d'Ivoire.

Keywords

Soil Acidity, Ca/Mg Ratios, Phosphate Fertilization, Rice Growing, Ivory Coast

1. Introduction

Rice constitutes the basis of the diet in Ivory Coast. Its production was estimated at 1,713,589 tonnes of paddy in 2022 [1]. Almost all of this production is mainly ensured by rainfed rice cultivation, practiced almost 70% on plateau and on acidic soils [2] [3] [4]. Crop systems are traditionally practiced on Ferrallitic soils highly desaturated in bases (hyperdystric Ferralsol) which have an acidity (pH < 5.5) favorable to the fixation of P by iron oxides and hydroxides (Fe-P) or aluminum (Al-P), thus disfavoring the phyto-availability of phosphorus [5] [6] [7]. To overcome such a situation, phosphorus considered as its first limiting factor was strongly recommended as a fertilizer in order to increase rice yields [8] [9] [10].

Numerous recommendations have led to the use of soluble phosphates at increasing doses, in rainfed rice cultivation in the forest zone of Côte d'Ivoire, with a limited effect on rice yield, despite the enrichment of the soil with this nutrient [2] [3] [10] [11]. In fact, rice yields have always remained below 2 $t \cdot ha^{-1}$, including for improved rice varieties whose potential would be 4 to 5 $t \cdot ha^{-1}$.

These results allowed us to hypothesize that other factors apart from the phytoavailability of phosphates, both from the soil and from fertilizers, could limit the use of these sources of phosphorus by rice. These then made it necessary to re-examine the use of different phosphate fertilizers in rainfed rice cultivation on acidic soils.

Therefore, it is therefore necessary to continue investigations aimed at optimizing rice nutrition in phosphorus (P) by taking into account other factors. To this end, a correction of the deficiency of the soil in exchangeable cations (calcium (Ca) and magnesium (Mg)) the most important in plant nutrition and of their balances involved, could be a path of hope.

In fact, the work of [12] and [13], showed a certain interaction of Ca, Mg and P, in acidic soil of humid forest zone, with positive effect on rice yield. In addition, the work of [2] [3] [14], showed a plateauing of yields, despite the addition of increasing doses of P, and the effectiveness of appreciable levels of P, Ca and Mg in the soil.

The effects of K and Mg doses on rice yield have been studied extensively [4] [10] [15], as well as those of P, Ca and Mg, in Ivory Coast, by [16] [17]. If these basic cations are probably the most important in the management of soil acidity and the availability of phosphate in the soil, their unbalanced or inappropriate use could make phosphate fertilization ineffective and therefore rice yield [17]. This is why the present study was undertaken to evaluate the impact of Ca/Mg ratios in order to propose a phosphate fertilization strategy for an increase in yields of rainfed plateau rice, on acidic Ferralsol of humid forest zone in Ivory Coast.

2. Materials and Methods

2.1. Experiment Site

This study was carried out in pots under semi-controlled conditions at the experimental station of the Central Biotechnology Laboratory (LCB) of the National Agronomic Research Center (CNRA) located in Adiopodoumé in Côte d'Ivoire (5˚19 N, 4˚07 W and 43 m). It is an area of tropical rainforest, with a unimodal rainfall regime, an average annual cumulative rainfall of around 1531 mm [15] (**Figure 1**). The soil used for the experiment is of the highly desaturated ferralitic type (Dystric Ferralsol). It was taken from a fall of more than 10 years at a depth of 20 cm.

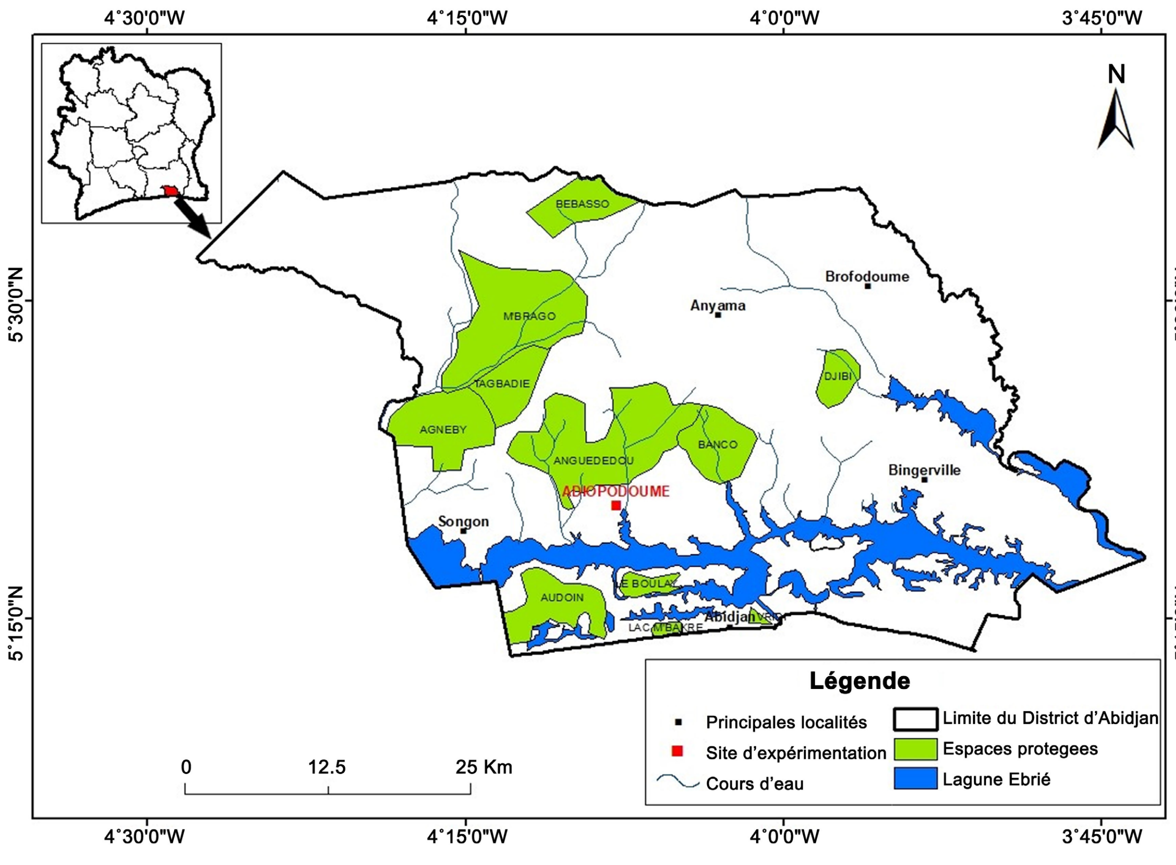

Figure 1. Location map of Adiopodoumé (experimental site).

2.2. Plant Material

The interspecific rice variety New Rice for Africa 5 (NERICA 5) was used as planting material. It is a short-cycle upland rice variety (95 - 100 JAG). It comes from the crossing of WAB 56 - 104 (*Oryza sativa* L.) of Asian origin and CG 14 (*Oryza glaberrima* Steud) of African origin. Its average height can reach 120 cm and it tills between 21 and 45 days after germination (JAG). NERICA 5 rice has a short cycle (95 - 100 JAG) and a potential yield of 5 $t \cdot ha^{-1}$ [18].

2.3. Experimental Device and Treatments

The experiment was conducted according to the random split-plot design with five (5) repetitions (blocks). Three (3) fertilizer sources were the factors studied. These are natural phosphate from Togo (35.4% P_2O_5 and 36.4% CaO), calcium carbonate-$CaCO_3$ and magnesium sulfate-Mg_2SO_4 (28% Mg) which respectively constituted the sources of P, Ca and Mg. Each fertilizer source was applied at four (4) different doses (0; 25; 50 and 75 kg P ha^{-1}). The blocks were subdivided into four (4) bands of 16 treatments corresponding to phosphorus (P). Each band is divided into four (4) sub-bands receiving, randomly, the different doses of calcium (Ca). Finally, the sub-bands received, randomly, the different doses of magnesium (Mg). In total, each block was composed of 64 treatments, *i.e.* 320 pots for each cultivation cycle.

2.4. Setting up the Experiment

The experiment was carried out on three (3) different dates on the same substrates. It was conducted from March to June 2012 (test 1), from March to June 2013 (test 2) and from September to December 2013 (test 3). In each test, urea (30 kg N ha^{-1}) and potassium chloride (50 kg K ha^{-1}) were used as background fertilizer, then urea (35 kg N ha^{-1}) was also contributed to tillering and heading of rice. Natural phosphate was applied only on the first try. However, calcium carbonate and magnesium sulfate were added to each test.

Six (6) grains of rice were sown per pot at a rate of two (2) grains per pocket. Ten (10) days after germination (JAG), demarcation was carried out to reduce the number of plants to three (3) per pot. These plants were watered every two (2) days with 20 mm of water in the absence of rain.

The rice was harvested at maturity, then weighed at 14% moisture to determine its grain yield (GDR) according to the following relationship:

$$\mathrm{RDG} = \frac{\mathrm{Grain\_weight} \times (100 - \mathrm{HUM})}{(\mathrm{Harvest\_area} \times 1000 \times 86)} \times 10000 \tag{1}$$

with RDG: grain yield in t/ha^{-1}; Grain weight in g; Humidity (HUM) in % and harvest area in m^2.

2.5. Soil Analysis

A sample of highly desaturated ferrallitic type soil (Dystric Ferralsol) under fallow served as a cultural substrate, was taken at a depth of 0 - 20 cm for the experiment after determining the physico-chemical characteristics. The analyses carried out are the particle size [19], soil pH, organic carbon [20] [21], total nitrogen [22], assimilable phosphorus [23], exchangeable bases, cation exchange capacity [24], exchange aluminum and free iron. The free iron contents of the soil by the method of [25], the exchangeable aluminum contents by the titrimetric method after extraction with potassium chloride from [26] and the phosphorus saturation rate (DSP) values by the method of [27] and [28] were also determined.

2.6. Statistical Analysis

The collected data were subjected to statistical analyzes using SAS (Statistical Analysis System) version 9.1 and R version 3.6.2 software.

The R software version 3.6.2 was used to carry out a principal component analysis (PCA) to highlight the fertilizer formulations which influence rice grain yield and a hierarchical ascending classification (CAH) to highlight the different homogeneous groups of fertilizer treatments.

As for the effects of doses of phosphate, calcium and magnesium on grain yields, an analysis of the response surface curves was carried out with SAS software (Statistical Analysis System) version 9.1. These analyses made it possible to determine optimal doses of phosphorus (P), calcium (Ca) and magnesium (Mg).

3. Results

3.1. Physico-Chemical Characteristics of the Soil before the Experiment

Table 1 shows the results of physicochemical Analyzes of the soil taken from the 0 - 20 cm layer and used for the experiment. It reveals that the soil is sandy-silty-clayey (sand 48%; silt 31% and clay 21%). The apparent density (Da), low (1.42 < 1.5 g/cm^3), indicates a good state of aeration and good porosity of the soil, and therefore subject to a good water storage capacity. The organic carbon (C) content is low (3.6 g·kg^{-1} < 40 g·kg^{-1}) for an equally insufficient content (<1 g·kg^{-1}) of total nitrogen (N) determined at 0.2 g·kg^{-1} coupled with a high (18/1) C/N ratio (>10/1). The contents of exchangeable cations Ca, Mg and K are, respectively, 5.5 cmol·kg^{-1} (>2 cmol·kg^{-1}), 3.9 cmol·kg^{-1} (>0.20 cmol·kg^{-1}) and 0. 2 cmol·kg^{-1} (>0.10 cmol·kg^{-1}), yet with a very low CEC (4.68 cmol·kg^{-1}) below the critical threshold (<20 cmol·kg^{-1}). The Ca/Mg (1.41 < 10) and K/CEC (0.043 < 0.05) ratios are low. However, the Mg/K ratio of 19.5 is large (>2). The strongly acidic pH H_2O (4.6) is coupled with an insufficient content of assimilable phosphorus (modified Olsen method) of 3 mg·kg^{-1}, well below the threshold of 10 mg·kg^{-1}). The soil is rich in free iron-Fe (25.5 cmol·kg^{-1}) and exchangeable aluminum-Al (3.58 cmol·kg^{-1}) characteristic of acidic Ferralsol, while the degree of phosphorus saturation (DSP) of 33.31%, is greater than 20% (critical value).

Table 1. Physico-chemical characteristics of the soil at 0 - 20 cm depth before the experiment.

Soil characteristics	Values
Clay ($g \cdot kg^{-1}$)	210
Silt ($g \cdot kg^{-1}$)	310
Sand ($g \cdot kg^{-1}$)	480
Da ($g \cdot cm^{-3}$)	1.42
pH H_2O	4.6
pH KCl	4.1
ΔPh	0.5
Organic carbon—C ($g \cdot kg^{-1}$)	3.6
Total nitrogen—N ($g \cdot kg^{-1}$)	0.2
C/N	18
CEC ($cmol \cdot kg^{-1}$)	4.68
Pa ($mg \cdot kg^{-1}$)	3
Ca ($cmol \cdot kg^{-1}$)	5.5
Mg ($cmol \cdot kg^{-1}$)	3.9
K ($cmol \cdot kg^{-1}$)	0.2
Ca/Mg	1.41
Mg/K	19.5
K/CEC	0.043
Free Fe ($cmol \cdot kg^{-1}$)	25.5
Exchangeable Al ($cmol \cdot kg^{-1}$)	3.58
PSD (%)	33.31

Da: Apparent density; CEC: Cation exchange capacity; DSP: Degree of phosphorus saturation.

3.2. Effects of Fertilizers on Rice Grain Yield and Soil Physicochemical Characteristics

The principal component analysis made it possible to determine the most contributing fertilizer treatments and measured parameters (Figure 2 and Figure 3). Concerning the fertilizer treatments evaluated, those which made the expected average contributions for the formation of the first two dimensions of the PCA (Dim 1 and Dim 2) are as follows: 0P 0Ca 0Mg, 0P 0Ca 25Mg, 0P 0Ca 75Mg, 0P 0Ca 50Mg, 0P 25Ca 0Mg, 0P 25Ca 50Mg, 0P 25Ca 75M g, 0P 25Ca 25Mg, 0P 75Ca 25Mg, 0P 50Ca 0Mg. Furthermore, the analysis showed that the most contributing variables were the Ca/Mg ratio, Pass, Mg, DSP, Al, Fe.

The PCA carried out on the most contributing individuals and variables resulted in obtaining two factorial axes (Figure 4). These factorial axes have eigenvalues of 81.09% for the first dimension (Dim 1) and 11.37% for the second factorial axis (Dim 2). This information shows that the fertilizer treatments which

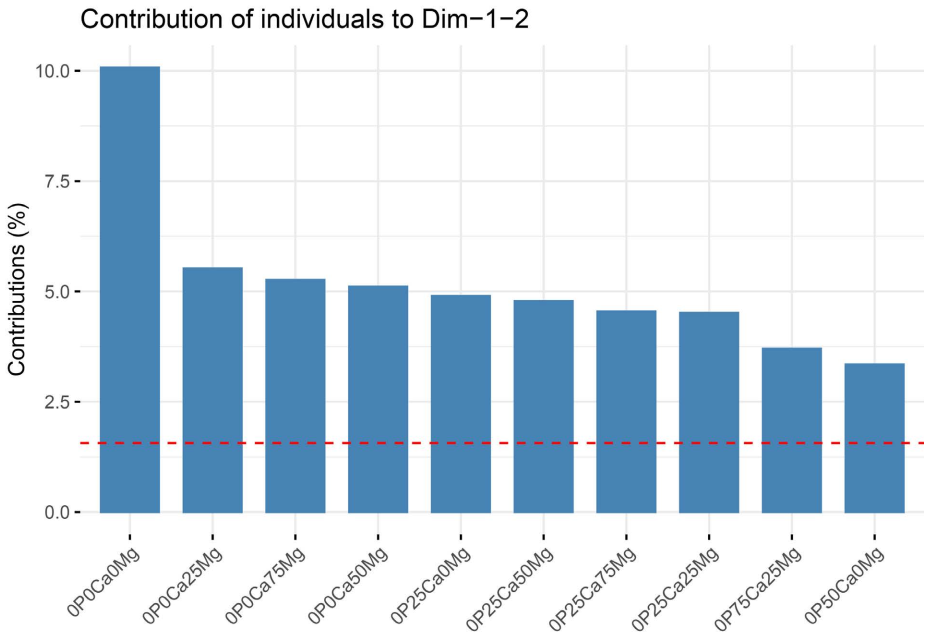

Figure 2. Fertilizing treatments (individuals) contributing to axes 1 and 2. The red dotted line in the graph above indicates the average expected contribution for each fertilizer treatment.

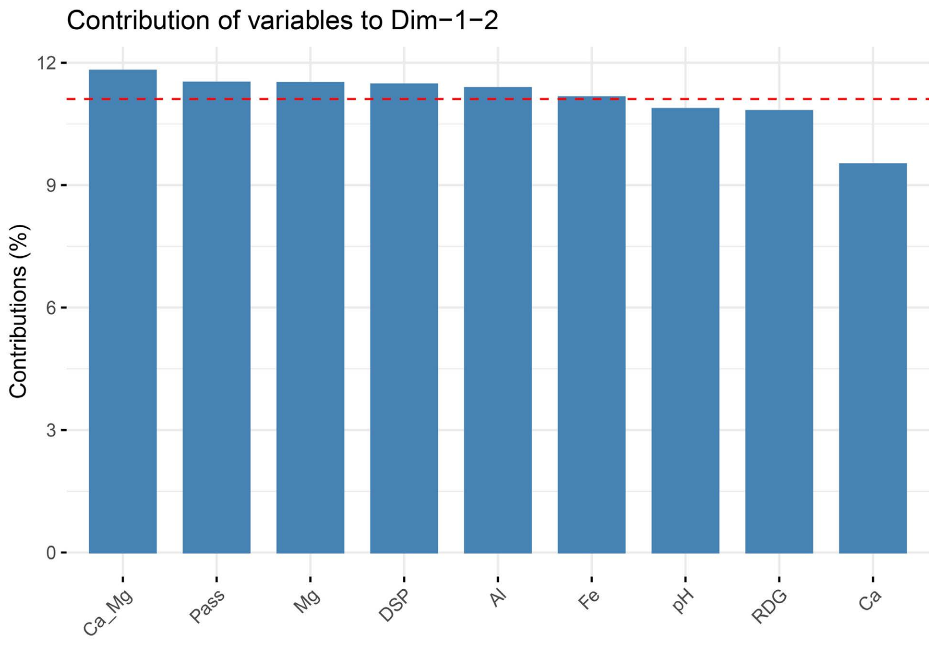

Figure 3. Agronomic parameters and chemical characteristics contributing to axes 1 and 2. The red dotted line, in the graph above, indicates the average expected contribution for each of the measured variables.

influence the chemical parameters and yield are given by the first dimension (Dim1) (**Figure 4**). Also, **Table 2** relating to the correlations between the variables of the two main axes of the PCA, shows that the parameters RDG, Pass, Fe, DSP, and Mg are positively correlated with the first dimension. As for Al, Ca and Ca/Mg, these parameters are negatively correlated with the first dimension.

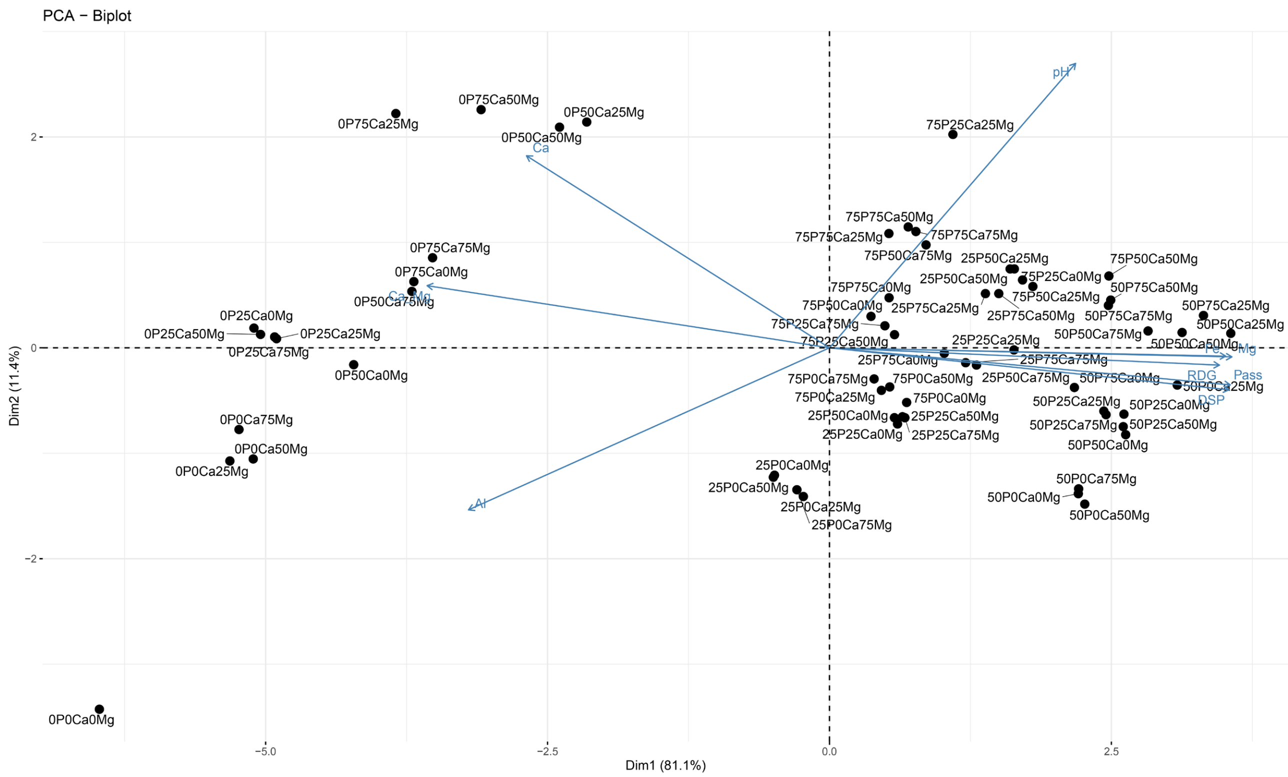

Figure 4. Superposition of fertilizer treatments on rice agronomic parameters and soil chemical characteristics in the factorial design. The black and blue colors respectively indicate the fertilizer treatments and measured variables (agronomic parameters of the rice and chemical parameters of the soil.

Table 2. Matrix of eigenvalues and correlations of variables with the two main axes of the PCA.

	Axis 1	Axis 2
Own variance	7.30	1.02
% total variance	81.1	11.4
% total accumulated variance	81.1	92.5
RDG	0.9475921	−0.0449835
pH	0.5981226	0.73928712
Pass	0.9740066	−0.0962885
Al	−0.8772236	−0.4211743
Fe	0.9630347	−0.0216064
DSP	0.9706372	−0.1090435
That	−0.736343	0.49919414
Mg	0.9780663	−0.02356
Ca/Mg	−0.9777669	0.16155789

Only pH is strongly correlated, positively, with axis 2 (**Table 2**). All these parameters have a factorial weight greater than 0.7 taken in absolute value, for the axes of which they contribute effectively to their formations. A negative correlation was thus established between grain yield and the Ca/Mg ratio (**Figure 5**).

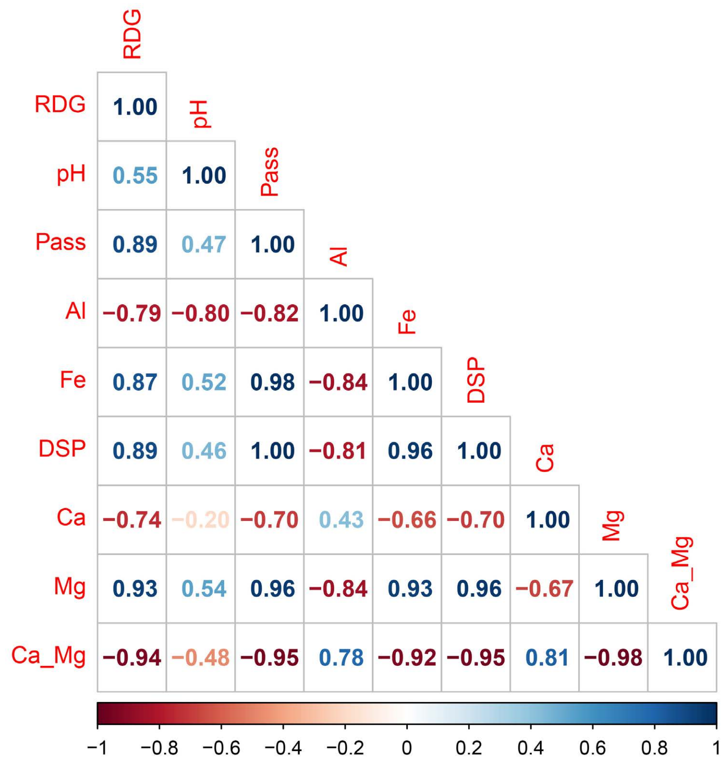

Figure 5. Correlation matrix between rice grain yield and soil chemical characteristics. Positive correlations are shown in blue and negative correlations in red. The color legend shows the correlation coefficients and corresponding colors.

The dendrogram obtained after the ascending hierarchical classification (CAH) shows the existence of two groups of fertilizers following their effects on the agronomic parameters of rice and the chemical characteristics of the soil (Figure 6). This dendrogram clearly shows that fertilizers not containing phosphorus lead to a low rice grain yield unlike those composed of phosphorus, calcium and magnesium which boost the RDG.

The analyzes carried out showed that the fertilizer treatments favored gains in rice grain yield (P = 0.000) (Table 3). The highest yields were obtained with the fertilizers 50P 25Ca, 50P 75Ca 25Mg, 50P 50Ca 25Mg and 50P 25Mg. However, the lowest yield gains were observed with the 25Mg treatment (Table 3).

3.3. Determination of Optimal Doses for Increasing Rice Grain Yield

Analysis of rice response to interactive doses of P, Ca and Mg indicates a very highly significant response for both linear and quadratic regression types (Table 4). However, the coefficient of the quadratic trend (0.22) is higher than that (0.20) of the linear trend. The fertilizer coefficients remain low (1/1000) for both the linear trend and the quadratic trend.

No significant contribution of the interactions (P, Ca and Mg) is observed in the expression of the yield contrasting with P2, Ca2 and Mg2 whose respective coefficients are negative. This interaction reveals quadratic patterns for P, Ca

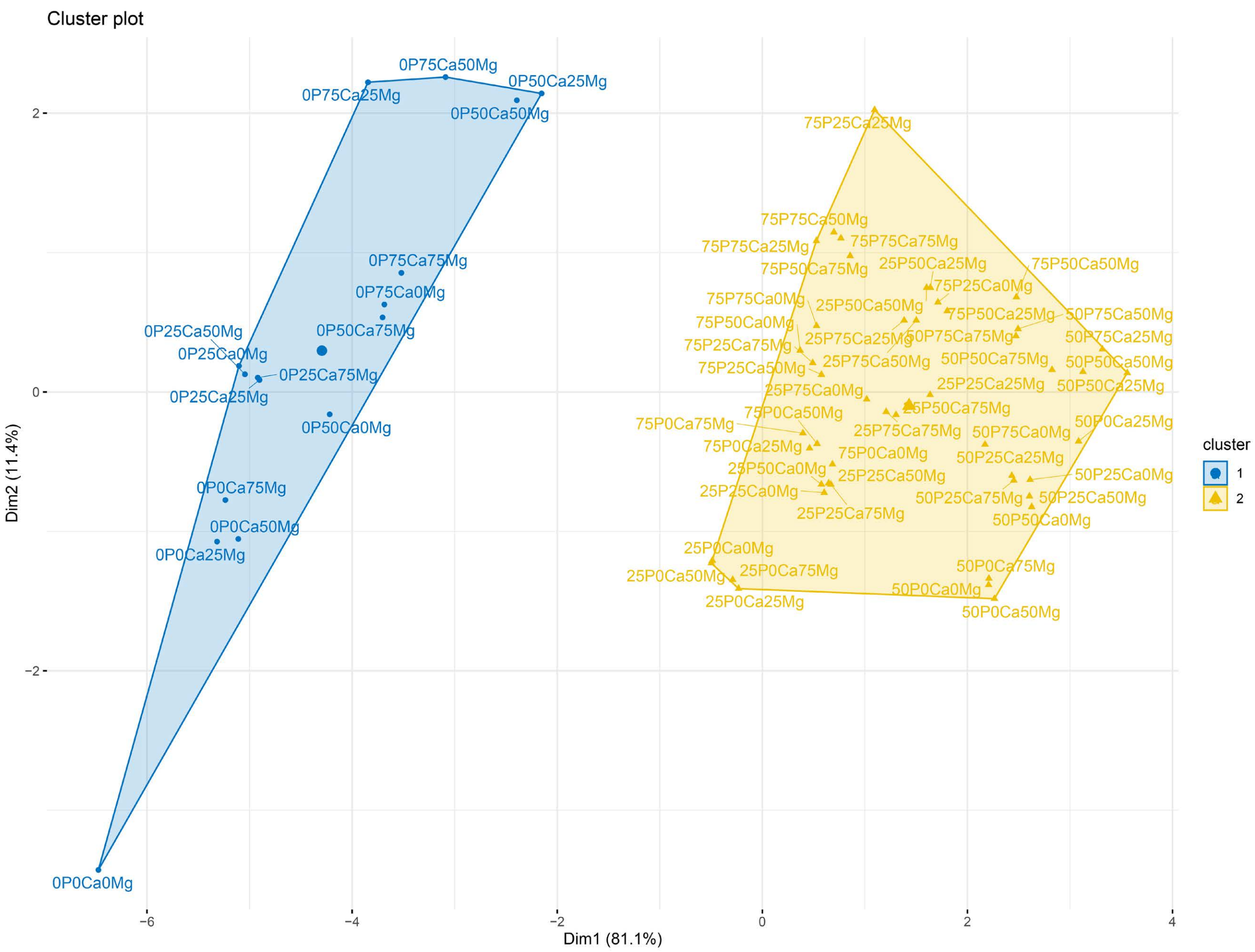

Figure 6. Dendrogram of fertilizer treatments according to their effects on the agronomic parameters of rice and on the chemical characteristics of the soil. Identical colored fertilizer treatments belong to the same group.

Table 3. Gains in grain yield after application of fertilizer treatments to rice plant.

Treatment	Grain yield gain (%)
0P0Ca0Mg	0.00 ± 0.00c
25Mg	5.20 ± 1.38c
25Ca50Mg	11.97 ± 3.32bc
50Ca	12.86 ± 2.34bc
25Ca75Mg	13.01 ± 1.83bc
75Ca25Mg	16.36 ± 6.76bc
25Ca	16.38 ± 4.09bc
75Ca75Mg	16.86 ± 6.23bc
75Ca50Mg	17.68 ± 6.83bc
50Mg	18.91 ± 5.95bc
75Mg	19.53 ± 7.95bc
25Ca25Mg	21.05 ± 6.42bc
75Ca	22.27 ± 10.80bc
50Ca75Mg	31.43 ± 18.67bc

Continued

75P25Ca	101.82 ± 84.56abc
50P50Ca75Mg	110.76 ± 18.20ab
50P50Ca	111.82 ± 18.93^{ab}
50P50Mg	112.18 ± 18.99^{ab}
50P50Ca50Mg	113.55 ± 15.60^{ab}
75P50Ca50Mg	115.31 ± 89.17^{ab}
50P25Ca	133.99 ± 64.06^{has}
50P75Ca25Mg	136.32 ± 67.44^{has}
50P50Ca25Mg	142.09 ± 13.73^{has}
50P25Mg	142.22 ± 59.82^{has}
Probability (p)	0.000
Significance	HRT

Note: In the column, the means followed by the same letter are not significantly different at the 5% threshold (Student Newman-Keuls Test). HRT: Very highly significant.

Table 4. Characteristics of rice response to interactive doses of phosphorus, calcium and magnesium.

Regression	Coefficients		Pr > F
Linear	0.2051		<0.0001
Quadratics	0.2258		<0.0001
Cross product	0.0016		0.5608
Total model	0.4324		<0.0001
Settings	**Coefficients**		**Pr > |t|**
Constant	1.5141		<0.0001
P	0.0522		<0.0001
That	0.0086		0.0007
Mg	0.0060		0.0268
W × W	−0.0005		<0.0001
P × Ca	−0.00001		0.4696
P × Mg	−0.00002		0.2568
Ca × Ca	−0.0001		0.0012
Ca × Mg	0.00001		0.6300
Mg × Mg	−0.00007		0.0121
P × Ca × Mg	4.63×10^{-8}		0.8953
Critical values			
Factors	**Critical dose (kg/ha)**	**Optimal dose (kg/ha)**	**RDG (t/ha)**
P	48.49	41	
That	40.23	37	3.06
Mg	33.07	29	

Note: RDG: grain yield.

and Mg with respective optimal doses of 41; 37 and 29 kg·ha^{-1} for an average yield of 3.06 t·ha^{-1} (**Table 4**).

4. Discussion

The soil used for the experiment was very acidic (pH_{H2O} = 4.6) with a strong phosphorus-P deficiency (<7 mg·kg^{-1}). It was also marked by a high free iron content (25.5 cmol·kg^{-1}), a high Al/CEC ratio (76.50%) with a Ca/Mg ratio of 1/1 (Ca = 5.5 cmol·kg^{-1} and Mg = 3.9 cmol·kg^{-1}) and a degree of phosphorus saturation (33.31%) greater than the critical value of 20%. Thus, the high levels of aluminum and iron in the soil lead to a complexation of P by these metals, the consequences of which could be toxicity of the rhizosphere and problems of inhibition of P absorption by the roots [29]. Indeed, the descriptive analyzes carried out show that phosphorus-free fertilizers recorded the lowest yields of rice grains. These results indicate that rice nutrition can be primarily influenced by phosphorus. These observations confirm those of several authors who have shown that phosphorus is the most limiting factor for rice production on humid tropical soils [29] [30].

Also, the addition of calcium (Ca) and magnesium (Mg) fertilizers at different doses coupled with phosphorus seems to improve rice grain yield and certain soil chemical parameters (Pass, DSP and Mg).

These results corroborate those of [31] and [32] who showed that the availability of phosphorus in the soil was not the sole fact of the quantities of phosphate provided in the form of phosphate fertilizer, but and above all, the result of different equilibrium reactions and the action of numerous other factors.

These results would demonstrate that calcium and magnesium are important for the mineral nutrition of plants [30] [33] [34]. Also, other authors have affirmed that any influence of the availability of phosphorus (P) in the soil could modify the architecture of the root system and impact the uptake and export of P [35] [36] [37].

The highly significant correlation between assimilable phosphorus in the soil and grain yield confirms the effective contribution to the nutrition of rice plants by phosphorus available in the soil. Overall, it was necessary to bring respectively 41; 37 and 29 kg·ha^{-1} to (P, Ca and Mg), to reach 3.06 t·ha^{-1} in rice grain, *i.e.* a 1/1 ratio of Ca/Mg for 41 kg P ha^{-1}. Thus, the grain yields observed attest that the availability of nutrients such as calcium, magnesium, aluminum and iron, as well as the reaction of the soil would influence the phosphate nutrition of rice. It is therefore necessary to control the application of calcium fertilizers, such as magnesium, to acidic soils, in particular, to optimize plant nutrition in phosphorus-P.

The application of the three nutrients (P, Ca and Mg) in a Ca/Mg ratio of 3/1, with 50 kg P ha^{-1} or 1/1 with 75 kg P ha^{-1} would offer optimal conditions for better yields rice. Indeed, these soil Ca/Mg ratios of approximately 3/1 and 1/1 are acceptable thresholds for good mineral nutrition of crops [38]. These results confirm the fact that the availability of phosphorus-P in the soil is not solely due to the quantities of P provided in the form of phosphate fertilizers [32] or organic amendments [39] [40], but and above all the result of the action of numerous factors [31] [32] and different equilibrium reactions [12] [28] [34].

We could admit that an application of the three nutrients (P, Ca and Mg) in a Ca/Mg ratio of 1/1 with a dose of around 50 kg P ha^{-1}, would offer optimal conditions for better harvests. and sustainability of rice cultivation in the agroecology studied. Taking into account the Ca/Mg ratio of input is therefore necessary for a strategy of phosphate fertilization of rice, on acidic soil, in the humid forest agroecology of the tropical zone. For work by [38] [41], average rice yields can be achieved with an average Ca/Mg ratio of around 1/1 and average inputs of 41 kg P ha^{-1}, 38 kg Ca ha^{-1} and 34 kg Mg ha^{-1}. In addition to this report, [16] [17] argued that in soils where the calcium content is high, the soil Ca/Mg ratio should be increased to 3/1 to optimize phosphate nutrition.

5. Conclusion

The present work consisted in studying the response of NERICA rice to different doses of calcium (Ca) and magnesium (Mg) fertilizers coupled with doses of phosphorus, depending on the yield and some physicochemical parameters of the soil. Thus, the yield of rice and certain soil parameters (Pass, DSP and Mg) seems to improve with increasing doses of P, Ca and Mg. However, the results indicate that the best rice yield are obtained when there is a Ca/Mg ratio of 1/1 and 3/1 for respective applications of 50 $kg \cdot ha^{-1}$ and 75 $kg \cdot ha^{-1}$ of phosphate fertilizer. Furthermore, for good management of the Ca/Mg ratio and an increase in RDG, the results show that calcium should be used at doses lower than 75 $kg \cdot ha^{-1}$, but also, that DSP and Fer (Fe) have strong influences on yield. The availability of phosphorus in the soil does seem to be solely due to the quantities of phosphate fertilizers, but is above all the result of different equilibrium reactions and the action of many other factors. The Ca/Mg ratio and Fe would therefore have synergistic effects on phosphate fertilization in an acid environment.

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Conflicts of Interest

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

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