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Development and productivity of 'Terra Maranhão' plantains influenced by soil fertilization with nitrogen, phosphorus and potassium

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ABSTRACT

Plantains are plants of the genus *Musa* that require substantial amounts of nutrients applied to the soil, highlighting nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) as being the most critical. This nutrient demand is often unmet in the acidic soil, highly weathered and presenting low natural fertility. Mineral fertilizers are used to correct deficiencies in soil nutrients and enhance crop productivity. Establishing optimal application rates is essential for the success and sustainability of agricultural systems. This research aimed to evaluate the effects of different fertilization rates of N, P_2O_5 and K_2O on the parameters of growth, development, and productivity of 'Terra Maranhão' plantain in Brazil. Seventeen combinations of N (0–700 kg ha^{-1}), P_2O_5 (0–450 kg ha^{-1}) and K_2O (0–1370 kg ha^{-1}) were assessed. The design used was randomized blocks with three replications, each plot consisting of 10 plants. Data were subjected to regression analysis, which tested polynomial and linear univariate models. Fertilization with N, P_2O_5 and K_2O significantly influenced the growth, development and productivity parameters, fitting quadratic or linear univariate models. The quadratic models showed maximum physical efficiency rates for the productivity parameters ranging from 430 to 513 kg ha^{-1} of N ($p < 0.001$), 281–285 kg ha^{-1} of P_2O_5 ($p < 0.001$), and 723–868 kg ha^{-1} of K_2O ($p = 0.001$ to $p < 0.001$), resulting in a bunch mass of 45.9–46.2 kg, average hand mass of 4.12–4.13 kg, and productivity of 61–62 t ha^{-1}. Plants with a pseudostem circumference of 95 cm, pseudostem height of 4.5 m and 16 leaves per plant presented productivity greater than 65 t ha^{-1}. These findings contribute to the optimization of the 'Terra Maranhão' plantain production system, providing recommendations for fertilization rates of N, P_2O_5 and K_2O that maximize productivity in a shorter production cycle.

1. Introduction

Musa spp. are fruit plants of global importance, with a production of 135 million tons per year (FAOSTAT, 2024). This species represents one of the principal agricultural crops in world trade (Zhang et al., 2019; Guimarães et al., 2023). In humid tropic regions, these plants typically mature and bear fruit within a year and a half of cultivation, contrasting with many other fruit trees that require 3–5 years to produce fruit, this scenario offers a rapid return on investment (Aba et al., 2020). A specific type of *Musa* is the plantain, which are perennial monocotyledons with a triploid and bispecific genome (Marie-Laure et al., 2021). Plantains produce fruits with a harder skin and greener color, with a high starch content, rich in vitamins and minerals (Marie-Laure et al., 2021; Coffi et al., 2023). They are eaten boiled, fried or roasted, and they are important for human nutrition in tropical and subtropical countries (Borges et al., 2002; Marie-Laure et al., 2021). In Brazil, the 'Terra'

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variety is among the most widely produced plantains, featuring a lengthy cycle (~16 months) and requiring significant nutrient inputs (Berilli et al., 2022).

Plantains extract large amounts of nutrients from the soil, and the availability of soil nutrients significantly affects plant productivity (Silva et al., 2011; Dépigny et al., 2019; Marie-Laure et al., 2021). Nutrients are allocated within plant tissues, and a portion of them is exported by the fruits (Silva et al., 2011, 2012). It is important to state that nitrogen, phosphorus and potassium are the nutrients most applied to the soil (Silva et al., 2003; Ho et al., 2020). Nitrogen contributes to the vegetative development of the aerial part of the plant (Ahmed et al., 2017; Marie-Laure et al., 2021). Phosphorus acts in the respiration processes, energy production and cell division (Leonel et al., 2020). Potassium is vital for enzyme activation, osmotic adjustment, regulation of turgor pressure, and the electrical potential of the membrane, impacting photosynthetic activity and growth rate (Ho et al., 2020). However, highly weathered acidic soils, predominant in tropical regions, are characterized by low organic matter content, high acidity, and a limited capacity to supply nutrients as nitrogen, phosphorus and potassium to plants (Leonel et al., 2020; Zhang et al., 2020; Guimarães et al., 2023), which limits commercial production (Zhang et al., 2019; Sun et al., 2020).

Mineral fertilizers are used to correct soil deficiency in plant nutrients and to improve crop productivity (Carmona et al., 2016; Dépigny et al., 2019). Soil fertility depletion is one of the main impediments to sustainable agricultural productivity (Erkossa and Teklewold, 2009). Prezotti et al. (2007) recommend applying 120–500 kg ha^{-1} of N, 20–260 kg ha^{-1} of P_2O_5, and 80–700 kg ha^{-1} of K_2O to fertilize soils under *Musa* spp. in acidic soils in southeastern Brazil, which sustains a productivity that can vary from 10 to 80 t ha^{-1}. In practice, farmers with more technology and greater financial capacity to be invested are the ones who apply 250–400 kg ha^{-1} of N, 150–250 kg ha^{-1} of P_2O_5, and 500–800 kg ha^{-1} of K_2O to the soil under plantains in southeastern Brazil. These fertilizer applications contribute to improving soil fertility over time (Lacerda et al., 2015), which results in a pH from 5.0 to 6.1, organic matter content from 1.1 to 2.4 %, phosphorus content from 2.4 to 8.1 ppm and potassium content from 0.1 to 0.3 cmol$_c$ dm^{-3} (Silva et al., 2011, 2012, 2013), which allows agricultural crops to reach their productive potential (Guimarães et al., 2023). However, the high cost of fertilizers used in plantain cultivation is reported by small farmers as an economic challenge, limiting crop profitability (Lacerda et al., 2015; Dépigny et al., 2019; Monono et al., 2023). The scientific literature still lacks information that optimizes fertilization rates of N, P_2O_5 and K_2O for plantain in acidic and highly weathered soil conditions.

Defining the maximum efficiency rates is essential for the success and sustainability of agroecosystem. Silva et al. (2012) recommended a rate of N from 410 to 521 kg ha^{-1}, obtaining the maximum physical efficiency for the banana plants determined by polynomial regression models. Silva et al. (2011) observed that the estimated rates for maximum technical efficiency of production were 827 and 835 kg ha^{-1} of K_2O, respectively. The maximum technical efficiency rate is equivalent to 90 % of maximum productivity, considered the rate of maximum physical efficiency (Silva et al., 2012; Guimarães et al., 2023). Silva et al. (2003) obtained maximum productivity with the application of 962 kg ha^{-1} of K_2O, and higher rates resulted in reduced productivity. Thus, both the lack and excess of nutrients decrease banana production (Silva et al., 2011; Guimarães et al., 2023). The application of excess nutrients to the soil may not provide effects or may even reduce banana production due to nutritional imbalance in the banana plant (Borges et al., 2002; Silva et al., 2012; Monono et al., 2023). Furthermore, the excessive use of fertilizers poses significant threats to the environment and human health (Ahmed et al., 2017; Liu et al., 2021).

Improving soil fertility contributes to greater growth and development of banana plants (Marie-Laure et al., 2021; Coffi et al., 2023). Borges et al. (2002) observed that N fertilization ranging from 0 to 500 kg ha^{-1} influenced the pseudostem height, number of fruits per bunch and fruit diameter and length. Silva et al. (2013) increased productivity parameters, such as bunch mass, number of hands per bunch, number of fruits per bunch, and fruit mass and diameter, by applying increased rates of K_2O up to 1200 kg ha^{-1}. However, the interaction between the fertilization rates of N, P_2O_5 and K_2O has not yet been fully elucidated, and there may be processes of antagonism and synergy between the nutrients which impact the development and productivity of plantains. Furthermore, growth and development parameters directly influence plant productivity (Marie-Laure et al., 2021), and therefore defining these limits serves as a valuable field indicator to help farmers estimate productivity and make decisions related to production.

This research tests the hypothesis that plantain cultivation needs fertilization rates of N, P_2O_5 and K_2O that are different from the rates presented in the scientific literature and, therefore, lacks field calibrations that aimed at maximizing fertilizer efficiency and avoiding overestimated rates, which may result in agricultural, economic and environmental impacts. The objective of this study was to evaluate the effect of fertilization rates of N, P_2O_5 and K_2O on the growth, development and productivity parameters of 'Terra Maranhão' plantains, aiming to improve the efficiency of those nutrients applied to the soil, with a focus on a more sustainable agricultural production.

2. Material and methods

2.1. Area characterization and soil preparation

The experiment was carried out in a commercial plantain crop in Colatina, Brazil (19° 30′ 10″ S, 40° 31′ 55″ W, 52 m above sea level). The climate of the region is classified as Aw with the rainy summer and dry winter, according to the Köppen and Geiger, 1928. Plantains of the 'Terra Maranhão' variety (AAB) were transplanted in October 2022, with a spacing of 2.2 × 2.4 m in double rows 3.7 m apart (1412 plants ha^{-1}). The seedlings were 35 cm tall. The soil is classified as a Red Yellow Latosol (dos Santos et al., 2018) with a clayey texture and flat slope. The chemical characterization of the soil presents the content: hydrogen potential (pH) - 6.3; phosphorus - 7.3 ppm; potassium - 0.2 cmol$_c$ dm^{-3}; calcium - 3.7 cmol$_c$ dm^{-3}; magnesium - 1.6 cmol$_c$ dm^{-3}; aluminum - 0.0 cmol$_c$ dm^{-3}; potential acidity (H + Al) - 1.9 cmol$_c$ dm^{-3}; sum of bases - 5.6 cmol$_c$ dm^{-3}; potential soil cation exchange capacity - 7.5 cmol$_c$ dm^{-3}; base saturation - 75.2 %, and organic matter - 1 %, according to Teixeira et al. (2017). The soil sample was collected in the 0–0.2 m layer before soil preparation and application of fertilizer rates. Before soil preparation, 600 kg ha^{-1} of dolomitic limestone was applied to the soil surface. The soil was turned with plowing and harrowing, and the limestone was incorporated into the 0–0.2 m soil layer. A planting furrow was opened with a tractor and furrower, and only phosphate fertilizer was applied within the furrow, as detailed below.

2.2. Experimental design

The treatments were obtained from a factorial design with combinations of N, P_2O_5 and K_2O rates, distributed in a randomized block design with three replicates. The nutrient rates tested were: N (0, 40, 120, 260, 420, 600 and 700 kg ha^{-1}), P_2O_5 (0, 25, 140, 240, 330 and 450 kg ha^{-1}) and K_2O (0, 75, 430, 720, 1000 and 1370 kg ha^{-1}), resulting in 17 combinations, referred to as treatments (Table 1).

Each rate of N and K_2O was divided into twelve parts, monthly applied to the projection of the canopy of each plant in the plot, while P_2O_5 was divided into two applications, with 67 % applied to the planting furrow and 33 % on the surface five months after planting (Table 2). The experimental plots consisted of ten useful plants (two rows with five plants), totaling 510 plants (0.36 ha). The fertilizers used were urea (45 % N), simple superphosphate (18 % P_2O_5) and potassium chloride (60 % K_2O). Each fertilizer was applied individually and manually to the soil surface.

Table 1
Treatments obtained by combinations of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) rates applied to the soil under 'Terra Maranhão' plantain.

Treatment	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
1	260	140	430
2	260	140	1000
3	260	330	430
4	260	330	1000
5	420	140	430
6	600	140	1000
7	420	330	430
8	600	330	1000
9	120	140	430
10	700	330	1000
11	260	25	430
12	600	450	1000
13	120	140	75
14	700	330	1370
15	420	240	720
16	40	25	75
17	0	0	0

Table 2
Splitting of fertilization rates of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) used for treatments.

Year	Month	N (%)	P_2O_5 (%)	K_2O (%)
2022	October	0	67	0
	November	0	0	0
	December	3	0	2
2023	January	5	0	2
	February	5	0	3
	March	5	0	3
	April	10	33	6
	May	10	0	12
	June	12	0	12
	July	0	0	0
	August	10	0	12
	September	10	0	12
	October	10	0	12
	November	10	0	12
	December	10	0	12

2.3. Crop management

The plants were irrigated by micro-sprinkler, using a sprinkler with a flow rate of 60 L h^{-1} for four plants. At planting, the seedlings used were treated with fungicide (benzimidazole) and insecticide (neonicotinoid). Throughout the cycle, four applications of fungicide (triazole and/or dithiocarbamate) and four applications of insecticide (neonicotinoid) were carried out, rotating the products and active ingredients. In the double rows (3.7 m), surface harrowing was performed every three months to control weeds, while in the inter-row of single rows (2.2 m), weed control was carried out with herbicide until ten months after planting. During the cycle, two defoliations were performed to eliminate senescent leaves. A foliar application of micronutrients was performed according to Prezotti et al. (2007). During the cluster-filling period, plants were supported using 6 m eucalyptus stems, which were buried 1 m deep. These activities followed the production system adopted by farmers in the region.

2.4. Evaluation of growth and development parameters of plantains

Plant growth was assessed in November 2023 by measuring pseudostem circumference and height. Development parameters were evaluated by the number of functional leaves and the plantation-harvest interval in the same period. Measurements were performed on five plants in the center of the plot, when 50 % of the plants had emitted bunches.

2.4.1. Pseudostem circumference and height

Pseudostem circumference was measured 10 cm above the ground, and pseudostem height was measured from the ground up to the V formed by the last two leaves produced (Borges et al., 2002; Silva et al., 2012; Marie-Laure et al., 2021; Coffi et al., 2023).

2.4.2. Number of leaves per plant and plantation-harvest interval (PHI)

The number of functional leaves per plant was determined by direct counting, and the PHI was measured in days between planting and harvesting the bunch of each plant (Atsin et al., 2024; Marie-Laure et al., 2021; Coffi et al., 2023).

2.5. Evaluation of productivity parameters of plantains

The productivity parameters measured were bunch mass, number of hands per bunch, average hand mass, productivity, number of fruits per hand, average fruit mass, fruit length and circumference. Measurements were taken on five plants in the center of the plot.

2.5.1. Bunch mass (BM)

Bunches from five central plants were harvested, and the bunch mass was measured (Dépigny et al., 2019). The bunches were harvested when the fruits were completely green, i.e., at ripeness stage 1 (Leonel et al., 2020).

2.5.2. Number of hands per bunch (NHB)

Immediately after harvesting the bunches, the hands were manually separated and counted (Crisostomo et al., 2008; Silva et al., 2012).

2.5.3. Average hand mass (AHM)

After separating the hands from the bunch, the stalk was weighed. The AHM was obtained by Equation (1):

$$AHM = (BM - SM) / NHB \quad (1)$$

where, SM is the stalk mass. BM and SM were measured with a portable digital scale (Líder, LD-1050, Araçatuda, Brazil).

2.5.4. Productivity (PROD)

The PROD was obtained by Equation (2), adapted from Crisostomo et al. (2008) and Silva et al. (2012).

$$PROD = (BM - SM) * NPH \quad (2)$$

where, NPH is the number of plants per hectare.

2.5.5. Number of fruits per hand (NFH)

The third hand of the bunch was selected, and the number of fruits (fingers) were counted manually (Borges et al., 2002; Crisostomo et al., 2008; Silva et al., 2012; Leonel et al., 2020).

2.5.6. Average fruit mass (AFM)

The third hand mass (THM) was also weighed with a portable electronic scale (Ohaus, Compass CX2200, Barueri, Brazil). The FAM was obtained by Equation (3):

$$AFM = THM / NFH \quad (3)$$

2.5.7. Fruit length and circumference

A central fruit from the third hand was used to measure the length and circumference (Crisostomo et al., 2008; Silva et al., 2012). The length was measured with a tape measure from the pedicel to the apex, and the circumference was measured in the center of the fruit also using a tape measure (Marie-Laure et al., 2021).

2.6. Statistical analysis

The data were subjected to analysis of variance to test the interactions among the factors (N x P_2O_5 x K_2O), with non-significant results (F test, $p > 0.05$). The data were subjected to regression analysis for isolated factors, testing univariate polynomial and linear models. The models were selected based on the significance of the analysis of variance of the regression (F test, $p > 0.05$) and the test of the model coefficients (Student's t-test, $p > 0.05$), with the N, P_2O_5 and K_2O rates as independent variables and the plant data as dependent variables.

In order to obtain the maximum physical efficiency (MPE) rate, the polynomial models had the first derivatives set equal to zero, using the N, P_2O_5 and K_2O rates (Silva et al., 2011, 2012; Carmona et al., 2016). The maximum technical efficiency (MTE) rate was obtained with a rate equivalent to 90 % from the response obtained with the MPE rate for N, P_2O_5 and K_2O (Silva et al., 2012; Guimarães et al., 2023).

Pearson correlation analysis was performed to identify significant relationships between growth, development and productivity parameters. The analyses were developed using R Core Team (2017). Productivity intervals were used to evaluate growth and development parameters.

3. Results

3.1. Growth and development parameters

Soil fertilization with N, P_2O_5 and K_2O significantly influenced the pseudostem circumference and height of the plants (Fig. 1A–F). The pseudostem circumference and height ranged from 83.8 to 105.5 cm and from 3.9 to 4.8 m, respectively. The univariate quadratic models showed the best fit for the circumference and height of the pseudostem at the rates of N ($p = 0.001$ and $p < 0.001$), P_2O_5 ($p = 0.002$ and $p < 0.001$), and K_2O ($p < 0.001$ and $p < 0.001$). The coefficient of determination (R^2) values of the models ranged from 25 to 43 % for N, from 23 to 33 % for P_2O_5 and from 45 to 61 % for K_2O, and the model coefficients were significant ($p < 0.04$).

The models presented maximum physical efficiency rates of 528 and 524 kg ha^{-1} for N, 290 and 281 kg ha^{-1} for P_2O_5 and 1135 and 1105 kg

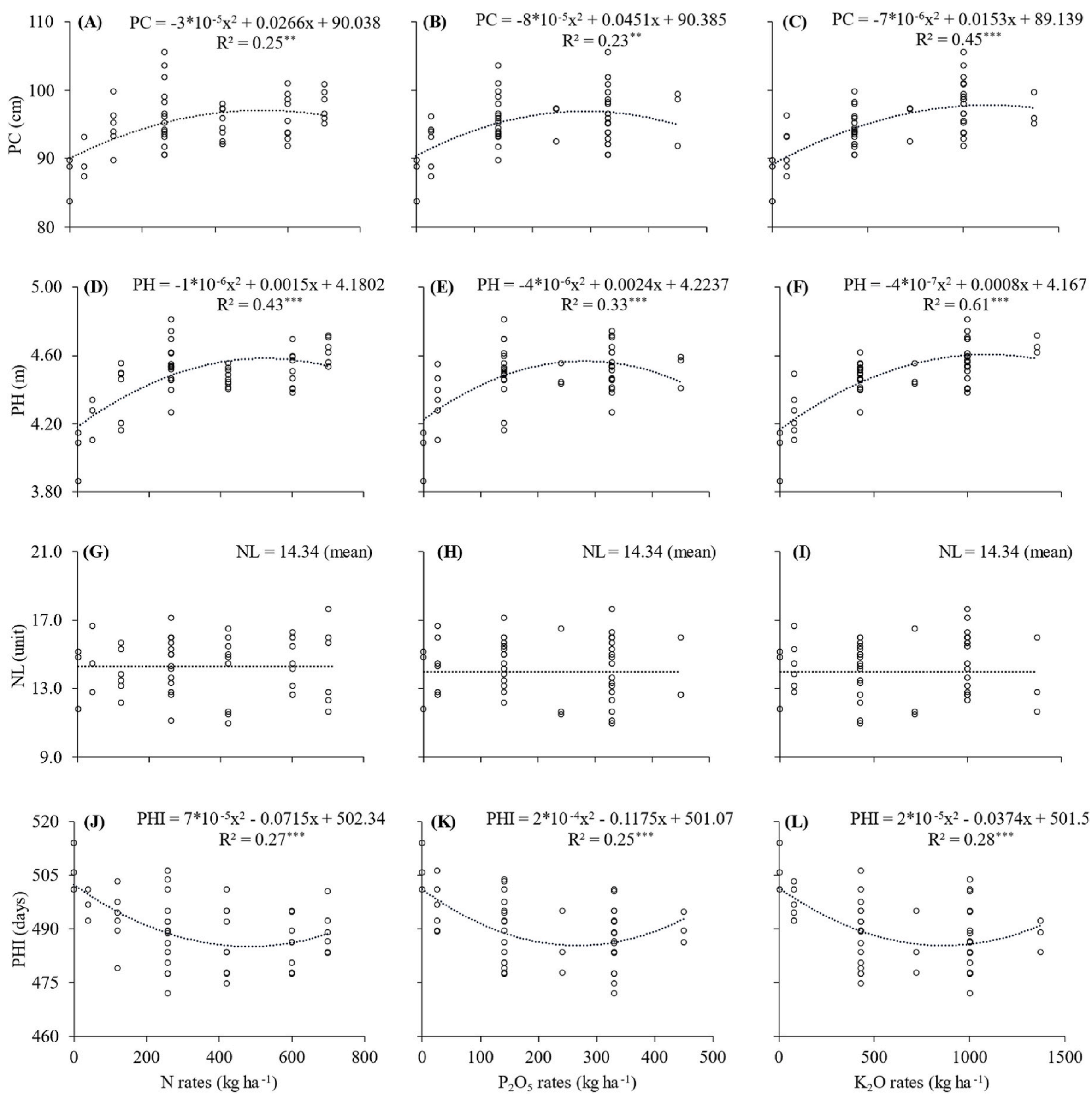

Fig. 1. Pseudostem circumference (PC, A-C) and height (PH, D-F), number of leaves per plant (NL, G-I) and plantation-harvest interval (PHI, J-L) of bunches of 'Terra Maranhão' plantain with different fertilization rates of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). ** and *** indicate significant values at $p < 0.01$ and 0.001, respectively. x of the models represents the N, P_2O_5 and K_2O rates.

ha^{-1} for K_2O for pseudostem circumference and height, respectively. The models presented maximum technical efficiency rates of 89 and 129 kg ha^{-1} for N, 40 and 52 kg ha^{-1} for P_2O_5 and 283 and 305 kg ha^{-1} for K_2O, resulting in a pseudostem circumference of 96.2–97.8 cm, and pseudostem height of 4.57–4.68 m. The number of leaves per plant did not show significant adjustment for the tested models ($p > 0.05$), with values ranging from 11.0 to 17.7 leaves per plant and an average of 14.3 leaves per plant (Fig. 1G, H, I).

Soil fertilization with N, P_2O_5 and K_2O significantly influenced the plantation-harvest interval (PHI) of plantain bunches (Fig. 1J, K, L). The PHI ranged from 472 to 514 days, i.e., from 15.7 to 17.1 months, respectively. The univariate quadratic models showed the best adjustment for the PHI at the rates of N ($p < 0.001$), P_2O_5 ($p = 0.001$) and K_2O ($p < 0.001$). The R^2 values of the models were 28, 25 and 28 % for N, P_2O_5 and K_2O, respectively, with significant model coefficients ($p < 0.008$). The models showed the lowest PHI at rates of 485, 267 and 859 kg ha^{-1} for N, P_2O_5 and K_2O, respectively, resulting in a PHI from 484 to 485 days.

3.2. Productivity parameters

Soil fertilization with N, P_2O_5 and K_2O significantly influenced bunch mass, number of hands per bunch, average hand mass and productivity (Fig. 2A–L), except for the average hand mass, which did not show significant adjustment for the models tested at the P_2O_5 rates ($p > 0.05$). The bunch mass, number of hands per bunch, average hand mass, and productivity of plantains ranged from 32.80 to 51.05 kg per bunch, from 9.00 to 11.50 hands per bunch, from 3.28 to 4.67 kg per hand, and from 43.78 to 69.04 t ha^{-1}, respectively.

The univariate quadratic models presented the best adjustments for bunch mass, average hand mass, and productivity at the rates of N ($p < 0.001$), P_2O_5 ($p < 0.001$) and K_2O ($p = 0.001$ to $p < 0.001$), while the univariate linear models presented the best adjustments for number of hand per bunch at the rates of N ($p < 0.001$), P_2O_5 ($p < 0.001$) and K_2O ($p < 0.001$). The R^2 values of the models ranged from 26 to 48 % for N, from 28 to 38 % for P_2O_5, and from 25 to 46 % for K_2O, with highly significant model coefficients ($p < 0.002$). The univariate polynomial models showed maximum physical efficiency at rates ranging from 430

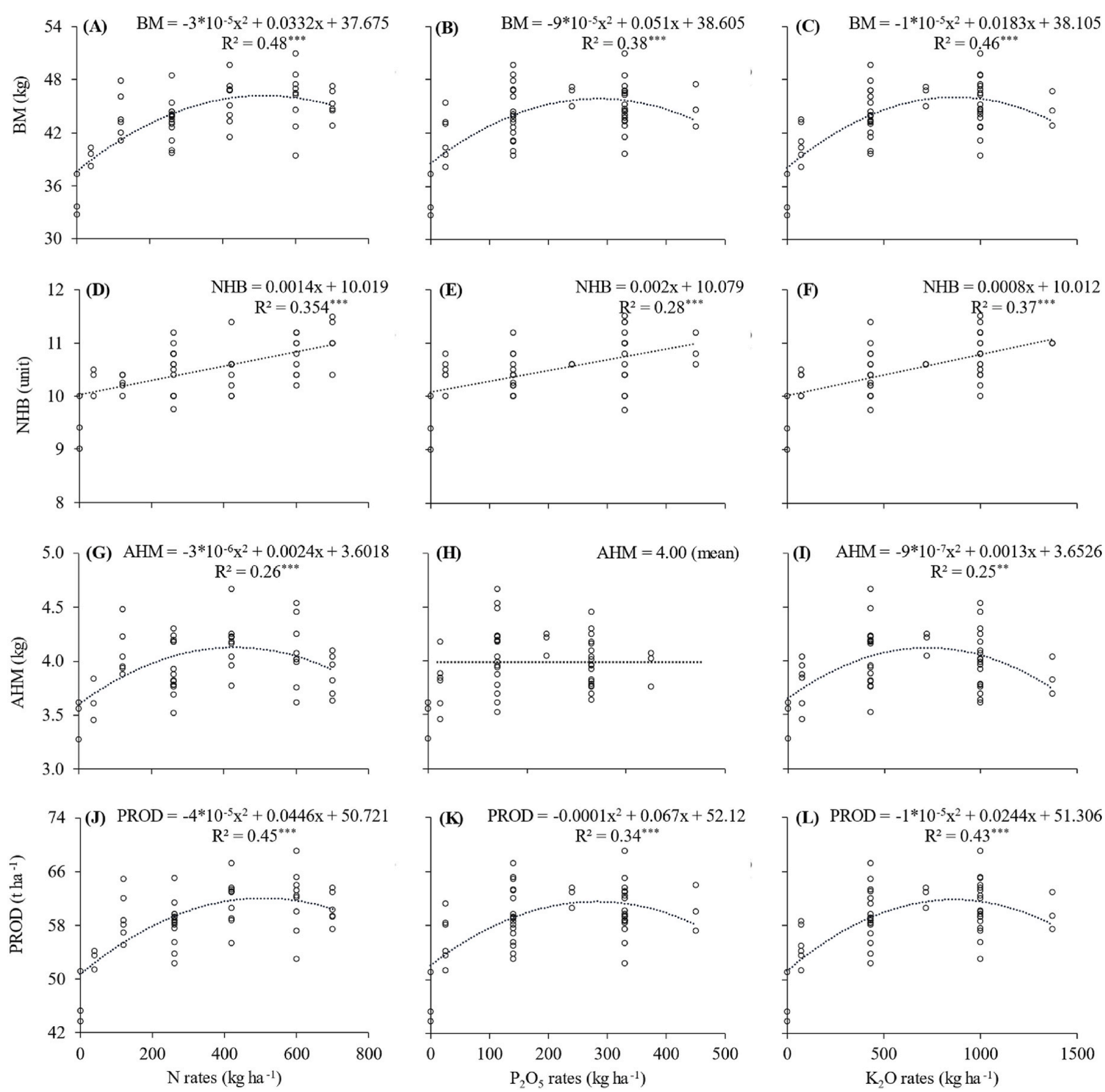

Fig. 2. Bunch mass (BM, A-C), number of hands per bunch (NHB, D-F), average hand mass (AHM, G-I) and productivity (PROD, J-L) of 'Terra Maranhão' plantain with different fertilization rates of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). ** and *** indicate significant values at $p < 0.01$ and 0.001, respectively. x of the models represents the N, P_2O_5 and K_2O rates.

to 513 kg ha^{-1} for N, 281–285 kg ha^{-1} for P_2O_5, and 723–868 kg ha^{-1} for K_2O, resulting in a bunch mass of 45.9–46.2 kg, average hand mass of 4.12–4.13 kg, and productivity of 61–62 t ha^{-1}. The models showed maximum technical efficiency at rates of 49–135 kg ha^{-1} for N, from 54 to 58 kg ha^{-1} for P_2O_5, and from 45 to 207 kg ha^{-1} for K_2O.

Soil fertilization with N, P_2O_5 and K_2O significantly influenced the number of fruits per hand and average fruit mass (Fig. 3A–F), except for the average fruit mass of P_2O_5 rates ($p > 0.05$). The number of fruits per hand and average fruit mass ranged from 15.00 to 17.40 fruits per hand and from 248.43 to 331.75 g per fruit, respectively. The univariate quadratic models showed the best adjustments for the number of fruits per hand and average fruit mass at N ($p = 0.002$ and $p = 0.037$) and K_2O ($p = 0.001$ and $p = 0.016$) rates, while the linear model showed the best adjustment for number of fruits per hand at P_2O_5 rates ($p < 0.015$). The R^2 values of the models ranged from 13 to 23 % for N, 12 % for P_2O_5 and 16–24 % for K_2O, with significant model coefficients ($p < 0.018$). The univariate polynomial models showed maximum physical efficiency rates of 454 and 376 kg ha^{-1} for N and 868 and 623 kg ha^{-1} for K_2O for the number of fruits per hand and average fruit mass, respectively, resulting in a bunch mass of 16.62–16.64 units, and of 304–305 g.

The fruit length and circumference did not present significant adjustments for the tested models ($p > 0.05$), with values ranging from 21.05 to 29.10 cm and from 14.86 to 18.00 cm, with averages of 24.76 and 16.00 cm, respectively (Fig. 3G–L).

3.3. Pearson correlation and productivity intervals

Significant positive correlations ($p < 0.05$) were found between productivity parameters and growth and development data ($r = 0.19^*$ to 0.50^*), indicating the additive effect of larger plant structure on increased productivity (Fig. 4). In contrast, productivity parameters showed significant negative correlations ($p < 0.05$) with plantation-harvest interval ($r = -0.16^*$ to -0.38^*), indicating an inverse linear relationship, where earlier harvests were associated with increased productivity parameters.

Pseudostem circumference and height increased with increasing productivity up to the range of 55–65 t ha^{-1}, reaching 96.2 ± 0.6 cm and 4.52 ± 0.03 m, respectively (Fig. 5A and B). Subsequently, the values

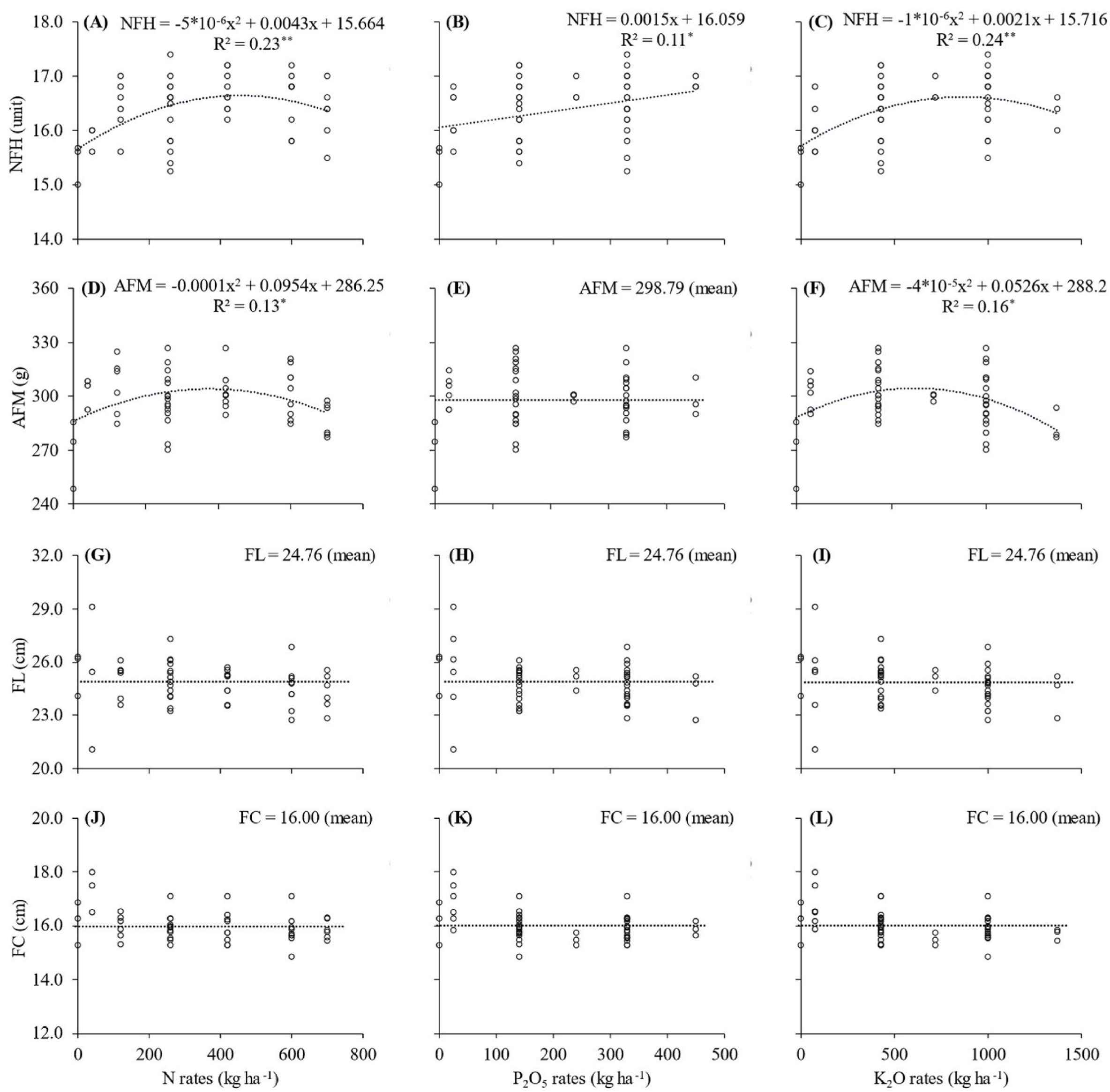

Fig. 3. Number of fruits per hand (NFH, A-C), average fruit mass (FAM, D-F), fruit length (FL, G-I) and circumference (FC, J-L) of 'Terra Maranhão' plantain with different fertilization rates of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). * indicate significant values at $p < 0.05$. x of the models represents the N, P_2O_5 and K_2O rates.

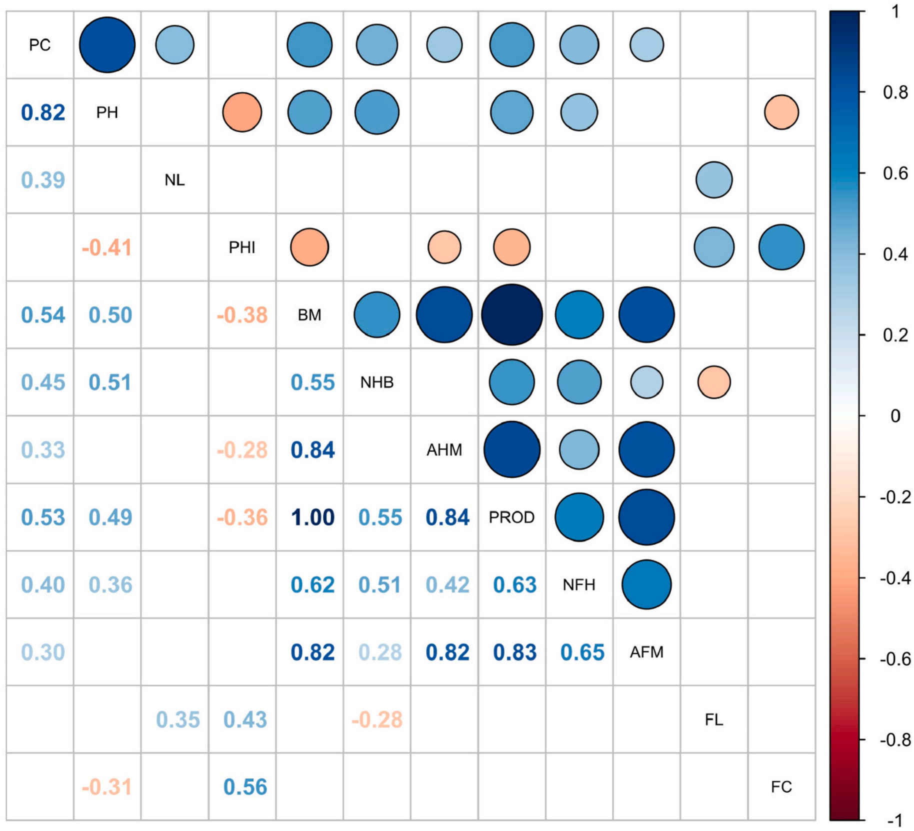

Fig. 4. Pearson correlation matrix of growth, development and productivity parameters of 'Terra Maranhão' plantain with different fertilization rates of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). PC: pseudostem circumference; PH: pseudostem height; NL: number of leaves per plant; PHI: plantation-harvest interval, BM: bunch mass; NHB: number of hands per bunch; AHM: average hand mass; PROD: productivity; NFH: number of fruits per hand; AFM: average fruit mass; FL: fruit length; FC: fruit circumference. Values presented were significant ($p < 0.05$).

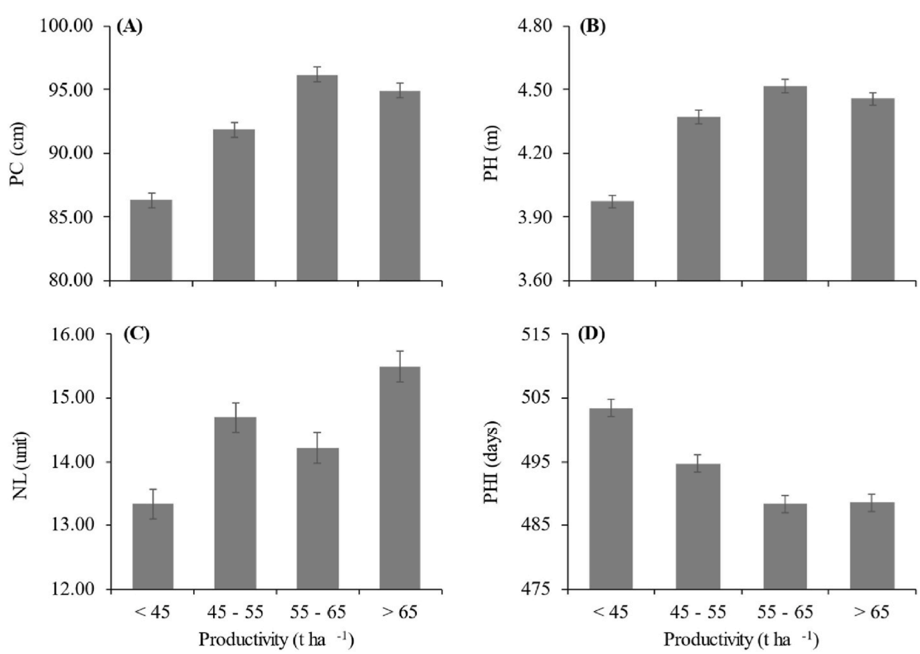

Fig. 5. Pseudostem circumference (PC, A) and height (PH, B), number of leaves per plant (NL, C) and plantation-harvest interval (PHI, D) with different productivity intervals of 'Terra Maranhão' plantain. Bars represent standard errors.

stabilized. For the number of leaves per plant, there was a linear growth, reaching a value of 15.5 ± 0.24 leaves per plant for the productivity range >65 t ha^{-1} (Fig. 5C). PHI showed a reduction in days with increasing productivity, with 488 ± 1.3 days in the productivity range >65 t ha^{-1} (Fig. 5D).

4. Discussion

4.1. Growth and development parameters of plantains

Increasing the rates of N, P_2O_5 and K_2O increased the height and circumference of the pseudostem of the plantains up to the point of maximum physical efficiency. However, this occurred in isolation for each nutrient applied, which was also observed by Silva et al. (2003) and Lacerda et al. (2015). This is because the nutrients nitrogen, phosphorus and potassium are essential for the growth and development of plantains (Leonel et al., 2020; Marie-Laure et al., 2021). Monono et al. (2023) also found greater height and circumference of the pseudostem of the plantains in treatments that received application of fertilizers containing N and P_2O_5. The increased growth and development of the vegetative part is a consequence of the absorption of greater amounts of nutrients, contributing to the physiological and metabolic processes of the plants (Leonel et al., 2020; Souza et al., 2021). On the other hand, greater nutrient absorption by plants depletes the soil more quickly and, therefore, will require external inputs of nutrients to sustain productivity (Baiyeri and Ortese, 2007; Sun et al., 2020).

The lower N, P_2O_5 and K_2O rates applied to the soil limited plant growth and development. According to Coffi et al. (2023), the absence of fertilizers resulted in stunted growth and even death of plantains. However, the excess of these nutrients also reduced plant growth and development (Crisostomo et al., 2008; Silva et al., 2011; Sun et al., 2020). Maintaining soil fertility requires a balanced application of nutrient sources (Erkossa and Teklewold, 2009). Therefore, defining the maximum efficiency rates is necessary to improve the economic and productive viability of agricultural systems (Carmona et al., 2016; Monono et al., 2023).

Nitrogen and potassium are involved in the vegetative development of all aerial parts of plantains (Marie-Laure et al., 2021). Improving K_2O rates gradually increased photosynthetic efficiency and decreased non-photochemical extinction, rising biomass (Ho et al., 2020). Similarly, higher P_2O_5 rates are necessary to increase development and productivity parameters (Leonel et al., 2020). A significant increase in height, circumference and leaf production of plantain was observed with rates of 240 kg ha^{-1} of N and 658 kg ha^{-1} of K_2O (Marie-Laure et al., 2021), which were lower than the maximum physical efficiency rates, but higher than the maximum technical efficiency rates found in this research. The growth and vegetative development of plantains requires an adequate supply of nutrients throughout the crop cycle (Leonel et al., 2020). Coffi et al. (2023) found that bananas fertilized with 257 g $plant^{-1}$ of N (~360 kg ha^{-1}) had 12 leaves per plant, were 2.64 m tall, and had a circumference of 57.68 cm, which was smaller than those observed in this study.

Greater availability of nutrients in the soil also increases the number of functional leaves (Sun et al., 2020; Marie-Laure et al., 2021; Coffi et al., 2023). Plants with a greater number of functional leaves have a larger leaf area for light interception and the capacity to perform photosynthesis, which results in a greater accumulation of photoassimilates for cluster formation (Monono et al., 2023). Therefore, the number of functional leaves at flowering is a good indicator of correct fruit development (Atsin et al., 2024). The metabolism and transport of photoassimilates (carbohydrates) are closely related to agricultural productivity (Monono et al., 2023). Carbohydrates are the main products of photosynthesis, and their content reflects the rates of plant metabolism and carbon assimilation and are directly related to nutrients fertilization rates (Sun et al., 2020).

Improving soil fertility by applying maximum physical efficiency rates of N, P_2O_5 and K_2O reduced the plantation-harvest interval, resulting in earlier harvesting, which is advantageous for the producer due to the faster economic return. Coffi et al. (2023) also found a reduction in the plantation-harvest interval for *Musa* spp. plants, ranging from 347 to 374 days (11.6–12.5 months), with improved soil fertility. Marie-Laure et al. (2021) showed that rates of 240 kg ha^{-1} of N and 987 kg ha^{-1} K_2O reduced the production cycle of bananas, being lower and higher than the rates found in this study for N and K_2O, respectively. Increasing the N content in the soil stimulates the leaf meristem and allows the banana to complete its cultivation cycle more quickly (Atsin et al., 2024). Marie-Laure et al. (2021) reported that applying the recommended rate of N accelerates flowering, which contributes to reducing the plantation-harvest interval. Knowledge of the plantation-harvest interval is important because it allows predicting the fruit ripening period in advance and better planning harvesting and marketing activities (Atsin et al., 2024).

4.2. Productivity parameters of plantains

Increasing N, P_2O_5 and K_2O rates in the soil increased bunches and hand mass and the productivity of plants up to the maximum physical efficiency rate. From this point on, there was a reduction in the value observed. Again, this behavior occurred in isolation for each nutrient. Similar results were observed by Crisostomo et al. (2008), Silva et al. (2011, 2012, 2013) and Leonel et al. (2020). N fertilization affects several physiological characteristics of plants, such as chlorophyll concentration, activities of plant metabolic enzymes and soluble proteins that impact bunch mass (Sun et al., 2020). The application of N fertilizers was positively correlated with the increase of bunch mass (Dépigny et al., 2019). Phosphorus absorbed by the plant participates in energy transfers, synthesis of nucleic acids and starch, respiration, synthesis and stability of membranes, activation of enzymes, redox reactions and carbohydrate metabolism, and actions related to increased productivity (Leonel et al., 2020). Potassium is essential for critical processes for plant performance, including photosynthesis, carbon assimilation and stress response, directly influencing productive development (Ho et al., 2020). Greater phosphorus absorption also results in a parallel increase in nitrogen absorption, improving the vegetative structure of the plant (Marie-Laure et al., 2021; Berilli et al., 2022), thus resulting in positive correlations between plant growth and productivity, as observed in this research.

Fertilized plantains showed better agromorphological performance than unfertilized ones, showing the positive effect of fertilizer usage on bunch mass and productivity (Coffi et al., 2023). Dépigny et al. (2019) also observed higher bunch weights in production systems with greater access to mineral fertilizer. Inadequate nutrient supply associated with acidic and low-fertility soils has been one of the main causes of low development and productivity in banana plants (Leonel et al., 2020). The high cost of growing plantains, particularly due to the inputs required, is often cited by farmers as a reason for the limited success of this crop (Dépigny et al., 2019). Aba et al. (2020) reported that adequate nutrient supply with 400, 100 and 600 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, also resulted in the production of high-quality fruits and greater nutritional value. Sun et al. (2020) observed lower bunch mass than this study, ranging from 11.78 to 21.83 kg with rates of up to 455 g per N plant (~758 kg ha^{-1}).

The maximum physical efficiency rates found for the productivity parameters were equivalent to those reported by Silva et al. (2012), ranging from 410 to 521 kg ha^{-1} of N for the 'Prata Anã' banana, and close to fertilization rates practiced by farmers in the region. Leonel et al. (2020) found a maximum physical efficiency rate for the 'Prata' banana productivity of 35 kg ha^{-1} of P_2O_5, lower than those observed in this study due to the smaller size and productivity of the banana plants. The application of reduced rates of fertilizers can result in good productivity due to the constructed soil fertility (Lacerda et al., 2015; Guimarães et al., 2023) but tending to impoverish the soil and not maintaining economic levels of productivity in the long term (Lacerda et al., 2015). Guimarães et al. (2023) found maximum physical and technical efficiency rates for 'Prata' banana of 765 and 389 kg ha^{-1} of P_2O_5 and 850 and 550 kg ha^{-1} of K_2O, respectively, higher than those observed. In practice, many farmers are conditioned by the price the market pays for fruit, which allows them to invest in higher or lower fertilizer rates and other inputs.

The application of very high fertilizer rates to the soil can favor nutritional imbalance in the banana plant, which reduces productivity and also generates unnecessary costs (Guimarães et al., 2023; Sun et al., 2020). The increased salinity and toxicity caused by high concentrations of phosphate fertilizer reduce root growth and, consequently, affect nutrient uptake, which may justify the decrease in production parameters with high fertilizer rates (Leonel et al., 2020). This can also be explained by the acidification of the root environment in the presence of high rates of N (Marie-Laure et al., 2021; Sun et al., 2020). Furthermore, consumption of foods with high concentration of nitrate, resulting from excessive use of N fertilizers, has contributed to endogenous nitrosation, which can lead to thyroid problems, cancer, neural diseases and diabetes in humans (Ahmed et al., 2017). The application of fertilizers to the soil in excessive quantities also favors the loss of nutrients through water erosion and the eutrophication of surface water, increasing environmental pollution (Liu et al., 2021).

Greater development in the vegetative structure of the plants, such as pseudostem circumference and height, results in higher values in productivity parameters, an effect of greater nutrient availability in the soil (Guimarães et al., 2023). Pseudostem circumference and height are parameters highly correlated with banana production parameters (González-García et al., 2021). In this research, a pseudostem circumference of 94.94 cm, a pseudostem height of 4.46 m and 15.5 leaves per plant resulted in productivity greater than 65 t ha^{-1} and a greater harvest precocity. This is because this greater vegetative structure is related to greater photosynthetic capacity and photoassimilate production and results in greater fruit development (Souza et al., 2021). Furthermore, the definition of these biometric indicators helps farmers in estimating production and planning post-harvest and marketing actions.

5. Conclusions

Soil fertilization with N, P_2O_5 and K_2O significantly influenced the growth, development and productivity of 'Terra Maranhão' plantains. The adjustment of quadratic univariate models allowed us to define the maximum physical and technical efficiency rates for soil fertilization. The fertilization rates found for the productivity parameters ranging from 430 to 513 kg ha^{-1} of N, from 281 to 285 kg ha^{-1} of P_2O_5 and from 723 to 868 kg ha^{-1} of K_2O, resulting in a bunch mass of 45.9–46.2 kg, average hand mass of 4.12–4.13 kg, and productivity of 61–62 t ha^{-1}. Furthermore, plants with a vegetative structure with a pseudostem circumference of 95 cm, pseudostem height of 4.5 m and 16 leaves per plant presented productivity greater than 65 t ha^{-1}, considered high for the region. Thus, these results contribute to optimizing the production system of 'Terra Maranhão' plantains in acidic and highly weathered soils, promoting a more sustainable agricultural production.

CRediT authorship contribution statement

Gustavo Soares de Souza: Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Marciano Kaulz:** Visualization, Methodology, Investigation. **Gabriel Fornaciari:** Visualization, Methodology, Investigation. **Luís Otávio Suldine dos Santos:** Writing – original draft, Investigation, Formal analysis, Data curation. **Rafael Jaske Caetano de Almeida:** Validation, Investigation, Data curation. **Vitor Emanuel Barros Bionde:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Otávio Cezar Dalmaso:** Methodology, Investigation, Formal analysis, Data curation. **Otacílio José Passos Rangel:** Writing – review & editing, Project administration, Methodology. **André Guarçoni Martins:** Writing – review & editing, Visualization, Validation, Methodology. **Sávio da Silva Berilli:** Writing – review & editing, Project administration, Funding acquisition. **Anderson Martins Pilon:** Writing – review & editing, Visualization, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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