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PHOSPHORUS APPLICATION METHODS AND AGRONOMIC PERFORMANCE OF MAIZE

MÉTODOS DE APLICAÇÃO DE FÓSFORO E DESEMPENHO AGRONÔMICO DO MILHO

MÉTODOS DE APLICACIÓN DE FÓSFORO Y RENDIMIENTO AGRONÓMICO DEL MAÍZ

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ABSTRACT

Maize (Zea mays L.) is one of the main agricultural crops in Brazil, and the efficiency of phosphate fertilization is decisive for its productive performance. In tropical soils, phosphorus availability and the mode of application can interfere with nutrient uptake, affecting growth and yield. This study aimed to evaluate different forms of phosphorus application on the development and productivity of maize at the UNIVAG experimental field in Várzea Grande, Mato Grosso State, Brazil. The experiment was carried out between July and November 2021, in a randomized complete block design, with five replications and four treatments: application in single furrow, double furrow, broadcast, and control. At sowing, 30 kg N ha^{-1}, 120 kg P ha^{-1}, and 60 kg K ha^{-1} were applied; in topdressing, 180 kg N ha^{-1} and 90 kg K ha^{-1} were used. Sowing was performed manually, at a spacing of 0.45 m, and plots were managed according to technical recommendations for the crop. Plant height, stem diameter, and grain yield were evaluated. Data were subjected to analysis of variance, and means were compared using Tukey's test at 5% probability. No significant effects of the phosphorus application methods were observed for stem diameter (mean of 20.6 mm) or grain yield (mean of 9,051.7 kg ha-1). On the other hand, a significant effect was verified for plant height, with double-furrow (2.34 m) and broadcast (2.32 m) applications showing higher values compared to single furrow (2.20 m) and control (2.12 m). It was concluded that, under the evaluated conditions, the different forms of phosphorus application did not alter maize grain yield but influenced vegetative growth, with double-furrow and broadcast applications favoring greater plant height without translating into productive gains.

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Keywords: Fertilizers. Phosphate Fertilization. Productivity. Zea Mays.

RESUMO

O milho (Zea mays L.) é uma das principais culturas agrícolas do Brasil, e a eficiência da adubação fosfatada é decisiva para seu desempenho produtivo. Em solos tropicais, a disponibilidade de fósforo e o modo de aplicação podem interferir na absorção de nutrientes, afetando o crescimento e a produtividade. Este estudo teve como objetivo avaliar diferentes formas de aplicação de fósforo no desenvolvimento e na produtividade do milho no campo experimental da UNIVAG, em Várzea Grande, Mato Grosso, Brasil. O experimento foi conduzido entre julho e novembro de 2021, em delineamento de blocos casualizados, com cinco repetições e quatro tratamentos: aplicação em sulco simples, sulco duplo, a lanço e controle. Na semeadura, foram aplicados 30 kg N ha^{-1}, 120 kg P ha^{-1} e 60 kg K ha^{-1}; na cobertura, foram utilizados 180 kg N ha^{-1} e 90 kg K ha^{-1}. A semeadura foi realizada manualmente, com espaçamento de 0,45 m, e as parcelas foram manejadas de acordo com as recomendações técnicas para a cultura. Foram avaliadas a altura da planta, o diâmetro do colmo e a produtividade de grãos. Os dados foram submetidos à análise de variância e as médias foram comparadas pelo teste de Tukey a 5% de probabilidade. Não foram observados efeitos significativos dos métodos de aplicação de fósforo para o diâmetro do colmo (média de 20,6 mm) ou para a produtividade de grãos (média de 9.051,7 kg ha^{-1}). Por outro lado, verificou-se efeito significativo para a altura da planta, com as aplicações em sulco duplo (2,34 m) e a lanço (2,32 m) apresentando valores superiores em comparação com o sulco simples (2,20 m) e o controle (2,12 m). Concluiu-se que, nas condições avaliadas, as diferentes formas de aplicação de fósforo não alteraram a produtividade de grãos do milho, mas influenciaram o crescimento vegetativo, com as aplicações em sulco duplo e a lanço favorecendo maior altura da planta sem se traduzirem em ganhos produtivos.

Palavras-chave: Fertilizantes. Adubação Fosfatada. Produtividade. Zea Mays.

RESUMEN

El maíz (Zea mays L.) es uno de los principales cultivos agrícolas en Brasil, y la eficiencia de la fertilización fosfatada es decisiva para su rendimiento productivo. En suelos tropicales, la disponibilidad de fósforo y el modo de aplicación pueden interferir con la absorción de nutrientes, afectando el crecimiento y el rendimiento. Este estudio tuvo como objetivo evaluar diferentes formas de aplicación de fósforo en el desarrollo y la productividad del maíz en el campo experimental UNIVAG en Várzea Grande, Estado de Mato Grosso, Brasil. El experimento se llevó a cabo entre julio y noviembre de 2021, en un diseño de bloques completos al azar, con cinco réplicas y cuatro tratamientos: aplicación en surco simple, surco doble, voleo y control. En la siembra, se aplicaron 30 kg N ha^{-1}, 120 kg P ha^{-1} y 60 kg K ha^{-1}; en la cobertura, se utilizaron 180 kg N ha^{-1} y 90 kg K ha^{-1}. La siembra se realizó manualmente, con un espaciamiento de 0,45 m, y las parcelas se manejaron según las recomendaciones técnicas del cultivo. Se evaluaron la altura de la planta, el diámetro del tallo y el rendimiento de grano. Los datos se sometieron a un análisis de varianza y las medias se compararon mediante la prueba de Tukey al 5%. No se observaron efectos significativos de los métodos de aplicación de fósforo en el diámetro del tallo (media de 20,6 mm) ni en el rendimiento de grano (media de 9.051,7 kg ha-1). Por otro lado, se verificó un efecto significativo en la altura de la planta, con aplicaciones a doble surco (2,34 m) y al voleo (2,32 m) que mostraron valores superiores en comparación con las aplicaciones a un solo surco (2,20 m) y el control (2,12 m). Se concluyó que, en las condiciones evaluadas,

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las diferentes formas de aplicación de fósforo no alteraron el rendimiento de grano del maíz, pero sí influyeron en el crecimiento vegetativo, ya que las aplicaciones a doble surco y al voleo favorecieron una mayor altura de la planta sin traducirse en ganancias productivas.

Palabras clave: Fertilizantes. Fertilización Fosfatada. Productividad. Zea Mays.

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1 INTRODUCTION

In the current global and national production scenario, maize (*Zea mays* L.) stands out as a strategic crop for Brazilian agriculture, being cultivated in all regions of the country and present in more than two million farming establishments (Contini et al., 2019). According to the National Supply Company (Conab, 2025), Brazilian maize production in the 2024/2025 season is estimated at 137.0 million tons, an increase of 18.6% compared with the 2023/2024 season, with an average yield of 6,320 kg ha^{-1} and a cropped area of 21.68 million hectares. Mato Grosso remains the leading producing state, with record yields and an estimated production of 53.54 million tons in the second season crop (Conab, 2025).

In addition to its high production volume, maize has broad socioeconomic importance and multiple industrial applications, ranging from human and animal nutrition to products such as starches, flours, syrups, films and biodegradable packaging (Paes, 2006). It is also a raw material for fuel ethanol and generates co-products such as distillers dried grains with solubles (DDGS), which are widely used in animal feeding (Rosentrater & Zhang, 2021). This diversification of uses reinforces the need for management strategies that ensure high grain yield and quality, including phosphorus fertilization (Freiling et al., 2022; Sharifi et al., 2024).

Phosphorus (P) is essential for plant energy and structural processes and influences root system architecture, favoring exploration of the soil volume and the uptake of water and nutrients (Shen et al., 2011; Vetterlein et al., 2022). In maize, there is evidence that P-use efficiency and yield respond both to the applied rates and to fertilizer placement in the soil (Dube & Chimdi, 2022). Phosphorus availability in the soil is strongly mediated by microorganisms, which promote nutrient solubilization and mineralization, contributing to its use in the soil–plant system (Richardson & Simpson, 2011). Under low P availability, plants remodel root architecture, enhancing soil exploration and nutrient acquisition (Shen et al., 2011). In maize, there is evidence that P-use efficiency and yield are affected by both application rate and fertilizer placement (Dube & Chimdi, 2022; Freiling et al., 2022).

In soils with low available phosphorus or with a high capacity to fix the phosphate anion (PO_4^{3-}), the application of higher P rates becomes necessary to ensure adequate nutrition of maize plants and to allow higher yields (Roy et al., 2016; Withers et al., 2018). This limitation is particularly marked in highly weathered tropical soils, where acidity, the presence of iron and aluminum oxides, and the surface properties of clay minerals favor phosphate adsorption, restricting its availability to plants (Shen et al., 2011; Roy et al., 2016).

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Even with the use of phosphate fertilizers, a substantial proportion of the nutrient can become unavailable through fixation and retention processes in the soil, reducing its use efficiency in the soil–plant system (Roy et al., 2016; Withers et al., 2018). In view of these limitations, fertilizer placement methods become decisive to reduce losses and optimize uptake, with evidence of yield gains when P is placed in localized/banded positions rather than broadcast on the soil surface (Freiling et al., 2022; Sharifi et al., 2024).

Application methods influence phosphorus efficiency in maize. When the fertilizer is placed in localized bands and below the soil surface, P remains closer to the roots and its contact with sorption sites is reduced, which increases use efficiency and usually results in greater nutrient accumulation and yield (Freiling et al., 2022; Dube & Chimdi, 2022).

Broadcast surface application, in turn, favors P stratification. In calcareous soils or shortly after liming, the greater contact with carbonates can precipitate less soluble Ca–P forms and reduce phosphate mobility in the soil profile (Penn & Camberato, 2019; Wang et al., 2022). Because P moves mainly by diffusion, placing the fertilizer in the subsurface helps maintain greater water continuity and improves nutrient supply to the roots, especially under low moisture in the surface layer (Sharifi et al., 2024).

Moreover, recent studies have reinforced the search for more efficient phosphorus sources and fertilization techniques. Under controlled conditions, deep band application of N and P increased uptake efficiency and P accumulation in maize tissues compared with surface methods (Sharifi et al., 2024). In field conditions, greater placement depth has been associated with higher yield and a lower carbon footprint of the crop (Huang et al., 2024). In addition, understanding phosphorus availability and speciation in the soil is essential to improve nutrient use efficiency and to guide management strategies (Laan et al., 2024).

Therefore, given the importance of maize for Brazilian agriculture and the constraints imposed by low phosphorus availability in tropical soils, this study aimed to evaluate the agronomic performance of the crop under different phosphorus application methods, seeking to identify management strategies that improve nutrient use efficiency.

2 MATERIALS AND METHODS

The experiment was conducted from July 10 to November 5, 2021, at the experimental field of the Centro Universitário de Várzea Grande (UNIVAG), in Várzea Grande, Mato Grosso State, Brazil, located at 15°38'40.6" S and 56°05'52.6" W. The local climate is classified as Aw, according to Köppen and Geiger, characterized by a rainy

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summer and a dry winter. The region has a mean annual temperature of 26.3 °C and an average annual rainfall of approximately 1,445 mm.

Chemical characterization of the soil, was obtained from samples collected with an auger in the 0–20 cm layer (Table 1). Simple samples were taken at several points in the experimental area and homogenized to form a composite sample, which was sent to an analytical laboratory in the same municipality. The soil analysis indicated conditions suitable for maize cultivation, allowing an expected yield of 10 t ha^{-1} (Sousa & Lobato, 2004).

Table 1

Chemical and physical analysis results of the soil in the experimental area before establishment of the maize crop (Várzea Grande, MT, 2021)

Depth.	pH	pH	P	K	Ca+Mg	Ca	Mg	Al	H	H+Al	OM
(m)	(H_2O)	($CaCl_2$)	(mg dm^{-3})		---------------- (cmolc·dm^{-3}) ----------------						(g dm^{-3})
0.0 – 0.20	6.60	5.80	20.01	89.10	2.01	1.16	0.85	0.00	0.90	0.90	6.35
	Complementary results										
Depth. (m)	K	Ca	Mg	H	Al	m	Ca/Mg	Ca/K	Mg/K	Ca + Mg/K	
	--------- Element saturation (%) ---------					(%)	-------------------- Ratio --------------------				
0.0 – 0.20	7.32	36.94	27.07	28.66	0.00	0.00	1.36	5.04	3.70	8.74	
	Sulfur, micronutrients and physical analysis (sand, silt and clay)										
Depth. (m)	**S**	**Zn**	**Cu**	**Fe**	**Mn**	**B**	Sand		Silt		Clay
	------------------------ (mg dm^{-3}) ------------------------						---------------- (g ka^{-1}) ----------------				
0.0 – 0.20	5.05	4.00	0.80	72.10	25.27	0.39	78.23		6.90		14.85

Source: Plante Certo Agricultural Laboratory - Várzea Grande, MT (2021).

The experimental design was a randomized complete block design with five blocks and four treatments: phosphorus fertilization in a single furrow (fertilizer 5 cm below the seed), in a double furrow (5 cm deep on each side of the sowing row), broadcast application (manual surface distribution without incorporation), and a control (no P). Each plot consisted of five plant rows, 3 m in length. For evaluations, the useful area of each experimental unit was defined as the three central rows, excluding 0.50 m from each end of the rows.

The maintenance fertilization applied at sowing consisted of 30 kg N ha^{-1}, 120 kg P ha^{-1} for the treatments that received this fertilization, and 60 kg K ha^{-1}, whereas topdressing fertilization supplied 180 kg N ha^{-1} and 90 kg K ha^{-1}. The fertilizer sources used were urea (45% N), potassium chloride (60% K_2O) and single superphosphate (18% P_2O_5). Soil preparation included one pass with a disk harrow followed by pre-planting desiccation with the herbicide glyphosate, applied with a backpack sprayer. Weed control within the plots was carried out manually by hoeing.

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Sowing was carried out manually, with 0.45 m spacing between rows and three seeds per meter, targeting a plant population of 66,000 plants ha^{-1}. The maize hybrid used was Pioneer X40P583VYHR Leptera (inbred line), which is glyphosate-tolerant and resistant to fall armyworm, with seeds industrially treated with insecticides (Demarcor, Poncho), fungicides (Derosal Plus, Maxim XL) and grain protectants (K-Obiol 25 EC, Actellic 500 EC). All crop management practices followed technical recommendations for maize, including supplemental irrigation using a center-pivot system.

The agronomic traits evaluated were plant height (PH), stem diameter (SD), and grain yield (GY). Plant height was measured in meters with a measuring tape, from the soil surface to the insertion point of the tassel. Stem diameter was measured in millimeters with a caliper at the middle of the second internode above the plant base. These two variables were recorded at tasseling (VT stage) (Ritchie et al., 1993). At physiological maturity (R6 stage), the ears from the useful area of each plot were harvested, shelled, and weighed. Grain moisture was then determined and adjusted to 14% to calculate GY, expressed in kg ha^{-1}.

The data obtained were first organized and subjected to analysis of variance (ANOVA) to verify whether there were statistical differences among the treatments. When significance was detected by the F-test, the means were compared using Tukey’s test at the 5% probability level. All statistical analyses were carried out using the SISVAR software.

3 RESULTS AND DISCUSSION

The analysis of variance, followed by Tukey’s test at the 5% probability level, showed that only plant height (Table 2) differed significantly among the phosphorus application methods, whereas stem diameter (mean ≈ 20.6 mm) and grain yield (mean ≈ 9,051.7 kg ha^{-1}) did not differ statistically among treatments.

The treatment with phosphorus applied in a double furrow resulted in the greatest mean plant height (1.83 m), differing statistically from the other treatments. The broadcast application (1.65 m) and the single-furrow application (1.60 m) showed intermediate results, with no statistical difference between them, but both were superior to the control, which had the lowest mean height (1.43 m) (Table 2). These results indicate that placing phosphorus in a double furrow favored vegetative development of maize, whereas the absence of fertilization markedly reduced plant stature, highlighting the role of the nutrient in the initial growth of the crop.

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Table 2

Mean plant height of maize (Pioneer X40P583VYHR Leptera line) as a function of phosphorus application methods. Várzea Grande, Mato Grosso, 2021

Treatment	Plant height (m)[1]
Double furrow	1.83 a
Broadcast	1.65 b
Single furrow	1.60 b
Control	1.43 c
CV (%)	4.00

[1]Means followed by different letters in the column differ from each other ($P \leq 0.05$), according to Tukey's test.

According to Sharifi et al. (2024), deep band application of N and P increases uptake efficiency, raising P concentration and accumulation in maize tissues. In this context, the superior performance observed for the double-furrow phosphorus application in the present study is likely due to greater nutrient availability in the soil volume explored by the roots, which optimizes P acquisition. Under field conditions, greater fertilizer placement depth has been associated with higher yield (Huang et al., 2024). From a physiological standpoint, there is evidence that deeper P placement improves root–shoot coordination and enhances photosynthetic performance (Chen et al., 2024).

For stem diameter (SD) and grain yield (GY), no significant differences were observed among the phosphorus (P) application methods. This behavior can be explained, at least in part, by the initial soil P content (20.01 mg dm^{-3} in the 0–20 cm layer), which is interpreted as adequate for the soil in the experimental area (Sousa & Lobato, 2004) and satisfactory for maize, thus reducing the likelihood of an additional response to the fertilizer.

Stem diameter (SD) is functionally related to carbohydrate storage in the stalk and to the availability of assimilates during grain filling, and there is wide genetic variability for this trait in grasses such as maize (Sekhon et al., 2016). In terms of stalk strength and architecture, studies show that structural traits explain stalk bending resistance and, consequently, lodging more than chemical composition alone (Robertson et al., 2022; Stubbs et al., 2022).

Among management and environmental factors, higher plant density tends to reduce stalk diameter and strength, increasing susceptibility to lodging (Feng et al., 2024; Shah et al., 2021). In addition, under dense planting conditions, stalk strength consistently declines across environments, even though morphological traits show relative stability (Kong et al., 2024). Furthermore, Zhang et al. (2023) emphasize that lodging resistance is closely associated with plant architecture and with how biomass is partitioned between stalk and ear, factors that can interact with plant density and affect crop stability.

Stem diameter is functionally associated with both assimilate storage and lodging resistance. Under water deficit, a reduction in shoot growth is observed and, in many cases, in stem diameter itself, which compromises stalk structure and the plant's supporting capacity (Yasin et al., 2024; Chen et al., 2023). Conversely, when soil P levels are adequate, differences between application methods (banded or broadcast) tend to be modest or inconsistent with respect to grain yield (Mallarino et al., 2021; Freiling et al., 2022). In addition, variability in crop response to phosphorus can be modulated by seasonal factors and soil biology; under field conditions, the effects of mycorrhizal inoculation and P fertilization were evident in only one of the evaluated years (de Souza Buzo et al., 2023).

Regarding grain yield (GY), it is worth emphasizing that, in maize cultivation, phosphorus fertilization is essential to achieve adequate productivity levels, because low phosphorus availability cannot be compensated for within the crop's relatively short cycle, especially under water deficit conditions, as demonstrated by Mahmood et al. (2025) in a trial with different field-capacity levels (100%, 80%, 60%, 40% and 20%). In this context, it should be highlighted that, in the present study, the experimental area was irrigated, ensuring adequate moisture throughout the cycle and avoiding water restrictions that could limit nutrient availability or uptake, as reported by Mahmood et al. (2025). Thus, the combination of an initially adequate P supply and the absence of water stress contributed to the uniformity of the yield results.

Moreover, grain yield (GY) depends on multiple interacting factors, such as climate, plant density, plant health, and the supply of other nutrients, and maize can internally remobilize phosphorus from vegetative tissues to the grains during filling, increasing nutrient use efficiency (Sun et al., 2023), which further reduces the likelihood of a response to fertilizer placement when the nutrient is not limiting. In this context, considering P cycling and availability in the soil–plant system, increases in P supply usually result in only marginal yield gains (Buczko et al., 2018; Shen et al., 2011).

It is worth highlighting that differences in phosphorus use efficiency are closely linked to the genetic characteristics of maize hybrids, rather than only to the mode of fertilizer application, as shown by Ampong et al. (2025) when comparing hybrids released in different commercial eras.

4 CONCLUSION

The application of phosphorus using different fertilization methods did not result in significant effects on maize stem diameter or grain yield. However, there was a significant difference in plant height, with the double-furrow treatment showing superior performance compared with the others. These results indicate that, although the mode of phosphorus application did not directly affect yield, localized placement in a double furrow favored vegetative growth of the crop.

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