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CROP PRODUCTION

Effects of phosphate fertilization on growth and yield of irrigated sesame in semi-arid regions

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ABSTRACT. Exploring the effects of phosphorus on sesame development and yield in semi-arid environments is crucial for refining agronomic practices and enhancing crop productivity. This research evaluated the response of sesame cultivars to varying phosphorus levels under irrigation in a semi-arid setting. Conducted at the Experimental Farm of the Federal Rural University of the Semi-Arid, two experiments ran from August to November in 2021 and 2022. A randomized block design with subdivided plots and four replicates was employed. Treatments consisted of five phosphorus doses (0, 60, 120, 180, and 240 kg ha^{-1} of P_2O_5) applied to main plots, while four sesame cultivars (CNPA G2, CNPA G3, CNPA G4, and BRS Seda) were assigned to subplots. Variables such as plant height, stem diameter, leaf count, capsule count, above-ground dry matter, thousand-seed weight, and seed yield were assessed. Phosphorus application significantly enhanced plant growth, which correlated positively with seed yield. Optimal phosphorus doses for peak seed yield in the first harvest were 170, 184, 167, and 152 kg ha^{-1} of P_2O_5 for cultivars CNPA G2, CNPA G3, CNPA G4, and BRS Seda, respectively. The second harvest showed maximum yields at doses of 149, 137, 125, and 164 kg ha^{-1} of P_2O_5. Notably, the second harvest yielded better plant development. Response to phosphorus varied among cultivars, with CNPA G3 and CNPA G4 showing the highest growth and productivity.

Keywords: *Sesamum indicum* L.; phosphorus nutrition; semi-arid agriculture; sesame yield; agronomic performance.

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Introduction

Sesame (*Sesamum indicum* L.) is an oilseed extensively grown in Brazil's Northeast Semi-Arid region, where climatic conditions promote the production of high-quality seeds and robust plant growth (Arriel et al., 2009). These optimal conditions include an average relative humidity of 60% and a minimum annual sunlight exposure of 2,600 hours (Amorim Neto et al., 2001).

The economic significance of sesame is notable, not only for its seeds but also for the oil and other derived products (Ribeiro et al., 2018; Lima et al., 2020). Sesame seed exports from Brazil surged from US$ 3.7 million in 2018 to US$ 25.4 million in 2019, a remarkable 596% increase (Azevedo et al., 2023). Despite this potential, low domestic production levels have hindered Brazil's competitiveness in the global market, influenced by high labor costs, limited technological advancements, and environmental challenges such as soil salinization, water contamination, and nutrient imbalances due to agricultural inputs (Santos et al., 2018). Addressing these challenges through strategic resource management, particularly phosphorus (P), is crucial.

Brazil is the third-largest global consumer of phosphorus, an element vital for plant growth yet naturally scarce in tropical soils (Raniro & Santner, 2023; Roy et al., 2016). The excessive application of phosphorus in these regions often leads to accumulation with low bioavailability, necessitating continual additions to maintain productivity (Gatiboni et al., 2020). This emphasizes the need for research on phosphorus management, particularly in tropical conditions. Therefore, investigating phosphorus's impact on plant development and productivity for specific crops is crucial for developing agronomic recommendations and promoting sustainable nutrient use. Additionally, assessing the response of different cultivars to phosphorus fertilization helps identify those best suited for cultivation in semi-arid regions, thereby enhancing resource use efficiency and boosting sesame production.

Phosphorus plays a critical role in photosynthesis, respiration, energy storage and transfer, and is a key component of nucleic acids and enzymes (Plaxton & Tran, 2011). Deficiencies in phosphorus can severely impact plant growth, leading to stunted growth, reduced crop yields, diminished root development, and decreased plant vigor and seed production (Ciereszko et al., 2011; Niu et al., 2013; Liu, 2021; Wang et al., 2016; Blandino et al., 2022; Javaid et al., 2021; Zangani et al., 2021).

This study investigates the effects of phosphorus on sesame under semi-arid and irrigated conditions, aiming to develop precise agronomic guidelines that optimize phosphorus availability and utilization to maximize yield across different cultivars.

Material and methods

The experiments took place from August to November in 2021 (first crop) and 2022 (second crop) at the Experimental Farm of the Federal Rural University of the Semi-Arid (UFERSA) in Mossoró (05°03'32" S; 37°23'47" W, 80 m), Rio Grande do Norte State, Brazil. According to the Köppen climate classification, the region's climate is categorized as BSh, a hot semi-arid tropical climate with an average temperature of 27.4°C and irregular annual rainfall averaging 673.9 mm (Alvares et al., 2013). The soil is classified as Typic Dystrophic Red Argisol (Rêgo et al., 2016). Seasonal data on air temperature, relative humidity, solar radiation, and accumulated rainfall were collected from the Automatic Weather Station at the farm (Figure 1).

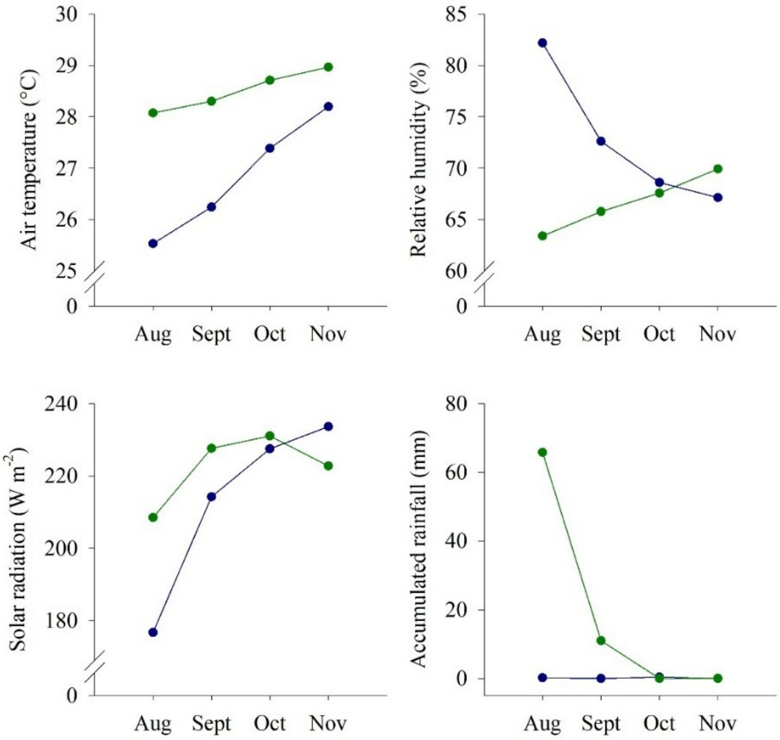

Figure 1. Air temperature (°C), relative humidity (%), solar radiation (W m^{-2}), and accumulated rainfall (mm) during the 2021 and 2022 agricultural seasons.

The study employed a randomized complete block design with four replications in a split-plot arrangement. Main plots were treated with five phosphorus doses (0, 60, 120, 180, and 240 kg ha^{-1} of P_2O_5), and subplots were assigned to four sesame cultivars (CNPA G2, CNPA G3, CNPA G4, and BRS Seda). Each plot contained four rows, spanning a total area of 7.2 m^2 (2.4 x 3.0 m), with row spacing of 0.60 m and plant spacing of 0.30 m. Two plants per hole resulted in 32 plants per experimental unit, focusing on the two central rows and excluding edge plants. The experiments covered a total area of 567.6 m^2 with a density of 111,111 plants per hectare. Soil preparation involved plowing and harrowing, and samples were collected from the top 20 cm for physical and chemical analysis prior to the experiments (Table 1).

Table 1. Physical and chemical soil properties (0 to 20 cm depth range) in sesame experimental areas during the 2021 and 2022 agricultural seasons.

pH	ECe	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	T	V
H_2O	dS m^{-1}	g kg^{-1}	mg dm^{-3}			cmol$_c$ dm^{-3}						%
6.70	0.06	3.52	2.9	66.7	8.4	0.90	0.80	0.0	0.83	1.91	2.74	70
7.00	0.05	2.20	5.1	58.7	8.4	1.30	1.10	0.0	0.16	2.59	2.75	94

pH: Hydrogen potential; ECe: Electrical conductivity of saturation extract; OM: Organic matter; P, Na^+, and K^+ extracted with Mehlich-1 at a soil: extractant ratio of 1: 10; Ca^{2+}, Mg^{2+}, and Al^{3+} extracted with 1 mol L^{-1} KCl at a soil: extractant ratio of 1: 10. H+Al potential acidity extracted with 0.5 mol L^{-1} calcium acetate at a soil: extractant ratio of 1: 15. SB: sum of bases; T: total cation exchange capacity (CEC); V: base saturation.

Sesame sowing was performed directly into planting holes at a depth of 2 cm, accompanied by basal fertilization based on specific sesame cultivation recommendations and soil fertility analysis (Gomes & Coutinho, 2008). The fertilizers used included urea, monoammonium phosphate (MAP) with 61% of P_2O_5 and 12% of N, and potassium chloride (KCl). Phosphorus was applied as MAP in doses of 0, 60, 120, 180, and 240 kg ha^{-1} of P_2O_5 during basal fertilization. Urea (46% N) was used as the nitrogen source, split into two topdressing applications, while potassium was applied as KCl (60% K_2O) during the second topdressing, with all applications performed via fertigation. Topdressings followed the recommendations for sesame cultivation. The first application was made after thinning, and the second was conducted 20 days after the first (Gomes & Coutinho, 2008).

Drip irrigation was implemented, with daily watering based on the crop's daily evapotranspiration using the crop coefficient (Kc) (Amaral & Silva, 2008). Thinning occurred ten days after emergence, leaving two plants per hole. Cultural practices and phytosanitary controls were maintained throughout the growth cycle. Sesame was harvested manually 100 days after sowing (DAS), once the plants displayed yellowing capsules and initial signs of opening. After cutting, the plants were bundled and dried for 15 days. The dried bundles were then threshed, and the seeds were cleaned with a seed cleaner blower (Eagri 2757 model) before being weighed on an analytical balance.

Phosphorus content in diagnostic leaves was assessed during the early flowering stage by collecting leaves from the upper third of the plants. The samples were thoroughly washed in running water, soaked in detergent water, rinsed again, and washed twice with distilled water. They were then dried in a circulating air oven at 65°C to a constant weight, ground, and stored in airtight containers. The dry samples underwent sulfuric digestion and phosphorus quantification through colorimetry (Association of Official Analytical Chemists [AOAC], 1995).

Plant height was measured from the soil surface to the top of the main stem using a measuring tape, while stem diameter was measured four centimeters above the soil with a digital caliper. The number of leaves and capsules was counted on each plant. For the aboveground dry mass (AGDM), four plants from the useful area were collected and separated into stems, leaves, and capsules. These components were washed, dried at 65°C until a constant weight was achieved, and weighed on a digital scale. The AGDM was calculated by summing the dry weights of the leaves, stems, and capsules.

Thousand seed weight was calculated by isolating subsamples of 100 seeds from each useful area and weighing them on a precision scale. Seed yield was measured by weighing all seeds from the plants in the useful area on a digital scale, adjusting for moisture content to a standard of 6% (Grilo Júnior & Azevedo, 2013).

Data analysis included an analysis of variance (ANOVA) conducted with SISVAR software (Ferreira, 2011), treating each crop year separately. A joint analysis was performed as per the method of Ferreira (2000). Significant differences in qualitative treatment means triggered the use of the Tukey test at a 5% significance level. For quantitative variables, response curves were fitted using the SigmaPlot 12.5 software.

Results and discussion

A significant interaction between the studied factors influenced sesame plant height. Plants exhibited shorter heights during the first cultivation season compared to the second (Figure 2A and B). Additionally, across both seasons, an increase in plant height was noted for all doses of P_2O_5 applied, compared to the control group without phosphate fertilizer (0 kg ha^{-1} of P_2O_5), which showed the lowest heights for all four evaluated cultivars.

The results indicate that the absence of phosphate fertilization significantly restricted sesame plant growth, underscoring the critical role of phosphorus in plant development. Phosphorus is essential for forming nucleic acids, phosphorylated sugars, ATP, and phospholipids, impacting photosynthetic efficiency and energy metabolism (Reich et al., 2009; Bloomfield et al., 2014; Cunha et al., 2016). A deficiency in phosphorus leads to reduced photosynthetic activity and energy production, consequently stunting plant growth.

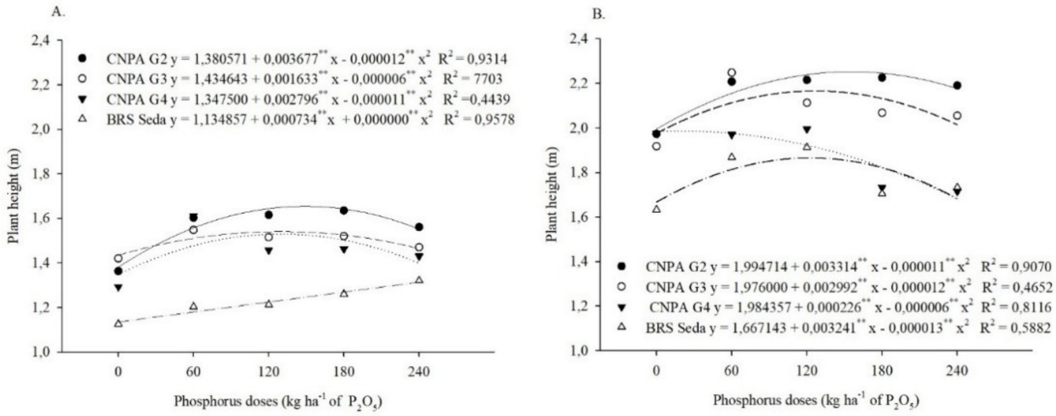

Figure 2. Plant height of all sesame cultivars fertilized with different phosphorus doses during the 2021 (A) and 2022 (B) agricultural seasons.

Among the cultivars, BRS Seda consistently showed the lowest height across all phosphorus doses and both seasons (Figure 2A and B). This finding is significant for cultivar selection, as shorter plants may provide advantages such as increased plant density for quicker soil coverage, easier management, and better adaptability to resource-limited environments (Emygdio & Teixeira, 2008; Almeida et al., 2000; Soratto et al., 2011). Additionally, shorter stature helps prevent lodging under adverse conditions like intense winds and heavy rain.

A significant interaction between phosphorus doses and cultivars was noted in the first season for stem diameter (Figure 3). While cultivars CNPA G3 and BRS Seda had smaller diameters across most doses, CNPA G4 displayed the smallest diameter at the highest dose (240 kg ha^{-1} of P_2O_5). The largest diameter (13.29 mm) was observed in CNPA G4 at a lower dose (60 kg ha^{-1} of P_2O_5) (Figure 3). The second season's data showed no significant differences in stem diameter due to the factors studied.

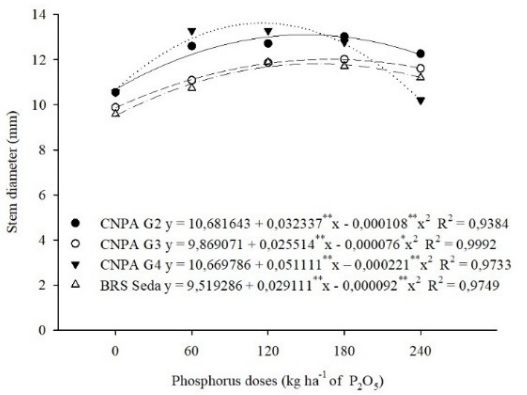

Figure 3. Stem diameter in sesame cultivars fertilized with phosphorus doses.

In sesame cultivation, stem diameter is a crucial agronomic trait, primarily due to its influence on plant lodging, which is affected by the soil and climate of the growing region. A larger stem diameter enhances resistance against lodging, providing better stability and support during growth (Vasquez et al., 2008).

Research on sesame stem diameter has been extensive. For instance, Grilo Júnior and Azevedo (2013) reported a maximum stem diameter of 25 mm for the BRS Seda cultivar in Ceará Mirim, Rio Grande do Norte State, Brazil. Similarly, Silva et al. (2016) found a maximum diameter of 10.26 mm for the same cultivar, indicating that growing conditions significantly influence stem development in sesame.

Regarding leaf count, the absence of phosphate fertilizer application consistently resulted in the fewest leaf number per plant. In contrast, during the second season, the highest phosphorus dose also resulted in fewer leaves (Figure 4). Seasonal comparisons revealed a higher leaf count in the second season, with 146 leaves per plant, compared to 64 in the first (Figure 4A and B). Among the phosphate treatments, cultivars CNPA G2 and G4 consistently had the highest leaf counts, while CNPA G3 and BRS Seda had the fewest, except at the 240 kg ha^{-1} dose in the second season, where CNPA G2 matched the leaf count of BRS Seda at 90 leaves per plant. Peak leaf counts reached 96 leaves for CNPA G4 at 60 kg ha^{-1} in the first season and 196 leaves for CNPA G2 at 120 kg ha^{-1} in the second season.

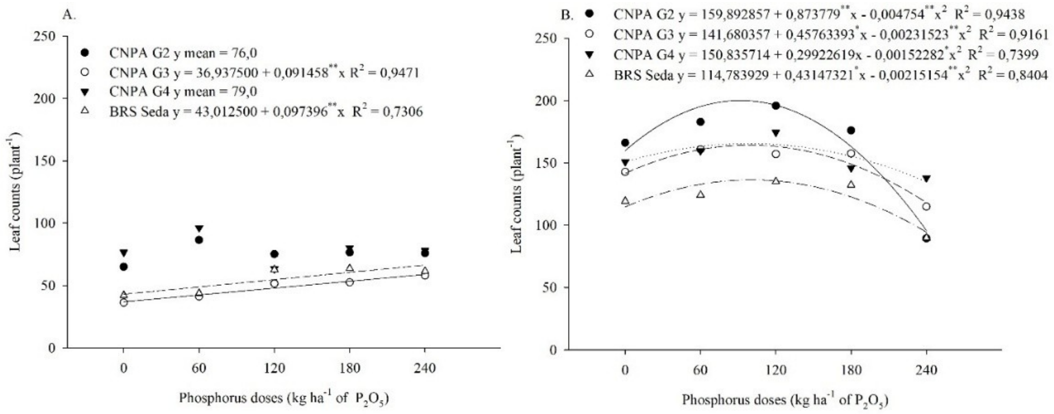

Figure 4. Leaf counts in sesame cultivars fertilized with varying phosphorus doses during the 2021 (A) and 2022 (B) agricultural seasons.

These results indicate that phosphate fertilizer application had a positive effect on leaf count, with cultivars CNPA G2 and G4 displaying the highest values. The second planting season recorded a notable increase in average leaf count, showing a 128% rise compared to the first season. This increase can be attributed to sesame's enhanced response to the more favorable soil and climatic conditions of the second season, including rainfall and milder temperatures, which facilitated greater leaf growth and expansion.

In the initial sesame crop, cultivar CNPA G4 produced the most capsules, with 103 capsules per plant at a P_2O_5 dosage of 60 kg ha^{-1}. Cultivars CNPA G2, CNPA G3, and BRS Seda reached their peak capsule counts at the 240 kg ha^{-1} of P_2O_5 dose. The average capsule count for this crop stood at 62 per plant (Figure 5A). The second crop saw an increase in capsule numbers across all doses, with an average of 126 capsules per plant, representing a 103% increase over the first crop. In both crops, cultivar CNPA G4 consistently showed the highest capsule counts at the 60 kg ha^{-1} of P_2O_5 dose (Figure 5B).

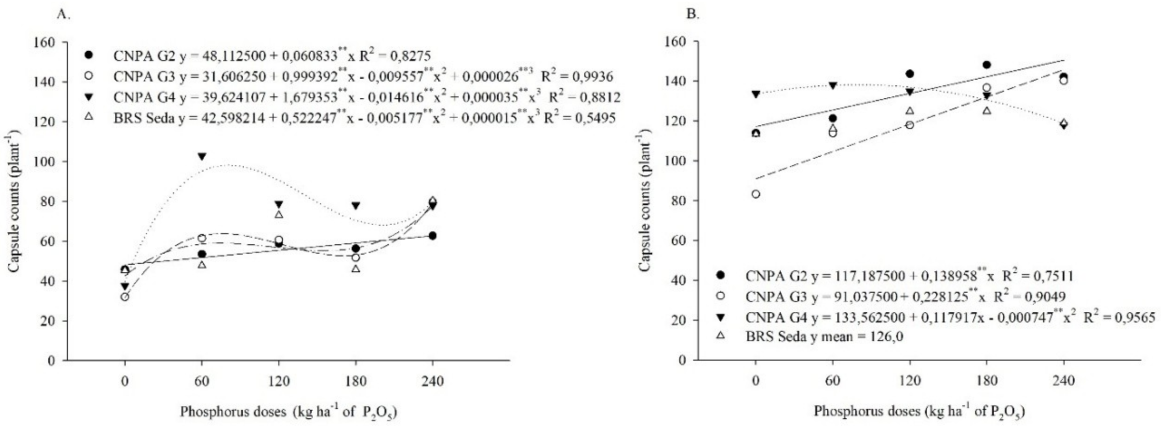

Figure 5. Capsule counts in sesame cultivars fertilized with varying phosphorus doses during the 2021 (A) and 2022 (B) agricultural seasons.

Mesquita et al. (2013), in a fertigation study with varying nitrogen doses, recorded an average of 143 capsules per plant. Bharathi et al. (2014), exploring the effects of different fertilizer types on sesame productivity, observed fruit counts ranging from 37 to 91 per plant, linking these figures to increased flower production, which directly contributes to fruit formation.

Grilo Júnior and Azevedo (2013) also identified a link between fruit count and overall crop yield, suggesting that more fruits per plant enhance sesame production.

In the initial crop season, the distribution of dry matter across different plant parts exhibited an ascending order, with the capsules accumulating the most at 27.12 g per plant, followed by the stem at 19.82 g, and the leaves at 4.63 g per plant (Figure 6A, B, and C). Shoot dry matter of sesame plants increased with higher phosphorus doses, peaking at 51.10 g per plant at a P_2O_5 dose of 240 kg ha^{-1} (Figure 6D). These findings demonstrate a clear increase in plant biomass with higher phosphorus applications.

When evaluating the variation among cultivars, BRS Seda showed the lowest production of MSPA, with an average of 34.62 g per plant, while cultivar CNPA G4 reached the maximum production of 53.67 g per plant (Table 2). Cultivars CNPA G2 and G3 did not differ from each other, with averages of 43.66 and 42.68 g per plant, respectively (Table 2). These results for MSPA in the first crop season reveal variation among cultivars, where cultivar CNPA G4 demonstrated greater efficiency in MSPA production compared to the other cultivars.

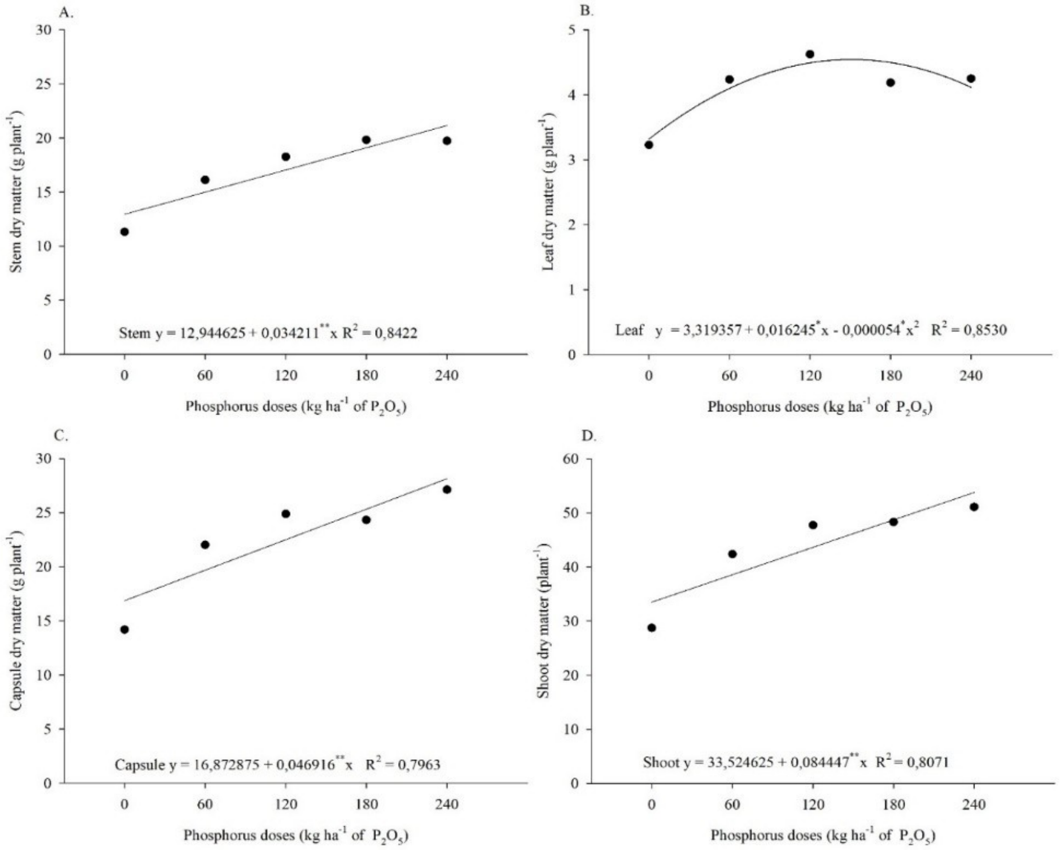

Figure 6. Stem (A), leaf (B), capsule (C), and shoot (D) dry matter in sesame cultivars fertilized with varying phosphorus doses during the first crop season.

Table 2. Shoot dry matter of sesame cultivars fertilized with varying phosphorus doses during the first crop season.

Shoot dry matter of sesame cultivars (g per plant)				
Cultivar	Stem	Leaf	Capsule	Shoot
CNPA G2	19.81a	3.89b	19.97bc	43.66b
CNPA G3	17.17a	2.51c	23.00b	42.68b
CNPA G4	19.66a	4.53ab	29.48[a]	53.67a
BRS Seda	11.57b	5.49a	17.56c	34.62c

Means followed by different lowercase letters within columns differ from each other by the Tukey's test at a 5% probability level.

In the second planting season, dry matter values showed a significant increase compared to the first season. A trend of increased production was observed across different plant parts up to a P_2O_5 dose of 120 kg ha^{-1}, beyond which a decrease occurred (Figure 7). The pattern of dry matter accumulation differed from the first season, with the lowest accumulation in the leaves and similar values recorded in the stem and capsules at 14.09, 46.38, and 48.31 g per plant, respectively. This distribution underscores the significance of managing phosphate fertilization, particularly the impact of specific doses up to 120 kg ha^{-1} of P_2O_5 on the growth dynamics of the above-ground parts of the sesame plant.

A study by Bonfim-Silva et al. (2022) on the impact of macronutrients on sesame's initial development highlighted the crucial role of phosphorus in crop growth. In treatments without phosphorus application, aboveground dry matter decreased by nearly 98% compared to treatments with complete fertilization. Phosphorus was the macronutrient that had the most significant negative effect on dry matter during the initial stages of development. Bhavana et al. (2022) and Bonfim-Silva et al. (2022) further noted that proper superphosphate application significantly improved plant height, leaf area index, and dry matter.

These findings explain the lower growth in plants without phosphorus application, which showed poor growth metrics. The reduced growth and lower dry mass accumulation in low-phosphorus conditions can be attributed to limited leaf area and reduced photosynthetic activity.

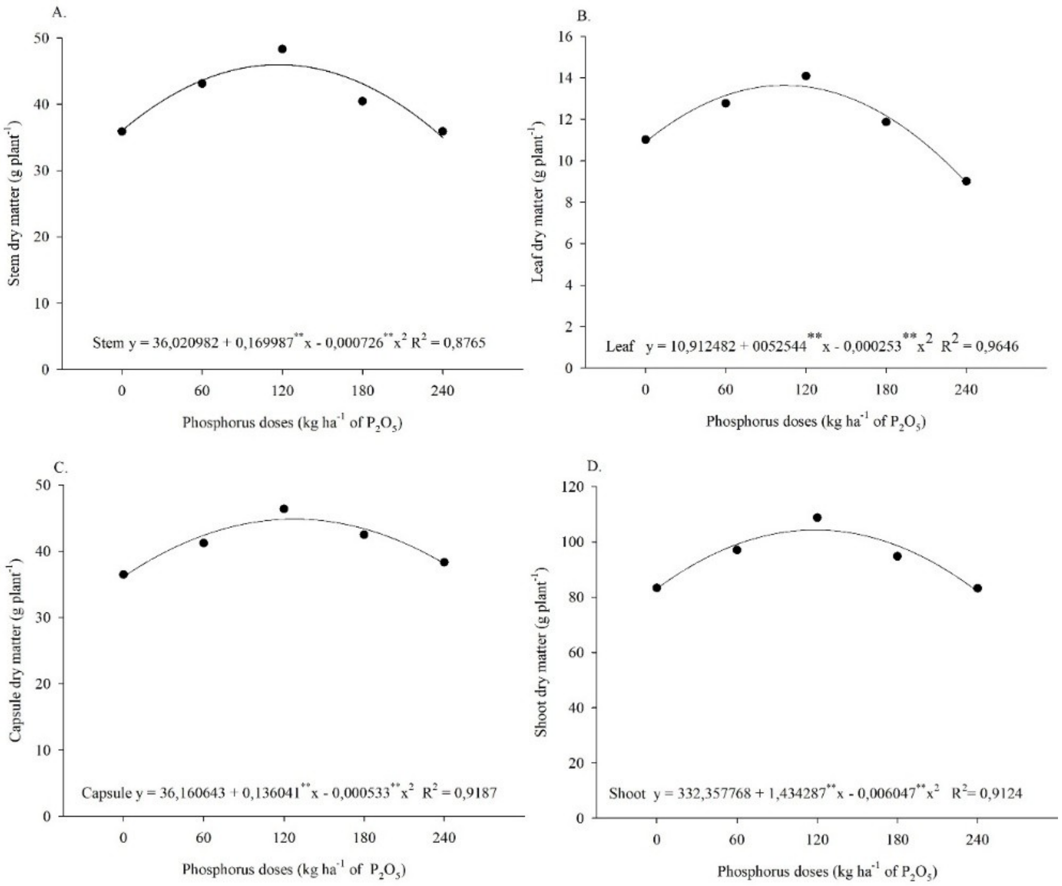

Figure 7. Stem (A), leaf (B), capsule (C), and shoot (D) dry matter in sesame cultivars fertilized with varying phosphorus doses during the second planting season.

Overall, the second planting season showed greater sesame plant growth compared to the first. This difference was due to more favorable environmental conditions in the second season. Arriel et al. (2009) reported that an average temperature of 27°C supports vegetative growth and fruit ripening in sesame, while temperature and precipitation are key factors influencing growth and development. Additionally, soil moisture benefits flowering and fruiting (Arriel et al., 2007), all these favorable conditions were present during the second season.

For the parameter thousand seed weight (TSW), both phosphorus doses and cultivars significantly affected TSW in both seasons. The highest TSW was observed at a phosphorus dose of 120 kg ha^{-1} of P_2O_5, reaching 3.59 g in the first season and 3.85 g in the second (Figure 8). In general, TSW was higher in the second season than in the first, regardless of the phosphorus dose (Figure 8).

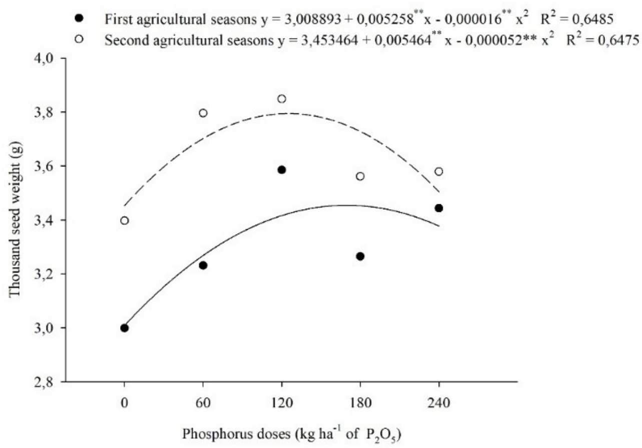

Figure 8. Thousand seed weight of sesame cultivars fertilized with different phosphorus doses during the 2021 (first) and 2022 (second) agricultural seasons.

The cultivar BRS Seda had the highest TSW values in both planting seasons, averaging 3.67 g in the first season and 4.04 g in the second. In contrast, cultivar CNPA G4 showed the lowest TSW values, with 3.05 g in the first season and 3.41 g in the second (Table 3).

Table 3. Thousand seed weight of sesame cultivars fertilized with varying phosphorus doses during the 2021 (first) and 2022 (second) agricultural seasons.

2021 (first) agricultural seasons	
Cultivar	TSW (g)
CNPA G2	3.17c
CNPA G3	3.35b
CNPA G4	3.05d
BRS Seda	3.67a
2022 (second) agricultural seasons	
Cultivar	TSW (g)
CNPA G2	3.45c
CNPA G3	3.64b
CNPA G4	3.41c
BRS Seda	4.04a

Means followed by different lowercase letters within columns differ significantly from each other by the Tukey's test at a 5% probability level.

The results showed that the 120 kg ha^{-1} of P_2O_5 dose consistently produced the highest thousand seed weights (TSW) in both planting seasons, with the highest values observed in the second season across all doses. This increase may be partly due to favorable rainfall during the second season, which likely enhanced dry matter accumulation in seeds and, consequently, increased TSW. Silva et al. (2014) reported similar findings, where the BRS Seda cultivar achieved a TSW of 3.92 g, higher than other cultivars evaluated.

These findings align with results from other crops, such as soybeans, sunflower, peanuts, and jatropha, which also showed a linear increase in TSW with phosphate fertilization (Freire et al., 2007; Silva et al., 2011; Sousa et al., 2012; Batistella Filho et al., 2013).

In the 2021 season, the highest yields were as follows: 1,558.40 kg ha^{-1} for CNPA G2 (at 170 kg ha^{-1} of P_2O_5), 1,774.43 kg ha^{-1} for CNPA G3 (at 184 kg ha^{-1} of P_2O_5), 1,634.60 kg ha^{-1} for CNPA G4 (at 167 kg ha^{-1} of P_2O_5), and 1,430.25 kg ha^{-1} for BRS Seda (at 152 kg ha^{-1} of P_2O_5) (Figure 9A). In the second season, yields increased to 2,555.38 kg ha^{-1} for CNPA G2 (at 149 kg ha^{-1} of P_2O_5), 2,544.14 kg ha^{-1} for CNPA G3 (at 137 kg ha^{-1} of P_2O_5), 2,486.37 kg ha^{-1} for CNPA G4 (at 125 kg ha^{-1} of P_2O_5), and 2,502.38 kg ha^{-1} for BRS Seda (at 164 kg ha^{-1} of P_2O_5) (Figure 9B). The average yield for the second season was 2,264 kg ha^{-1}, which was approximately 980 kg ha^{-1} (76%) higher compared to the first season's average yield of 1,284 kg ha^{-1}.

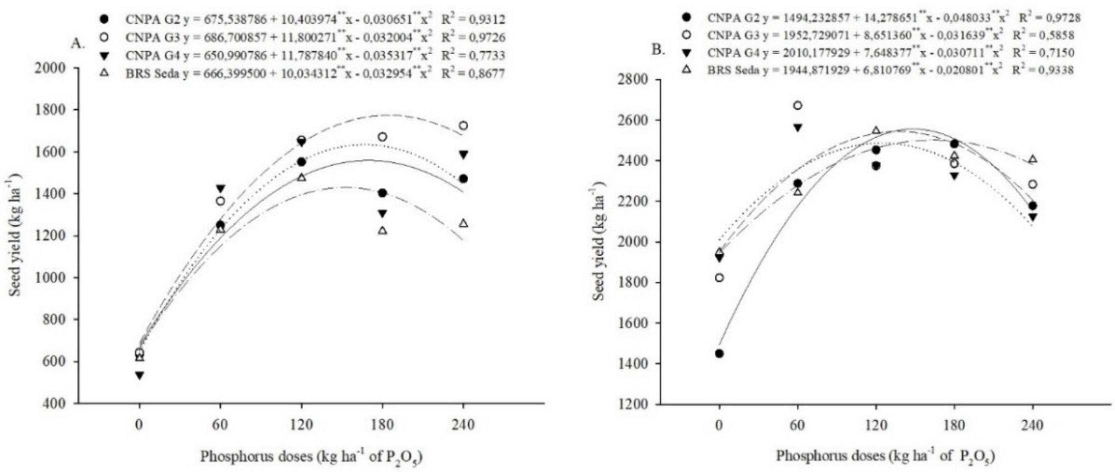

Figure 9. Seed yield of sesame cultivars fertilized with varying phosphorus doses during the 2021 (A) and 2022 (B) agricultural seasons.

Our findings align with those of Jahan et al. (2019) and Bhavana et al. (2022), who reported increased sesame seed productivity in response to phosphorus application, particularly at a dose of 60 kg ha^{-1} of P_2O_5. Moreover, recent studies have underscored the role of phosphorus in enhancing sesame seed yield (Priyadarshini et al., 2021; Jose et al., 2021; Mishra et al., 2022; Bunkar & Chaturvedi, 2022). Thus, our results corroborate existing literature, highlighting the importance of phosphorus fertilization for maximizing seed productivity. Proper phosphorus dosing can significantly enhance plant development and yield, offering valuable insights for farmers in their fertilization and crop management decisions.

Conclusion

The positive impact of phosphorus application on sesame plant development was demonstrated by increased plant height, stem diameter, leaf count, capsule number, dry matter production, and seed yield. In the first season, the optimal doses for maximum seed productivity were 170, 184, 167, and 152 kg ha^{-1} of P_2O_5 for cultivars CNPA G2, CNPA G3, CNPA G4, and BRS Seda, respectively. In the second season, the corresponding optimal doses were 149, 137, 125, and 164 kg ha^{-1} of P_2O_5 for the same cultivars. Notable variations in response to phosphate fertilization were observed among the cultivars.

Data availability

The data resulting from the study are available in Chapter 1 of the thesis, accessible through the repository of the Graduate Program in Crop Science at the Federal Rural University of the Semi Arid Region, via the following link: https://ppgfito.ufersa.edu.br/wp content/uploads/sites/222/2024/08/Tese_ANNA-KEZIA-SOARES-DE-OLIVEIRA-.pdf

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