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Scientific Article

Economic feasibility and cost analysis of phosphorus fertilization in irrigated sesame production

Viabilidade econômica e análise de custo da fertilização com fósforo na produção de gergelim irrigado

Anna K. S. de Oliveira[1], Elania F. da Silva[1], Ester dos S. Coêlho[1], Pablo H. de A. Oliveira[1], Antonio G. C. da Silva[1], Lindomar M. da Silveira[1], João E. da S. Ribeiro[2]*, Aurélio P. Barros Júnior[1]

[1]Department of Agronomic and Forestry Sciences, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil. [2]Center for Agricultural, Environmental and Biological Sciences, Universidade Federal do Recôncavo da Bahia, Cruz das Almas, BA, Brazil.

ABSTRACT – Sesame is an oilseed crop with growing global demand and high economic potential. Achieving sustainable profitability in production systems requires balanced fertilization management. In this context, phosphorus management plays a key role, as inappropriate application rates can compromise both yield potential and economic returns. Therefore, this study aimed to evaluate the production costs and economic feasibility of four sesame cultivars at different phosphorus fertilization doses under irrigated conditions. Field trials were conducted in two agricultural seasons (2021 and 2022) at the Federal Rural University of the Semi-Arid Region. A randomized block design with split 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. Production costs, gross and net income, return rate, and profitability index were evaluated. Phosphate fertilization significantly improved seed yield, increasing both gross and net income across cultivars. The economically optimal P_2O_5 doses closely aligned with those achieving maximum technical efficiency. In 2021, optimal doses were 149, 164, 148, and 133 kg ha^{-1} for CNPA G2, CNPA G3, CNPA G4, and BRS Seda, respectively; in 2022, they were 130, 108, 95, and 120 kg ha^{-1}. These results reinforce the need for cultivar-specific fertilization strategies to maximize the profitability of sesame production in irrigated systems.

Keywords: *Sesamum indicum* L. Phosphate fertilization. Economic analysis. Profitability. Technical and economic efficiency.

RESUMO - O gergelim é uma oleaginosa com crescente demanda global e alto potencial econômico. Alcançar lucratividade sustentável em sistemas de produção requer um manejo equilibrado da adubação. Nesse contexto, o manejo do fósforo desempenha papel fundamental, uma vez que doses inadequadas podem comprometer o potencial produtivo e os retornos econômicos. O objetivo deste estudo foi avaliar os custos de produção e a viabilidade econômica de quatro cultivares de gergelim sob diferentes doses de adubação fosfatada em condições irrigadas. Ensaios de campo foram conduzidos em duas safras (2021 e 2022) na Universidade Federal Rural do Semiárido, em delineamento de blocos casualizados em parcelas subdivididas com quatro repetições. As parcelas principais receberam cinco doses de P_2O_5 (0, 60, 120, 180 e 240 kg ha^{-1}) e as subparcelas as cultivares CNPA G2, CNPA G3, CNPA G4 e BRS Seda. As variáveis incluíram custos de produção, renda bruta e líquida, taxa de retorno e índice de lucratividade. A fertilização fosfatada melhorou a produtividade de sementes, aumentando tanto a renda bruta quanto a líquida entre as cultivares. As doses economicamente ótimas de P_2O_5 se alinharam estreitamente com aquelas que alcançaram a máxima eficiência técnica. Em 2021, as doses ótimas foram de 149, 164, 148 e 133 kg ha^{-1} para CNPA G2, CNPA G3, CNPA G4 e BRS Seda, respectivamente; em 2022, foram de 130, 108, 95 e 120 kg ha^{-1}. Os resultados reforçam a necessidade de estratégias de fertilização específicas para cultivares a fim de maximizar a lucratividade de gergelim em sistemas irrigados.

Palavras-chave: *Sesamum indicum* L. Adubação fosfatada. Análise econômica. Rentabilidade. Eficiência técnica e econômica.

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***Corresponding author**:
<j.everthon@hotmail.com>

INTRODUCTION

Sesame (*Sesamum indicum* L.) demonstrates high adaptability to the edaphoclimatic conditions of Brazil's semi-arid region, making it a promising alternative for agricultural diversification. Its seeds, rich in oil and of superior quality (CRUZ et al., 2019), are in increasing demand by the food and oil industries, which have grown at an annual rate of about 15% in processed consumer goods (MELO et al., 2019). In addition to profitability, sesame cultivation can enhance the livelihoods of rural workers by improving production systems when integrated with traditionally grown crops (MELO; VOLTOLINI, 2019).

Nutrient management is a critical factor influencing sesame yield, with phosphorus consistently highlighted as essential for growth and productivity (PRIYADARSHINI; UMESHA; MESHRAM, 2021; JOSE et al., 2021; MISHRA et al., 2022; BHAVANA et al., 2022). Since sesame seeds accumulate both oil and protein, biosynthetic processes require considerable energy (MELO; VOLTOLINI, 2019). Adequate phosphorus supply is, therefore, indispensable for sustaining metabolic efficiency and maximizing yield.

In Brazil, however, phosphorus fertilization faces structural challenges.

Domestic production of phosphate fertilizers is insufficient to meet demand, leading to heavy reliance on imports. This dependence exposes farmers to international price fluctuations, which directly affect production costs, particularly for small- and medium-scale producers (ARGENTA et al., 2023). Thus, decisions regarding phosphorus fertilization must balance agronomic benefits against economic limitations. Fertilizers, along with inputs such as labor, machinery, and crop protection, represent a major component of agricultural production costs (SPAGNUOLO et al., 2021).

Economic feasibility analysis is a valuable tool for supporting these decisions. Beyond estimating returns, such evaluations help identify strategies to optimize resource allocation and mitigate risks associated with market fluctuations, input prices, and climate variability (VIÉGAS; NOGUEIRA, 2019; OLIGINI et al., 2021). Previous research has emphasized the importance of incorporating production cost and feasibility assessments into agricultural planning to ensure profitability and sustainability (BEZERRA NETO et al., 2014; BAUMGRATZ et al., 2017; SILVA et al., 2021; OLIGINI et al., 2021; KRUGER; LOPES; GOTARDO, 2023).

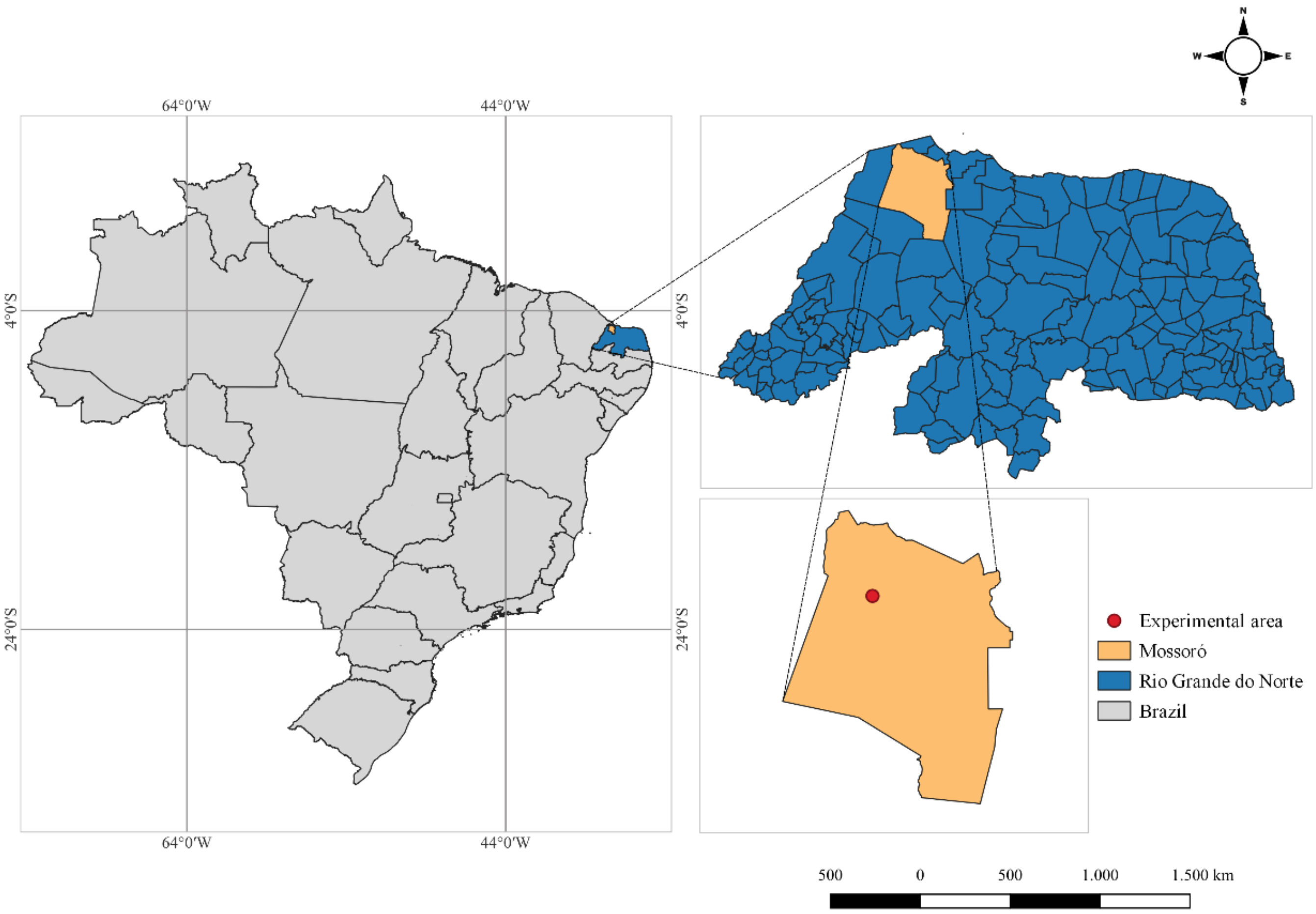
Despite these advances, previous studies have primarily focused on general agricultural planning or the economic analysis of other major crops, failing to address the specific economic dynamics of varying phosphorus fertilization rates on different sesame cultivars in semi-arid environments. This knowledge gap limits decision-making for farmers seeking to optimize production and profitability. Addressing this issue is particularly relevant for regions where input costs significantly influence the feasibility of adopting fertilization practices.

Therefore, the objective of this study was to evaluate the production costs and economic feasibility of sesame cultivars grown under different phosphorus fertilization levels in the semi-arid region of Brazil.

MATERIAL AND METHODS

The experiments were conducted at the Experimental Farm of the Federal Rural University of the Semi-Arid Region (UFERSA), Mossoró, Rio Grande do Norte, Brazil (5°03′32″ S, 37°23′47″ W), at an altitude of 80 m (Figure 1). The trials were carried out from August to November in 2021 (first agricultural season) and 2022 (second agricultural season).

Meteorological data on air temperature, relative humidity, solar radiation, and accumulated rainfall during the growing seasons were obtained from the Automatic Weather Station installed at the Experimental Farm (Figure 2).



Sources: IBGE (2022). Geographic coordinate system: SIRGAS 2000

Figure 1. Location of the experimental area in Mossoró, State of Rio Grande do Norte, Brazil.

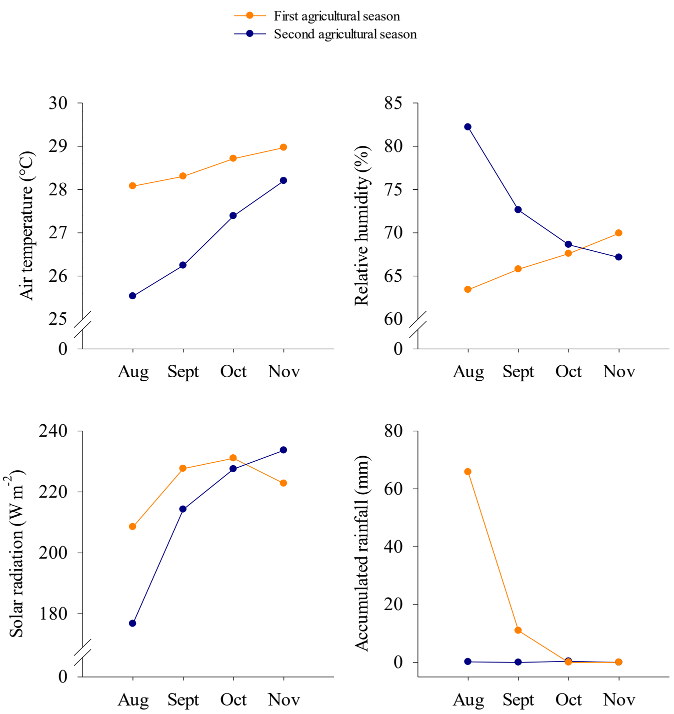


Figure 2. Air temperature (°C), relative humidity (%), solar radiation (W m^{-2}), and cumulative rainfall (mm) during the 2021 and 2022 growing seasons.

Soil was prepared by plowing and harrowing. Before establishing the experiments, samples were collected at a depth of 0-20 cm for chemical and textural analysis (Table 1).

A randomized complete block design with four replications was used in a split-plot arrangement. The main plots received five phosphorus doses (0, 60, 120, 180, 240 kg ha^{-1} of P_2O_5), while the subplots comprised four sesame cultivars (CNPA G2, CNPA G3, CNPA G4, and BRS Seda). Each experimental unit contained four plant rows, covering 7.2 m² (2.4 x 3.0 m), with 0.60 m between rows and 0.30 m between plants. Two plants were maintained per planting hole after thinning, resulting in 32 plants per plot for evaluation. Border plants were excluded, and only the two central rows were considered. The total experimental area was 567.6 m², with a density of 111,111 plants ha^{-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 was manually sown with ten seeds per hole at a depth of 2 cm. Basal fertilization was applied according to crop-specific recommendations and soil fertility analysis. Phosphorus was supplied as monoammonium phosphate (MAP; 61% P_2O_5, 12% N) at sowing. Nitrogen was applied as urea (46% N) in two split topdressings, and potassium was applied as potassium chloride (60% K_2O) during the second topdressing. All fertilizers were applied via fertigation using bypass tanks.

Drip irrigation was used, with laterals spaced 0.60 m apart and emitters every 0.30 m, each with a flow rate of 1.7 L h^{-1}. Irrigation was scheduled based on the crop coefficient (Kc) and daily evapotranspiration. Ten days after emergence, thinning was performed to maintain two plants per hole. Standard cultural practices and pest management were conducted throughout the crop cycle.

Sesame was manually harvested 100 days after sowing (DAS), when capsules turned yellow and began to open. Plants were cut, bundled according to subplot and treatment, and dried for 15 days. Bundles were threshed, and seeds were weighed. Seed yield was determined using a digital scale.

Production costs and economic indicators were estimated for one hectare of irrigated sesame under different phosphorus doses for the 2021 and 2022 seasons, following Conab (2010). Total production costs included fixed, variable, and operational expenses. Administrative costs (3%) and technical assistance fees (2%) were applied to total operational costs. A fixed amount of BRL 10.00 was included as the minimum annual Rural Land Tax (RLT), calculated using Equation 1.

Interest on financing was considered at 7.49% per year (Equation 2).

To calculate the depreciation of improvements and irrigation system installations for one hectare of sesame, the following components were considered: Polyethylene Drip Tapes: 16,667 meters, emitter spacing of 0.30 m, nominal diameter of 16 mm, purchase price of R$ 0.27 per meter, and a useful life of two years. PVC Pipes and Fittings: purchase price of R$ 1,423.25 and a useful life of 16 years. 3.0 hp Pump Set: purchase price of R$ 1,100.00 and a useful life of 16 years (Equation 3).

Periodic maintenance rates were calculated using Equation 4.

Considering that the producer's investment must be remunerated, ensuring a rate of return comparable to that obtained from alternative investments, the remuneration was calculated using a return rate of 6% (Equation 5).

Gross income (GI) was calculated as the product of seed yield and price (BRL 8.00 kg^{-1}), net income (NI) as GI minus total production costs (TC), return rate (RR) as GI/TC, and profitability index (PI) as NI/GI x 100. Maximum technical efficiency (MTE) doses of P_2O_5 were determined from the derivative of quadratic yield-to-dose equations. Economic optimum doses were estimated using the second derivative method with the product-to-input price ratio (RAIJ, 1991; NATALE et al., 1996) (Equation 6).

$$RLT\ (R\$\ ha^{-1}) = Value\ of\ Rural\ Land\ Tax\ (R\$)\ x\ \left(\frac{Cultivation\ cycle}{365}\right) \quad (1)$$

$$Interest\ (R\$\ ha^{-1}) = Cost\ value\ (R\$\ ha^{-1})\ x\ \left(\frac{Cultivation\ cycle}{365}\right) x\ 7.49\% \quad (2)$$

$$Depreciation\ (R\$\ ha^{-1}) = \left(\frac{Value\ of\ new\ asset\ (R\$\ ha^{-1})}{Useful\ life\ of\ the\ asset\ (days)}\right) x\ Cultivation\ cycle\ (days) \quad (3)$$

$$Maintenance\ (R\$\ ha^{-1}) = Value\ of\ new\ asset\ (R\$\ ha^{-1})\ x\ \left(\frac{Cultivation\ cycle\ (days)}{365}\right) x\ 1\% \quad (4)$$

$$Remuneration\ (R\$\ ha^{-1}) = Value\ of\ new\ asset\ (R\$\ ha^{-1})\ x\ \left(\frac{Cultivation\ cycle\ (days)}{365}\right) x\ 6\% \quad (5)$$

$$x' = \frac{b - Equivalence\ ratio}{2\ (-a)} \quad (6)$$

In this study, the prices used for phosphate fertilizer (MAP) and sesame seeds were BRL 10.40 kg^{-1} and BRL 8.00 kg^{-1}, respectively, for the first season, and BRL 14.16 kg^{-1} and BRL 8.00 kg^{-1} for the second season. Therefore, seed yield itself was used as the currency in calculating the economic dose of P_2O_5. The equivalence ratio between kilograms of input and kilograms of seeds was 1.3 in the first season and 1.8 in the second.

The production increase resulting from phosphorus fertilization was calculated as: seed yield at the economic dose minus seed yield at zero P_2O_5. The cost of P_2O_5 (kg ha^{-1} of seeds) was calculated using: P_2O_5 cost = (economic dose × price of P_2O_5)/ seed selling price. Profit from sesame production with phosphate fertilization was calculated as: production increase - fertilizer cost.

For statistical analysis, an analysis of variance (ANOVA) was conducted for each season individually, with cultivars and phosphorus doses as fixed effects and blocks as a random effect. The significance of the interaction between phosphorus doses and cultivars was evaluated. After verifying the homogeneity of variances across seasons, a combined analysis was performed. When significant differences were detected among qualitative treatment means, Tukey's test was applied at a 5% significance level. For the quantitative factor (P_2O_5 doses), polynomial regression was used to fit response curves. All statistical analyses were performed using SISVAR (FERREIRA, 2011) and SigmaPlot v. 12.5.

RESULTS AND DISCUSSION

Production Costs

Production costs were estimated for the first and second agricultural seasons. In the first, total costs were BRL 5,202.70, 6,161.69, 7,120.54, 8,079.39, and 9,038.24 for P_2O_5 doses of 0, 60, 120, 180, and 240 kg ha^{-1}, respectively. In the second agricultural season, total costs for the same doses were BRL 5,800.84, 7,133.59, 8,466.50, 9,799.30, and 11,132.09 (Table 2).

Table 2. Production costs of one hectare of irrigated sesame cultivated with different P doses during the 2021 and 2022 agricultural seasons.

Component	Unit	Quant.	1st Agricultural Season	Quant.	2nd Agricultural Season
Variable Costs					
Crop operating expenses					
1. Machinery rental	h	2	240.00	2	240.00
2. Labor					
Irrigation system assembly	daily	3	180.00	3	180.00
Sesame sowing	daily	5	300.00	5	300.00
Sesame thinning	daily	5	300.00	5	300.00
Fertigation	h	3	600.00	3	600.00
Manual weeding	daily	5	300.00	7	420.00
Spraying	daily	2	120.00	2	120.00
Harvesting (cutting and bundling)	daily	7	420.00	10	600.00
Threshing and sieving	daily	3	180.00	3	180.00
3. Seeds					
CNPA G2, CNPA G3, CNPA G4 and BRS Seda	kg	3	24.00	3	24.00
4. Fertilizers					
Urea (46% N)	kg	27.8	137.89	27.8	160.13
Potassium chloride (60% K_2O)	kg	66.67	373.35	66.67	501.36
MAP (61% P_2O_5 and 12% N)	kg	393.44	4,091.78	393.44	5,571.11
5. Pesticides					
Insecticide	L	1.2	197.40	1.35	221.40
6. Others					
Electricity for irrigation	kWh	527.21	189.80	505.53	192.10
Soil analysis	unit	1	58.00	1	58.00
Personal protective equipment	unit	1	80.00	1	80.00
Total crop operating expenses (R$)			7,712.21		9,668.10
Other expenses					
7. Administrative expenses (3% of crop operating costs)			231.37		290.04
8. Technical assistance (2% of crop operating costs)			154.24		193.36
9. Rural land tax - R$10.00 $year^{-1}$ (100 day cycle)			2.74		2.74
Total other expenses (R$)			388.35		486.14
Financial expenses					
10. Financing interest (7.49% $year^{-1}$)			158.41		198.58
Total financial expenses (R$)			158.41		198.58
Total variable costs (R$)			8,258.97		10,352.82
Fixed Costs					
11. Depreciation of improvements/structures			644.58		644.58
12. Maintenance of improvements/structures (1% $year^{-1}$)			19.24		19.24
Total fixed costs (R$)			663.82		663.82
Total (Variable + Fixed Costs)			8,922.79		11,016.64
Factor income					
13. Expected return on fixed capital (6% $year^{-1}$)			115.45		115.45
Total factor income (R$)			115.45		115.45
Total cost (R$)					
240 kg ha^{-1} P_2O_5			9,038.24		11,132.09
180 kg ha^{-1} P_2O_5			8,079.39		9,799.30
120 kg ha^{-1} P_2O_5			7,120.54		8,466.50
60 kg ha^{-1} P_2O_5			6,161.69		7,133.59
0 kg ha^{-1} P_2O_5			5,202.70		5,800.84

*The values refer to the P2O5 dose of 240 kg ha^{-1}.

The increase in production costs between agricultural seasons can be attributed to higher fertilizer prices. Additionally, rainfall during the second season increased weeding requirements. Taller sesame plants also demanded additional labor for harvest, further contributing to the higher costs.

In the first season, labor expenses accounted for approximately 46%, 39%, 34%, 30%, and 27% of total costs for P_2O_5 doses of 0, 60, 120, 180, and 240 kg ha^{-1}, respectively. In the second season, labor costs corresponded to 47%, 38%, 32%, 28%, and 24% of total costs for the same doses (Table 2). These results indicate that labor represented a significant portion of production costs in both seasons. Labor-intensive activities in sesame cultivation span the entire crop cycle, including irrigation system installation, sowing, thinning, weeding, pesticide application, and harvesting, which involves cutting, bundling, threshing, and sieving.

Expenditure on phosphate fertilizer increased with applied doses, representing 16.6% (60 kg ha^{-1}), 28.7% (120 kg ha^{-1}), 38% (180 kg ha^{-1}), and 45.3% (240 kg ha^{-1}) of total costs in the first season. In the second season, these figures were 19.5%, 32.9%, 42.6%, and 50%, respectively. Higher P_2O_5 doses had a greater impact on production costs, with the 240 kg ha^{-1} dose accounting for 45.3% and 50% of total costs in the first and second agricultural seasons (Table 2). The increasing cost of phosphate fertilizer with higher application rates highlights the need to balance expenses against expected yield gains when evaluating economic feasibility.

Santos (2021) reported similar findings in a study on the economic viability of organically colored cotton under different phosphorus doses in the Brazilian semi-arid region, where labor and fertilizer represented the largest components of production costs.

The variation in sesame production costs between agricultural seasons can also be attributed to fertilizer price adjustments, influenced by post-pandemic dynamics and the Russia-Ukraine conflict. Between January and June 2021, international fertilizer purchases increased by 60% compared to the pre-pandemic period, raising input costs, which accounted for 30-50% of total operational costs per hectare (PINHEIRO; KONDA; BONINI, 2022). Russia, responsible for 23.3% of Brazil's fertilizer imports in 2021, contributed to price volatility, with up to a 5.8% increase in major raw materials that are sources of nitrogen, phosphorus, and potassium in a single week (SILVA; SILVA; FRIGELG, 2023). Despite expectations of price stabilization in the second half of 2022 (JOAQUIM et al., 2023), shortages led to sharp increases, including 138% for urea, 103% for monoammonium phosphate, and 185% for potassium chloride (CNA, 2021).

Rising production costs reduce farmers' profit margins and can affect final consumer prices (JOAQUIM et al., 2023). Therefore, it is essential to compare production costs with yields to assess economic feasibility (MATARAN NETO et al., 2016). As highlighted by Peixoto et al. (2018), cost analysis is particularly challenging for farmers seeking to maximize profitability during periods of high input costs, such as those observed in this study.

Gross Income

In the first agricultural season, the maximum gross incomes for the cultivars were as follows: CNPA G2: BRL 12,467.12 ha^{-1} at 170 kg ha^{-1} of P_2O_5; CNPA G3: BRL 14,195.29 ha^{-1} at 184 kg ha^{-1}; CNPA G4: BRL 13,076.72 ha^{-1} at 167 kg ha^{-1}; and BRS Seda: BRL 11,442.01 ha^{-1} at 152 kg ha^{-1} (Figure 3A). In the second season, maximum gross incomes were: CNPA G2: BRL 20,443.10 ha^{-1} at 149 kg ha^{-1}; CNPA G3: BRL 20,353.01 ha^{-1} at 137 kg ha^{-1}; CNPA G4: BRL 19,890.99 ha^{-1} at 125 kg ha^{-1}; and BRS Seda: BRL 20,018.97 ha^{-1} at 164 kg ha^{-1} (Figure 3B).

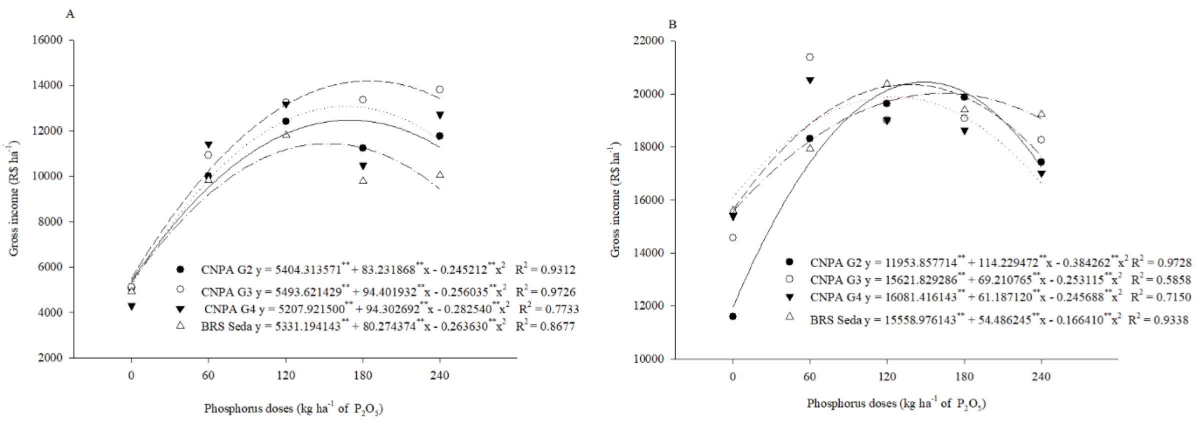


Figure 3. Gross income of sesame cultivars fertilized with phosphorus rates in the 2021 (A) and 2022 (B) agricultural seasons.

In both agricultural seasons, the lowest gross incomes occurred when no phosphate fertilizer was applied, highlighting the critical role of phosphorus in sesame yield. The initial increase in gross income is directly linked to the physiological role of P in plant metabolism. As a vital component of ATP, nucleic acids, and phospholipids, phosphorus is essential for energy transfer, photosynthesis, and root proliferation. In oilseed crops like sesame, adequate P supply is particularly crucial for lipid biosynthesis, which maximizes capsule formation and seed filling, thereby driving productivity and revenue. However, beyond a certain point, excessive fertilizer can cause negative plant responses, reducing gross income. Gross income values in the second season were higher than in the first, reflecting greater yields

(Table 2). CNPA G3 consistently showed the highest gross income in both seasons due to its superior yield compared to the other cultivars. Additionally, each cultivar exhibited an optimal phosphorus dose that maximized gross income in sesame production.

Net Income

In the first agricultural season, net income (NI) of the cultivars showed a quadratic response to phosphorus application, increasing up to a maximum point and then declining at the highest doses (Figure 4). CNPA G3 showed the largest gains in NI with increasing P doses. Maximum net incomes in the first season were: CNPA G2: BRL 4,663.20 ha^{-1} at 136 kg ha^{-1} P_2O_5; CNPA G3: BRL 6,295.68 ha^{-1} at 153 kg ha^{-1}; CNPA G4: BRL 5,432.90 ha^{-1} at 139 kg ha^{-1}; and BRS Seda: BRL 4,346.18 ha^{-1} at 118 kg ha^{-1} (Figure 4A).

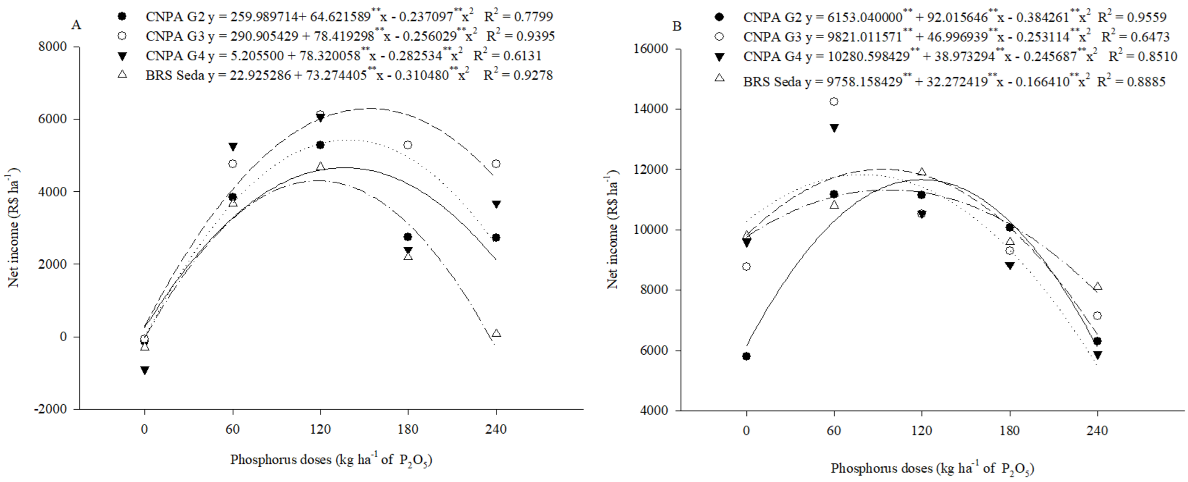


Figure 4. Net income of sesame cultivars fertilized with P_2O_5 rates in the 2021 (A) and 2022 (B) agricultural seasons.

In the second agricultural season, maximum net incomes were: CNPA G2: BRL 11,661.59 ha^{-1} at 120 kg ha^{-1} P_2O_5; CNPA G3: BRL 12,002.55 ha^{-1} at 93 kg ha^{-1}; CNPA G4: BRL 11,826.18 ha^{-1} at 79 kg ha^{-1}; and BRS Seda: BRL 11,322.83 ha^{-1} at 97 kg ha^{-1} (Figure 4B).

The average net income in the second agricultural season was BRL 9,643.80, representing a 50% increase over the first season (BRL 3,107.20). This increase can be attributed to more favorable growing conditions, which enhanced yield. CNPA G3 consistently achieved the highest net income in both seasons. This differential economic behavior among cultivars is tied to their distinct physiological traits and agronomic potentials, particularly regarding phosphorus use efficiency. Genotypes like CNPA G3 often exhibit a more vigorous root architecture and superior internal nutrient remobilization, allowing them to convert applied fertilizer into harvestable product and economic return more efficiently than the other evaluated cultivars (Table 2).

During the second agricultural season, CNPA G2 was the only cultivar without phosphate fertilizer whose production costs exceeded net income (Figure 4B). This indicates that, for this cultivar, the absence of phosphorus negatively affected yield, resulting in insufficient net income to cover costs. At the highest fertilizer doses (180 and 240 kg ha^{-1} P_2O_5), all cultivars experienced reduced net income below production costs. This suggests that excessive P_2O_5 increased fertilizer costs without producing proportional seed yield gains (Table 2), indicating that the highest doses may not be economically viable.

Return Rate

In the 2021 agricultural season (Figure 5A), the return rate (RR) was described by a quadratic regression model for all cultivars. Maximum return rates of 1.68, 1.88, 1.80, and 1.59 were achieved at 128, 139, 131, and 119 kg ha^{-1} P_2O_5 for CNPA G2, G3, G4, and BRS Seda, respectively. During this season, RR increased linearly with phosphorus application, followed by reductions at the highest doses (180 and 240 kg ha^{-1} P_2O_5). Among the cultivars, CNPA G3 exhibited the largest gains across the P doses evaluated.

In the 2022 agricultural season (Figure 5B), RR was described by a quadratic model for CNPA G2, with a maximum return rate of 2.43 at 91 kg ha^{-1} P_2O_5. For CNPA G3, CNPA G4, and BRS Seda, RR was described by decreasing linear models, indicating higher return rates at the lowest phosphorus doses.

In both agricultural seasons, the highest return rates were achieved by CNPA G3, reaching 1.88 in the first season and 3.00 in the second. In practical terms, an RR of 1.88 indicates that for every BRL 1.00 invested, the return was BRL 1.88, representing an additional gain of 88%. Similarly, an RR of 3.00 implies that for each BRL 1.00 invested, the return was BRL 3.00, corresponding to a 200% additional gain. These results highlight the superior capacity of CNPA G3 to provide returns on investment.

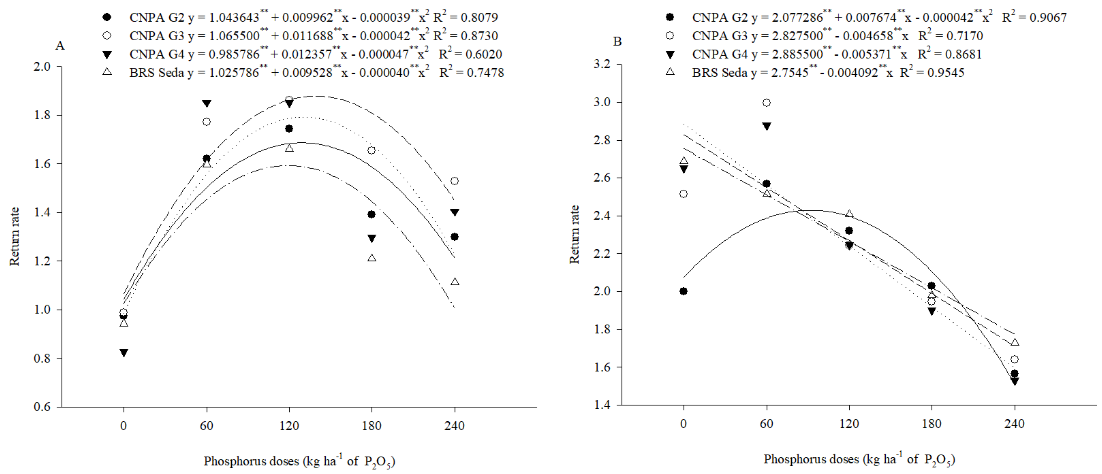


Figure 5. Return rate of sesame cultivars fertilized with P_2O_5 rates in the 2021 (A) and 2022 (B) agricultural seasons.

Profitability Index

In the first agricultural season, the profitability index (PI) was described by a quadratic regression model for all cultivars. CNPA G3 showed the largest gains in PI across the evaluated phosphorus doses. Maximum PIs for each cultivar were 40.20%, 50.11%, 47.56%, and 39.80% for CNPA G2, G3, G4, and BRS Seda, respectively (Figure 6A). The negative PI observed at 0 kg ha^{-1} P_2O_5 indicates that production costs exceeded revenue, resulting in a financial loss and highlighting the importance of input management to ensure profitability.

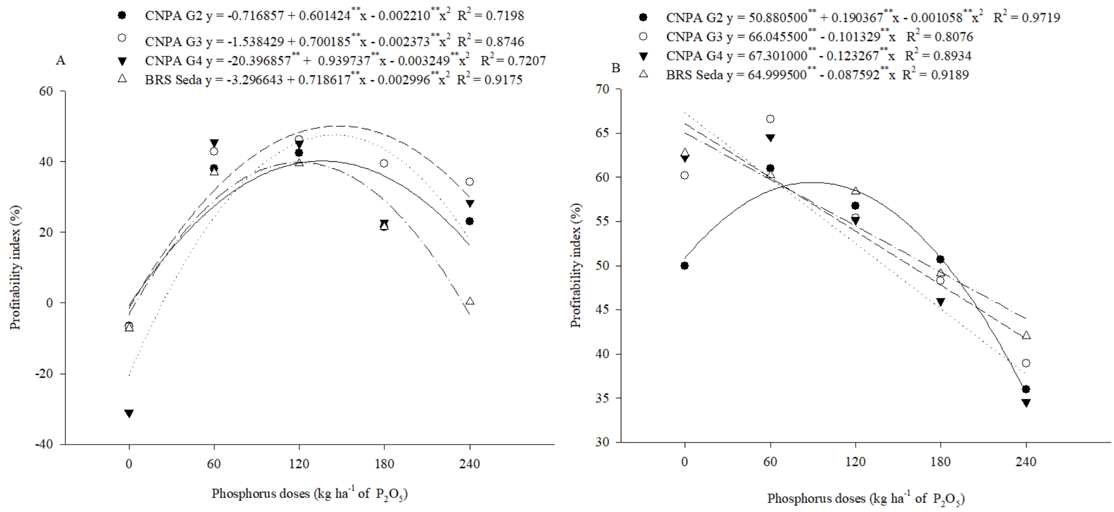


Figure 6. Profitability index of sesame cultivars fertilized with P_2O_5 rates in the 2021 (A) and 2022 (B) agricultural seasons.

In the second agricultural season, PI was described by a quadratic model for CNPA G2, reaching a maximum value of 59.44% at 90 kg ha^{-1} P_2O_5. For CNPA G3, CNPA G4, and BRS Seda, PI was described by decreasing linear models, indicating higher profitability at the lowest phosphorus doses. PI was positive across all conditions, indicating that revenue from sesame production was sufficient to cover production costs, resulting in profit (Figure 6B).

Previous studies have emphasized the role of fertilization in optimizing sesame production and economic viability. Shah et al. (2013) observed that sulfur fertilization significantly improved sesame yield, increasing financial returns. Santos et al. (2021), evaluating nitrogen fertilization in sesame in the Brazilian semi-arid region, observed significant increases in revenue, returns, and profit margins with higher nitrogen rates, specifically at 120 kg ha^{-1} N. These findings underscore the importance of appropriate fertilization in maximizing sesame cultivation profitability.

Economic Phosphorus Dose

The technically optimal phosphorus doses do not consider fertilizer cost or sesame market price. However, using the regression equations from Figure 3, the most economically efficient P doses for maximum seed yield were calculated. In the first season, for CNPA G2, the economic dose was 149 kg ha^{-1} P_2O_5, resulting in a production increase of 911 kg ha^{-1} seeds. The P cost was 193 kg ha^{-1} seeds, yielding a net gain of 718 kg ha^{-1} seeds (Table 3).

Table 3. Economic phosphorus rate, yield increase, fertilizer cost, profit, and production percentage relative to the technical rate for sesame fertilized with phosphorus doses in the 2021 and 2022 agricultural seasons.

Agricultural season	Cultivar	Economic doses	Yield increase	Phosphorus cost	Profit	Production[1]
		kg ha^{-1} (P_2O_5)	------------------------- kg seed ha^{-1} -------------------------			(%)
2021	CNPA G2	149	911	193	718	99.12
	CNPA G3	164	1,119	213	906	99.26
	CNPA G4	148	1,085	193	892	99.27
	BRS Seda	133	803	172	631	99.10
2022	CNPA G2	130	1,089	230	859	99.34
	CNPA G3	108	701	197	504	98.99
	CNPA G4	95	536	169	367	98.94
	BRS Seda	120	514	213	301	98.44

[1]Percentage of seed yield obtained with the most economical rate in relation to the maximum yield.

Applying the same methodology, economic P doses were determined for the other cultivars. In the first season, CNPA G3 had an optimal dose of 164 kg ha^{-1} P_2O_5, generating a 1,119 kg ha^{-1} increase in production, a P cost of 213 kg ha^{-1} seeds, and a profit of 906 kg ha^{-1} seeds. For CNPA G4, the dose was 148 kg ha^{-1} P_2O_5, with a 1,085 kg ha^{-1} production increase, 193 kg ha^{-1} P cost, and 892 kg ha^{-1} seeds profit. BRS Seda showed an optimal dose of 133 kg ha^{-1} P_2O_5, resulting in 803 kg ha^{-1} increased production, 172 kg ha^{-1} P cost, and 631 kg ha^{-1} seeds profit (Table 3).

In the second agricultural season, economic dose analysis revealed that CNPA G2 had an optimal dose of 130 kg ha^{-1} P_2O_5, producing an additional 1,089 kg ha^{-1} seeds. The associated P cost was 230 kg ha^{-1} seeds, yielding a net gain of 859 kg ha^{-1} seeds. CNPA G3 had an optimal dose of 108 kg ha^{-1} P_2O_5, with a 701 kg ha^{-1} production increase, 197 kg ha^{-1} P cost, and 504 kg ha^{-1} seeds profit. CNPA G4 dose was 95 kg ha^{-1} P_2O_5, generating 536 kg ha^{-1} more seeds, with a P cost of 169 kg ha^{-1} seeds and 367 kg ha^{-1} seeds profit. BRS Seda had an optimal dose of 120 kg ha^{-1} P_2O_5, yielding 514 kg ha^{-1} additional seeds, 213 kg ha^{-1} P cost, and 301 kg ha^{-1} seeds profit.

The importance of phosphate fertilization for sesame seed yield is evident from these results (Table 3). Yield increases ranged from 803 to 1,119 kg ha^{-1} seeds in the first season and 514 to 1,089 kg ha^{-1} seeds in the second season compared with the unfertilized treatments. On average, 192.75 kg ha^{-1} seeds were required to cover P fertilizer costs in the first season and 202.25 kg ha^{-1} seeds in the second season.

Yields obtained with the economic doses were close to the maximum yields (Table 4). In the first agricultural season, economic dose yields were 99% of the maximum for all cultivars, and in the second season, they ranged from 98% to 99%. Therefore, using economic doses allowed savings in phosphate fertilizer application without compromising seed yield. Overall, doses of 148 kg ha^{-1} P_2O_5 in the first agricultural season and 113 kg ha^{-1} P_2O_5 in the second agricultural season provided optimal economic efficiency.

Table 4. Estimated maximum technical and economic efficiency of phosphorus use and estimated seed yield in sesame cultivars in the 2021 and 2022 agricultural seasons.

Agricultural season	Cultivar	MTE	YS_{MTE}	MEE	YS_{MEE}	Yield
		kg ha^{-1} (P_2O_5)	kg ha^{-1} seeds	kg ha^{-1} (P_2O_5)	kg ha^{-1} seeds	(%)
2021	CNPA G2	170	1,558.40	149	1,544.62	99.12
	CNPA G3	184	1,774.43	164	1,761.23	99.26
	CNPA G4	167	1,634.60	148	1,622.64	99.27
	BRS Seda	152	1,430.25	133	1,417.43	99.10
Mean		168	1,599.42	148	1,586.48	99.19
2022	CNPA G2	149	2,555.38	130	2,538.51	99.34
	CNPA G3	137	2,544.14	108	2,518.53	98.99
	CNPA G4	125	2,486.37	95	2,460.00	98.94
	BRS Seda	164	2,502.38	120	2,463.44	98.44
Mean		144	2,522.07	113	2,495.12	98.93

MTE: Dose of maximum technical efficiency of phosphorus (kg ha^{-1} P_2O_5). YS_{MTE}: Simulated seed yield at the dose of maximum technical efficiency of phosphorus (kg ha^{-1} seeds). MEE: Dose of maximum economic efficiency of phosphorus (kg ha^{-1} P_2O_5). YS_{MEE}: Simulated seed yield at the dose of maximum economic efficiency of phosphorus (kg ha^{-1} seeds). Yield (%): Percentage of seed yield obtained with the most economical dose relative to the maximum yield.

CONCLUSION

Phosphate fertilization is a critical driver of economic viability in irrigated sesame production, significantly increasing gross and net revenues. Cultivar selection plays a pivotal role in this dynamic, with genotypes like CNPA G3 demonstrating superior economic efficiency and profitability. For farmers in the semi-arid region, it is highly recommended to adopt cultivar-specific fertilization strategies rather than uniform applications, as adjusting phosphorus rates to the economic optimum enables substantial fertilizer savings without compromising seed yield. However, producers must remain vigilant about economic risks, particularly the volatility of international fertilizer prices, which can significantly affect production costs and profit margins. Future research should focus on investigating long-term soil phosphorus dynamics and exploring alternative, cost-effective phosphorus sources further to enhance the sustainability and resilience of sesame production systems.

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