

Optimization of Seed and Oil Yield of Linseed under Semi-Arid Conditions through Balanced Nitrogen and Phosphorus Fertilization

İsmail DEMİR^{1*} 

Kırşehir Ahi Evran University, Faculty of Agriculture, Department of Field Crops, Kırşehir, Türkiye

*Corresponding author's email: ismail.demir@ahievran.edu.tr

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ABSTRACT

Nitrogen (N) and phosphorus (P) fertilization play a key role in improving the productivity of linseed under semi-arid conditions. This study evaluated the effects of three nitrogen rates (40, 80, and 120 kg N ha⁻¹) and five phosphorus rates (0, 20, 40, 60, and 80 kg P ha⁻¹) on the growth, seed yield, oil content, and oil yield of linseed during two growing seasons under rainfed conditions in Kırşehir, Türkiye. The experiment was conducted as a split-plot design with three replications. Data were analyzed using analysis of variance, mean comparisons, and second-order polynomial regression, and the responses were visualized using three-dimensional surface plots.

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Nitrogen and phosphorus significantly affected most measured traits, whereas their interaction varied among characteristics. Seed and oil yields increased with fertilizer application up to intermediate rates, with the highest values consistently obtained at 80 kg N ha⁻¹ and 60 kg P ha⁻¹. Oil content tended to decline at the highest nitrogen rate. Quadratic regression analysis indicated that balanced nutrient application was more effective than increasing nitrogen alone. Under the conditions of this study, the combination of 80 kg N ha⁻¹ and 60 kg P ha⁻¹ can be recommended to maximize seed and oil yield of linseed under semi-arid rainfed conditions.

1. INTRODUCTION

Linseed (*Linum usitatissimum* L.) is an important oilseed crop valued for its high-quality oil, seed quality, and adaptability to diverse agroecological conditions. Owing to its relatively low water requirement and tolerance to marginal soils, linseed has gained increasing attention as an alternative oil crop for rainfed and semi-arid regions. Its oil, which is rich in polyunsaturated fatty acids, is widely used in food, industrial, and bioenergy applications (Rahimi et al., 2011). In addition, linseed has numerous industrial applications and is considered a promising crop for sustainable agricultural production under water-limited environments (Diederichsen & Raney, 2006; Kaleri, 2024). Despite these advantages, linseed productivity under dryland conditions remains relatively low due to suboptimal nutrient management and environmental constraints (Singh et al., 2022).

Nitrogen (N) and phosphorus (P) are among the most important nutrients regulating linseed growth, development, and yield formation (Khakbazan et al., 2009). Nitrogen is essential for vegetative growth, canopy development, chlorophyll synthesis, and biomass accumulation (Fageria, 2014), whereas phosphorus plays a crucial role in root development, energy transfer, flowering, and seed formation (Lambers, 2022). Because these two nutrients act on largely complementary physiological processes, their combined availability often determines crop performance more strongly than either nutrient applied alone: adequate phosphorus can enhance root proliferation and nutrient uptake efficiency, thereby improving the plant's capacity to utilize applied nitrogen, while sufficient nitrogen supports the canopy growth needed to sustain phosphorus-driven reproductive development. In oilseed flax specifically, combined N and P application has been shown to enhance non-structural carbohydrate translocation to the seeds and to increase seed yield by 14.3-42.6% compared with either nutrient applied alone (Yan et al., 2018). Previous studies have demonstrated that appropriate N and P fertilization can significantly improve plant growth and seed yield under dryland conditions (Singh et al., 2022). However, phosphorus availability is often restricted in semi-arid soils because of fixation processes. Excessive nitrogen application, in turn, may reduce seed oil concentration, whereas insufficient phosphorus can limit vegetative growth and yield potential. Similar dose-response patterns have been reported for other oilseed crops under semi-arid environments, including mustard (Ozturk, 2021) and sunflower (Sefaoglu, 2021), where balanced nutrient management improved both yield and quality.

Although the individual effects of nitrogen and phosphorus on linseed have been extensively investigated, studies evaluating their interaction under rainfed semi-arid conditions remain limited, and the fertilizer combination associated with the highest predicted seed and oil yield under such conditions has not been clearly established. Most previous work has relied on single-factor trials or simple factorial mean comparisons rather than a quantitative modelling approach capable of describing the joint $N \times P$ response surface, so it remains unclear how these two nutrients should be combined to optimize productivity under water-limited conditions. Indeed, the combined effects of nitrogen and phosphorus on the growth, development, and yield formation of oilseed flax have often been overlooked, despite evidence that such combined application can enhance dry matter accumulation by 11.9-59.3% compared with unfertilized plants (Liu et al., 2020). Furthermore, seasonal variability in rainfall can substantially influence crop responses to fertilization, making it difficult to establish stable nutrient management recommendations for dryland production systems.

Therefore, this study aimed to evaluate the effects of different nitrogen and phosphorus levels and their interaction on growth characteristics, yield components, seed yield, oil content, and oil yield of linseed under rainfed conditions, and to identify, using response surface modelling, the fertilizer combination associated with the highest predicted seed and oil yield. It was hypothesized that balanced N and P fertilization would enhance seed and oil yield compared with single-nutrient application, that the $N \times P$ interaction would be adequately described by a quadratic response surface, and that crop responses would vary between growing seasons because of environmental variability.

Unlike previous studies that mainly examined the individual effects of nitrogen and phosphorus, the present study combines field experimentation with quadratic regression and three-dimensional response surface analysis to quantify and visualize nutrient interactions under rainfed semi-arid conditions. This approach provides additional insight into nutrient optimization and contributes to the development of practical fertilization recommendations for sustainable linseed production.

2. MATERIALS and METHODS

2.1. Experimental Site and Climatic Conditions

Field experiments were conducted during the 2023 and 2024 growing seasons at the Research and Application Farm of Kırşehir Ahi Evran University, Faculty of Agriculture (39.11° N, 34.10° E; altitude 1020 m), Türkiye. The region is characterized by a semi-arid continental climate. During the linseed growing period from March to July, mean monthly temperatures ranged from 6.6 to 24.2 °C in the experimental years. The mean temperature during this period was 16.6 °C in 2023 and 18.0 °C in 2024, compared with the long-term average of 16.3 °C. Total precipitation was 230.9 mm in 2023

and 169.0 mm in 2024, compared with the long-term average of 185.0 mm. Thus, precipitation was higher than the long-term average in 2023 but lower in 2024. Mean relative humidity was also lower than the long-term average in both experimental years (Table 1).

Table 1. Climate data of research area

Month	Temperature (°C)			Relative humidity (%)			Total precipitation (mm)		
	2023	2024	1990–2020	2023	2024	1990–2020	2023	2024	1990–2020
March	6.9	6.6	5.3	63.3	60.0	66.6	98.0	56.0	37.9
April	10.0	14.9	10.8	60.6	48.8	62.5	54.3	17.0	42.7
May	14.5	14.7	15.5	57.7	57.4	60.1	19.8	56.2	46.2
June	18.7	23.3	19.7	58.4	40.2	54.9	55.3	8.5	37.5
July	23.0	24.2	23.1	40.5	44.1	46.7	3.5	11.3	8.9
Mean /	16.6	18.0	16.3	52.4	48.4	56.2			
Total							230.9	169.0	185.0

2.2. Experimental Design and Crop Management

The experiment was arranged in a split-plot design with three replications. Nitrogen levels (40, 80, and 120 kg N ha⁻¹) were assigned to the main plots, whereas phosphorus levels (0, 20, 40, 60, and 80 kg P ha⁻¹) were allocated to the subplots. Each subplot measured 7.5 m² (1.5 m × 5.0 m) and consisted of six rows spaced 25 cm apart. The Turkish linseed cultivar 'Sarı Gelin', an early-maturing local variety widely grown by farmers in Central Anatolia and previously evaluated under the same Kırşehir ecological conditions, where it showed earlier emergence, flowering, and maturity than the Beyazgelin and Karakız varieties (Eseroğlu & Demir, 2022), was sown on 23 March 2023 and 21 March 2024 at a seed rate of 7 kg ha⁻¹. Nitrogen fertilizer (46% N, urea) was applied in two equal splits, with half applied at sowing and the remaining half top-dressed by hand into the inter-row spacing at the time of the final hand-hoeing, before flowering. Phosphorus fertilizer was applied as triple superphosphate (TSP) entirely at sowing. Both nitrogen and phosphorus rates were applied on an elemental basis. No additional fertilizers were applied, as the pre-sowing soil analysis indicated an already high potassium content (514.7–666.2 kg K ha⁻¹; Table 2). Agronomic research on nitrogen and phosphorus requirements is considerably more extensive for fibre flax than for oilseed linseed, for which dose-response information remains scarce; the nitrogen and phosphorus rates used here were therefore selected to span a graded series from deficient to potentially excessive supply.

Weed control was performed mechanically by hand hoeing twice, at 3 and 7 weeks after crop emergence. The experiment was conducted entirely under rainfed conditions, and no supplemental irrigation was applied during either growing season. The crop was harvested at physiological maturity on 20 July 2023 and 12 July 2024. Plant height, number of lateral branches, and number of capsules per plant were recorded from 20 randomly selected plants within the harvest area of each subplot, after excluding the border rows and end plants to avoid edge effects.

2.3. Soil Properties

Soil samples were collected from depths of 0–30 cm and 30–60 cm before fertilizer application and analysed for their physicochemical properties (Table 2). The experimental soil had a clay-loam texture and was slightly alkaline, calcareous, and non-saline. The soil was low in organic matter and nitrogen, contained adequate potassium, and had moderate available phosphorus levels.

Table 2. Soil characteristics of the research area

Soil parameter	0-30 cm depth	30-60 cm depth
Saturation (%)	55	55
pH	7.59	7.63
Soil EC (dS m ⁻¹)	0.52	0.56
CaCO ₃ %	27.9	28.39
Phosphor (P kg ha ⁻¹)	21.4	22.9
Organic Matter (%)	1.81	1.64
Potassium (K kg ha ⁻¹)	666.2	514.7
Total salt (%)	0.02	0.02

2.4. Statistical Analysis

The data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design using MSTAT-C statistical software (Eisensmith & Russell, 1989). Years, nitrogen levels, phosphorus levels, and their interactions were

considered fixed effects, whereas replications were treated as random effects. After verifying the homogeneity of error variances, a combined analysis across years was performed. Treatment means were separated using the Least Significant Difference (LSD) test at the 5% probability level ($P < 0.05$).

2.5. Quadratic Regression and Response Surface Analysis

To evaluate the combined effects of nitrogen (N) and phosphorus (P) fertilization and to describe their interaction mathematically, second-order polynomial regression models were fitted to the factorial $N \times P$ dataset. The quadratic model used was:

$$Y = \beta_0 + \beta_1 N + \beta_2 P + \beta_{12}(NP) + \beta_{11}N^2 + \beta_{22}P^2$$

where Y is the predicted response variable, β_0 is the intercept, β_1 and β_2 are the linear coefficients, β_{12} is the interaction coefficient, and β_{11} and β_{22} are the quadratic coefficients.

Model performance was evaluated using the coefficient of determination (R^2). Three-dimensional response surface plots were generated to visualize the interaction between nitrogen and phosphorus levels and to identify fertilization rates associated with the highest predicted responses. Regression analyses and graphical visualizations were performed using Python (v3.12) with the NumPy, Pandas, and Matplotlib libraries.

3. RESULTS and DISCUSSION

3.1. Plant height

Plant height was significantly affected by year (Y), nitrogen (N), phosphorus (P), and all interaction effects ($P < 0.05$ or $P < 0.01$), indicating that plant height was influenced by both nutrient management and seasonal environmental conditions (Table 3). Plant height was greater in 2023 than in 2024, reflecting the more favourable growing conditions during the first season. Nitrogen application significantly increased plant height in both years, with the highest values obtained at 80 and 120 kg N ha⁻¹, whereas phosphorus application increased plant height up to 60 kg P ha⁻¹, after which no further significant increase was observed (Table 4). Likewise, the significant $N \times P$ interaction demonstrated that the positive effect of phosphorus became more evident under adequate nitrogen supply (Figure 1).

Table 3. Mean squares from the combined ANOVA for year, nitrogen, phosphorus, and their interactions on agronomic and yield-related traits of linseed.

SV	Year (Y)	Nitrogen doses (N)	YxN	Phosphorus doses (P)	YxP	NxP	YxNxP	SE	CV (%)
PH	426.89**	1015.40**	25.19**	113.79**	7.14*	13.50**	9.27**	0.66	4.38
BN	32.448**	82.639**	3.398**	7.323**	0.961**	1.029**	0.177ns	0.18	10.85
CN	309.02**	749.16**	38.66**	70.30**	6.43**	14.43**	4.29**	0.55	9.13
SNC	5.427**	11.977**	1.524*	18.295**	0.799ns	0.654ns	0.446ns	0.13	9.17
TSW	9.06**	4.75**	1.23ns	4.24**	0.198ns	0.177ns	0.437*	0.08	6.73
SY	91794.27**	267942.56**	6311.89ns	192541.42**	3496.48ns	23521.47**	2529.26ns	1.48	5.48
OC	0.02ns	14.08**	0.01ns	7.46**	0.06ns	0.81ns	0.21ns	0.11	2.59
OY	13527.19**	34257.48**	976.44ns	37576.42**	625.86ns	3533.66**	474.61ns	0.62	6.27

** $p < 0.01$, * $p < 0.05$, ns: not significant, SV: Source of variation, PH: Plant height, BN: Number of branches per plant, CN: Number of capsules per plant, SNC: Number of seeds per capsule, TSW: Thousand seed weight, SY: Seed yield, OC: Oil Content, OY: Oil yield, SE: Standard Error, CV: Coefficient of Variation.

The response surface models adequately described the combined effects of nitrogen and phosphorus on plant height, explaining 95.7% and 86.7% of the total variation in 2023 and 2024, respectively (Figure 2). In both years, positive interaction coefficients indicated a synergistic response between nitrogen and phosphorus, although the effect of phosphorus was less pronounced during the drier second growing season.

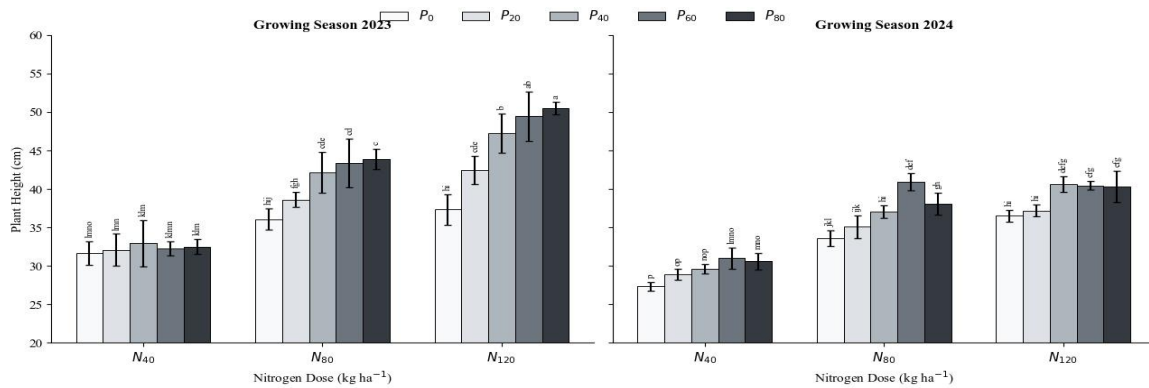


Figure 1. Interaction effects of nitrogen (N) and phosphorus (P) fertilization on plant height of linseed in 2023 and 2024. Bars represent mean values, and error bars indicate standard error (SE). Different letters above bars indicate significant differences among N × P combinations at P ≤ 0.05 according to the LSD test.

The increase in plant height following nitrogen fertilization is consistent with the essential role of nitrogen in chlorophyll formation, photosynthetic activity, and vegetative growth, resulting in greater biomass accumulation. However, the absence of a significant increase beyond 80 kg N ha⁻¹ suggests that additional nitrogen provided limited benefits under rainfed conditions. Phosphorus further promoted stem elongation by improving root development, energy transfer, and nutrient acquisition, thereby enhancing the efficiency of nitrogen utilization. Similar responses of flax to nitrogen and phosphorus fertilization have been reported by Rahimi et al. (2011), Grant et al. (2001), Hocking (2001), Dordas (2011), Kassaye et al. (2018), and Irshad et al. (2016) in the closely related crop linola, who likewise observed substantial improvements in vegetative growth under balanced nutrient management.

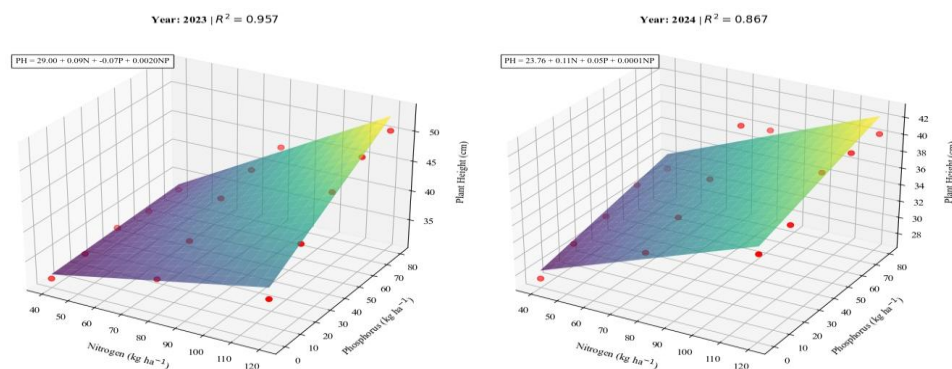


Figure 2. Three-dimensional (3D) response surface plots illustrating the interactive effects of nitrogen (N) and phosphorus (P) fertilization on the plant height of linseed during the 2023 and 2024 growing seasons.

Table 4. Analysis of variance results and the effect of different level of nitrogen and phosphorous applications on plant height, number of lateral branches, number of capsules per plant and number of seeds per capsule of linseed

	Doses kg ha ⁻¹	Plant height (cm)			Num. of lateral branches (branch plant ⁻¹)			Num. of capsules per plant (capsule plant ⁻¹)			Num. of seeds per capsule (seed capsule ⁻¹)		
		2023	2024	Average	2023	2024	Average	2023	2024	Average	2023	2024	Average
Nitrogen	N ₄₀	32.29 e	29.49 f	30.89 C	3.02d	2.49e	2.76C	6.11d	5.03d	5.57C	6.89c	6.86c	6.88C
	N ₈₀	40.83 b	36.94 d	38.88 B	6.74a	4.86c	5.80A	17.17a	12.25b	14.71A	8.37a	7.87b	8.12A
	N ₁₂₀	45.39a	39.02c	42.21 A	6.02b	4.83c	5.43B	16.19a	11.09 c	13.64B	8.15ab	7.22c	7.68B
	LSD _{0.05}		1.26	0.89		0.44	0.34		1.02	0.72		0.41	0.29
	P ₀	35.03cd	32.47e	33.75 D	4.09de	3.44f	3.77D	9.78de	7.30f	8.54D	6.55	6.08	6.31C
Phosphorus	P ₂₀	37.73b	33.70de	35.72 C	4.78c	3.76ef	4.27C	11.94bc	8.45e	10.20C	7.31	6.22	6.76C
	P ₄₀	40.77a	35.76 c	38.27 B	5.28b	4.29d	4.78B	12.87 b	10.20d	11.53B	7.73	7.66	7.69B
	P ₆₀	41.70a	37.47b	39.59 A	6.01a	4.45cd	5.23A	15.46a	10.55d	13.00A	8.76	8.07	8.41A
	P ₈₀	42.28a	36.33bc	39.31AB	6.14a	4.35cd	5.24A	15.75a	10.77cd	13.26A	8.69	8.56	8.62A
	LSD _{0.05}		1.55	1.09		0.48	0.34		0.98	0.69			0.46
Mean		39.50A	35.15B		5.26A	4.06B		13.16A	9.45B		7.81A	7.32B	

For each main effect, means in rows and columns followed by the same letter are not significant at P ≤ 0.05 according to the Least Significant Difference (LSD) test.

3.2. Number of branches per plant

The number of branches per plant was significantly affected by year (Y), nitrogen (N), phosphorus (P), and their two-way interactions ($P < 0.01$), whereas the three-way interaction ($Y \times N \times P$) was not significant (Table 3). Number of branches per plant was consistently higher in 2023 than in 2024, indicating that seasonal environmental conditions influenced vegetative development. Nitrogen application markedly increased the number of lateral branches, with the highest mean values obtained at 80 kg N ha⁻¹, while no further improvement was observed at 120 kg N ha⁻¹ (Table 4). Similarly, phosphorus fertilization significantly promoted branch formation, with maximum values recorded at 60 and 80 kg P ha⁻¹. The significant $N \times P$ interaction indicated that the stimulatory effect of phosphorus became more pronounced as nitrogen availability increased. Lateral branching is a major determinant of canopy development and contributes directly to the formation of reproductive structures in flax. The increase in number of branches per plant following nitrogen application is primarily associated with enhanced vegetative growth, increased photosynthetic capacity, and improved assimilate production. However, the limited response beyond 80 kg N ha⁻¹ suggests that additional nitrogen was insufficient to stimulate further branch initiation under rainfed conditions. Phosphorus supplementation further enhanced branching by promoting root growth, energy metabolism, and nutrient uptake, thereby supporting more vigorous vegetative development. The greater branching observed under balanced nitrogen and phosphorus nutrition demonstrates the complementary roles of these nutrients in regulating plant architecture.

These findings agree with previous studies reporting significant increases in branch number following balanced nitrogen and phosphorus fertilization in flax under semi-arid environments (Rahimi et al., 2011; Dordas, 2011; Kassaye et al., 2018). The lower branch number recorded in the second growing season was most likely associated with less favourable environmental conditions, which restricted vegetative growth despite similar nutrient responses.

3.3. Number of capsules per plant

The number of capsules per plant was significantly affected by year (Y), nitrogen (N), phosphorus (P), and all interaction effects ($P < 0.01$), demonstrating that capsule formation was strongly influenced by both nutrient management and seasonal environmental conditions (Table 3). Plants produced significantly more capsules in 2023 than in 2024 (Table 4). Nitrogen application markedly increased capsule number, with the highest values obtained at 80 kg N ha⁻¹, whereas no significant improvement was observed when the nitrogen rate was increased to 120 kg ha⁻¹. Likewise, phosphorus application significantly increased capsule number, reaching a maximum at 60 kg P ha⁻¹, after which the response plateaued. The significant $N \times P$ interaction further demonstrated that the positive effect of phosphorus became more pronounced under adequate nitrogen supply, with the highest capsule numbers recorded under the combined application of moderate nitrogen and higher phosphorus rates (Figure 3).

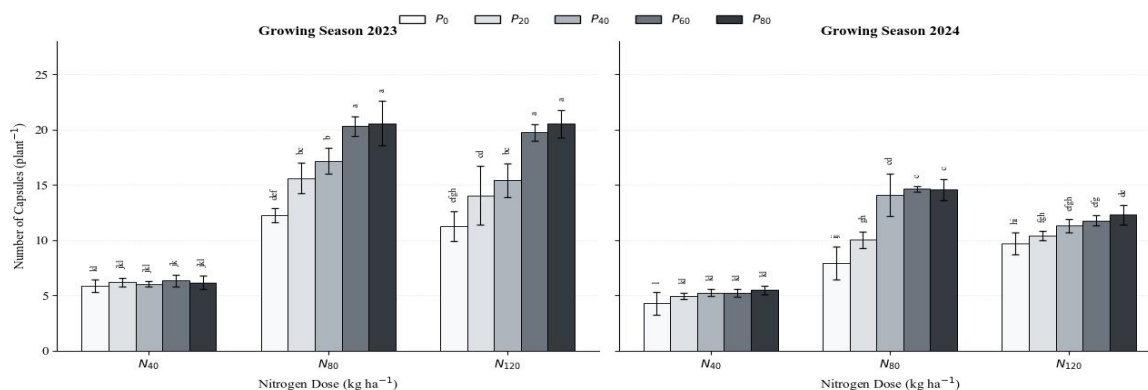


Figure 3. Interaction effects of nitrogen (N) and phosphorus (P) fertilization on number of capsules of linseed in 2023 and 2024. Bars represent mean values, and error bars indicate LSD_{0.05}. Different letters above bars indicate significant differences among $N \times P$ combinations at $P \leq 0.05$ according to the LSD test.

The three-dimensional response surface analysis supported the interaction between nitrogen and phosphorus and adequately described their combined effects on capsule formation (Figure 4). The regression models explained 73.0% and 60.4% of the total variation in 2023 and 2024, respectively, while the positive interaction coefficients obtained in both years confirmed the complementary roles of nitrogen and phosphorus in promoting reproductive development.

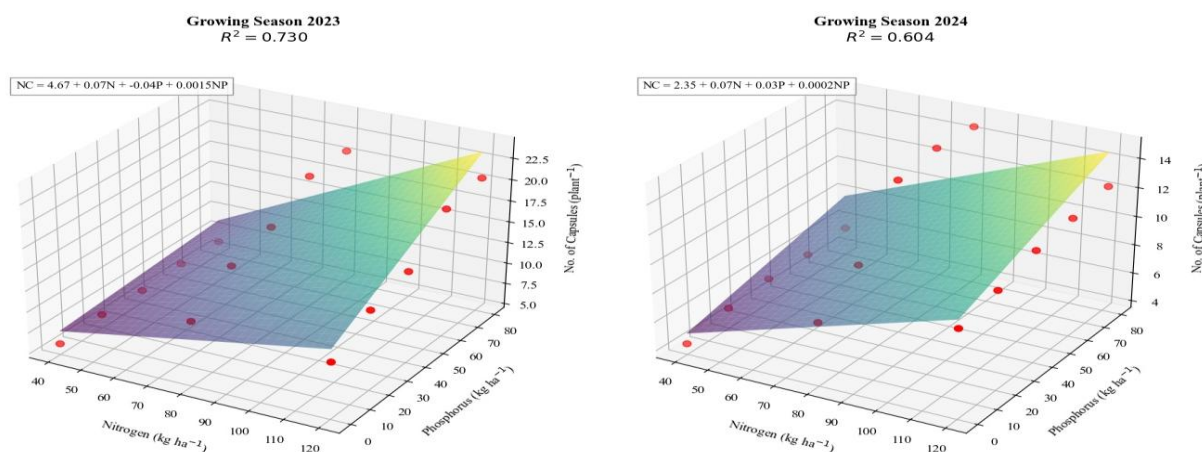


Figure 4. 3D response surface plots illustrating the interactive effects of nitrogen and phosphorus fertilization on the capsule number per plant of linseed across two growing seasons.

Capsule number is one of the most important yield components in flax because it largely determines the potential seed yield per plant. The increase in capsule number following nitrogen application reflects enhanced vegetative growth and greater assimilate availability for reproductive development. However, the absence of further improvement beyond 80 kg N ha⁻¹ suggests that excessive nitrogen did not provide additional benefits under rainfed conditions. Phosphorus further promoted capsule formation through its essential roles in root development, energy transfer, and flower retention, thereby improving the conversion of vegetative growth into reproductive structures. The plateau observed above 60 kg P ha⁻¹ indicates that the crop phosphorus requirement was largely satisfied at this application level.

These findings are consistent with those of Grant et al. (2001), Rahimi et al. (2011), Dordas (2011), and Kassaye et al. (2018), who also reported that balanced nitrogen and phosphorus fertilization significantly enhances capsule formation in flax. The lower capsule numbers recorded in 2024 were likely associated with less favourable environmental conditions, which restricted reproductive development despite similar fertilizer response patterns.

3.4. Number of seeds per capsule

The number of seeds per capsule was significantly affected by year (Y), nitrogen (N), phosphorus (P), and the Y × N interaction, whereas the Y × P, N × P, and Y × N × P interactions were not significant (Table 3). Plants produced significantly more seeds per capsule in 2023 than in 2024 (Table 4). Nitrogen application significantly increased the number of seeds per capsule, with the highest values recorded at 80 kg N ha⁻¹, while increasing the nitrogen rate to 120 kg ha⁻¹ did not result in a further significant improvement. Similarly, phosphorus fertilization increased the number of seeds per capsule, with the highest values generally obtained at 60 and 80 kg P ha⁻¹ (Table 4). The absence of a significant N × P interaction indicates that nitrogen and phosphorus affected this trait largely independently. Compared with capsule number, seed number per capsule remained relatively stable across fertilizer treatments, suggesting that nutrient management had a greater influence on the formation of reproductive structures than on the number of seeds developed within each capsule. Nitrogen supports seed development by enhancing photosynthesis and assimilate production during the reproductive stage, whereas phosphorus contributes to energy transfer, nutrient translocation, and reproductive development. Nevertheless, the relatively small variation among fertilizer treatments indicates that seed number per capsule was less responsive to nutrient management than capsule number. Consequently, the increases in seed yield observed in the present study were mainly associated with greater capsule production rather than substantial changes in the number of seeds per capsule. Similar responses have been reported by Rahimi et al. (2011), Dordas (2011), and Kassaye et al. (2018), who also found that seed number per capsule was comparatively stable across different fertilizer regimes.

3.5. Thousand seed weight

Thousand-seed weight (TSW) was significantly affected by year (Y), nitrogen (N), phosphorus (P), and the Y × N × P interaction ($P < 0.05$ or $P < 0.01$), whereas the Y × N, Y × P, and N × P interactions were not significant (Table 3). Mean TSW was significantly greater in 2023 than in 2024 (Table 5). Nitrogen application significantly increased TSW, with the highest values recorded at 80 and 120 kg N ha⁻¹, although no significant difference was observed between these two nitrogen rates. Likewise, phosphorus fertilization increased TSW, reaching maximum values at 60 and 80 kg P ha⁻¹ (Table 5). Although the N × P interaction was not statistically significant, the interaction plot showed a consistent increase in TSW with increasing nitrogen and phosphorus rates, particularly under moderate phosphorus application (Figure 5).

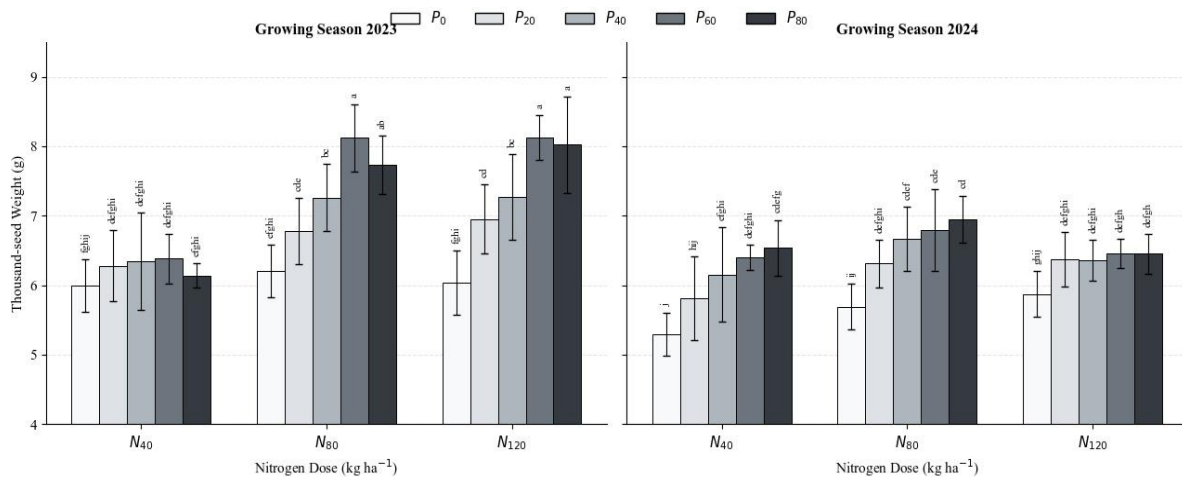


Figure 5. Interaction effects of nitrogen (N) and phosphorus (P) fertilization on the thousand-seed weight (TSW) of linseed during the 2023 and 2024 growing seasons. Error bars represent standard errors (SE). Different letters above the bars indicate significant differences according to the LSD test ($P < 0.05$).

The three-dimensional response surface analysis further illustrated the combined effects of nitrogen and phosphorus on TSW (Figure 6). The regression models explained 81.6% and 77.7% of the total variation in 2023 and 2024, respectively, indicating a satisfactory fit between the observed and predicted values. The regression equations also suggested that phosphorus had a greater influence on seed weight than nitrogen, particularly under the relatively drier conditions of the second growing season.

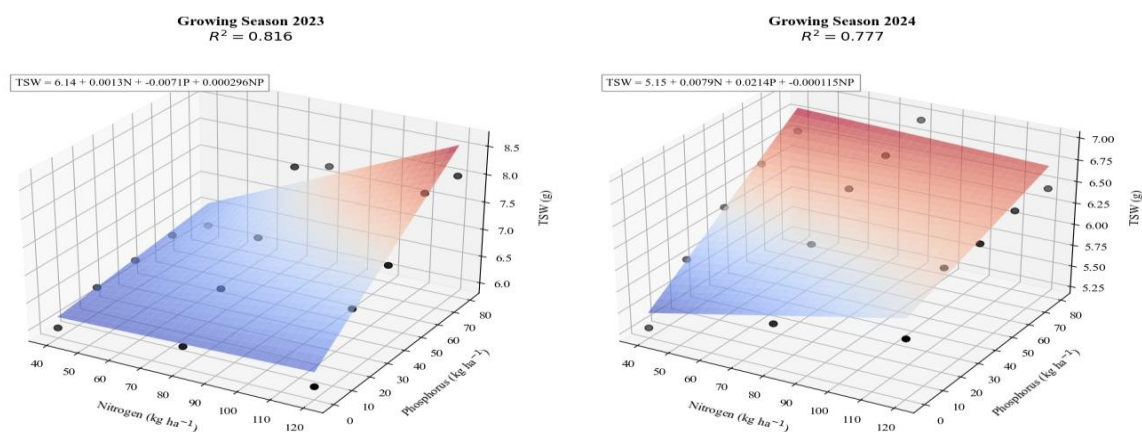


Figure 6. Three-dimensional (3D) response surface plots illustrating the interactive effects of nitrogen (N) and phosphorus (P) fertilization on the thousand-seed weight (TSW) of linseed during the 2023 and 2024 growing seasons.

Thousand-seed weight reflects the efficiency of seed filling during the reproductive stage and is influenced by both assimilate availability and environmental conditions. Nitrogen application improved seed filling by enhancing photosynthetic capacity and assimilate production, whereas phosphorus promoted dry matter accumulation through its roles in energy metabolism and assimilate translocation. However, the absence of further increases beyond 80 kg N ha⁻¹ indicates that additional nitrogen did not improve seed filling under rainfed conditions. Similarly, the plateau observed at phosphorus rates above 60 kg ha⁻¹ suggests that the crop phosphorus requirement for maximum seed weight was largely satisfied at this level.

These findings agree with previous studies reporting that balanced nitrogen and phosphorus fertilization improves thousand-seed weight in flax, whereas excessive nitrogen provides little additional benefit (Berti et al., 2009; Rahimi et al., 2011; Dordas, 2011; Kassaye et al., 2018). The lower TSW recorded in 2024 was most likely associated with less favourable environmental conditions during seed development, which limited assimilate accumulation despite similar responses to fertilizer application.

3.6. Seed yield

Seed yield was significantly affected by year (Y), nitrogen (N), phosphorus (P), and the N × P interaction ($P < 0.01$), whereas the Y × N, Y × P, and Y × N × P interactions were not significant (Table 3). Mean seed yield was significantly higher in 2023 than in 2024 (Table 5), indicating the influence of seasonal environmental conditions on crop productivity.

Nitrogen application markedly increased seed yield from 40 to 80 kg N ha⁻¹, whereas a further increase to 120 kg N ha⁻¹ did not result in additional yield gains. Similarly, phosphorus fertilization significantly improved seed yield, with the highest values recorded at 60 and 80 kg P ha⁻¹ (Table 5). The significant N × P interaction demonstrated that the response to nitrogen depended on phosphorus availability, with the maximum seed yield obtained from the combined application of 80 kg N ha⁻¹ and 60 kg P ha⁻¹ (Figure 7A).

Table 5. Analysis of variance results and the effect of different level of nitrogen and phosphorous applications on thousand seed weight (g), seed yield, oil rate and oil yield of linseed

	Doses kg ha ⁻¹	Thousand seed weight (g)			Seed yield (kg ha ⁻¹)			Oil rate (%)			Oil yield (kg ha ⁻¹)		
		2023	2024	Mean	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
Nitrogen	N ₄₀	6.23	6.04	6.13B	856.9	826.5	841.7B	39.17	39.23	39.20A	335.9	324.6	330.3C
	N ₈₀	7.22	6.48	6.85A	1052.4	972.9	1012.7A	38.96	38.98	38.97A	410.9	379.8	395.4A
	N ₁₂₀	7.28	6.30	6.79A	1037.9	956.2	997.1A	37.9	37.92	37.91B	394.0	363.0	378.5B
	LSD _{0.05}			0.31			24.46			0.43			12.46
Phosphorus	P ₀	6.08	5.62	5.84D	844.25	789.7	817.0D	37.76	37.76	37.76C	318.9	298.2	308.6D
	P ₂₀	6.67	6.16	6.41C	891.0	850.4	870.7C	38.25	38.47	38.36BC	340.6	326.8	333.7C
	P ₄₀	6.96	6.39	6.68BC	997.0	956.2	976.6B	38.83	38.82	38.83AB	387.0	371.4	379.2B
	P ₆₀	7.54	6.55	7.05A	1111.2	1005.3	1058.3A	39.40	39.31	39.36A	437.1	394.8	415.9A
	P ₈₀	7.30	6.65	6.97AB	1068.7	991.1	1029.9A	39.15	39.17	39.16A	417.9	387.9	402.9A
	LSD _{0.05}			0.30			34.90			0.67			15.46
	Mean	6.91A	6.27B		982.4A	918.6B		38.68	38.71		380.3A	355.8B	

For each main effect. Means in rows and columns followed by the same letter are not significant at $P \leq 0.05$ according to the Least Significant Difference (LSD) test.

The three-dimensional response surface analysis further confirmed the synergistic effects of nitrogen and phosphorus on seed yield (Figure 7B). The regression model explained 78.8% of the total variation in seed yield, indicating a good agreement between the observed and predicted values. The positive coefficient of the interaction term demonstrated that balanced nitrogen and phosphorus fertilization promoted seed production more effectively than increasing either nutrient alone. Seed yield is determined primarily by the number of reproductive sinks rather than by individual seed size. The substantial yield increase observed under balanced nitrogen and phosphorus fertilization was mainly associated with greater branching and capsule formation, which increased the number of productive sites per plant. Although thousand-seed weight also increased with fertilizer application, its contribution to overall yield improvement was comparatively smaller. The absence of additional yield gains beyond 80 kg N ha⁻¹ suggests that excessive nitrogen was unable to compensate for the limitations imposed by rainfed growing conditions and therefore did not improve crop productivity.

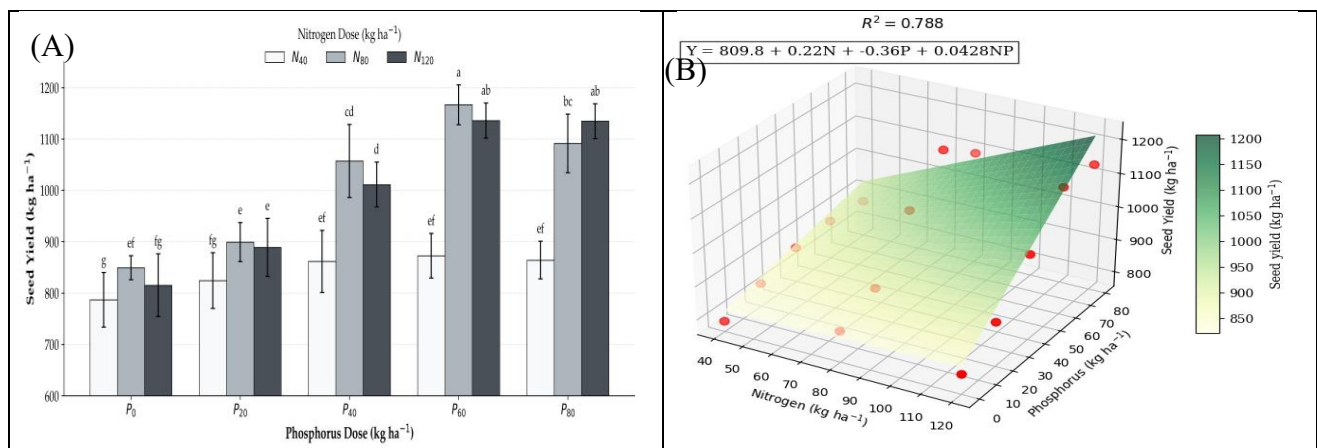


Figure 7. Interaction effects of nitrogen (N) and phosphorus (P) doses on seed yield (kg ha⁻¹); (A) Interaction of N and P levels with mean comparisons. Vertical lines above bars indicate standard error (±SE). Means followed by the same letter are not significantly different at $P < 0.05$ according to the LSD test. (B) 3D response surface plot of seed yield with the corresponding regression equation and coefficient of determination (R^2).

The positive response to phosphorus reflects its essential role in root development, energy metabolism, and assimilate translocation, which enhanced reproductive growth and seed filling. The superior performance of the 80 kg N ha⁻¹ × 60 kg P ha⁻¹ treatment indicates that balanced nutrient management was more effective than increasing the application rate of either nutrient individually.

These findings are consistent with those of Berti et al. (2009), Rahimi et al. (2011), Dordas (2011), Kassaye et al. (2018), and Patel et al. (2023), who reported that moderate nitrogen combined with adequate phosphorus maximized flax seed yield, whereas excessive nitrogen provided little or no additional benefit under water-limited environments.

3.7. Oil content and oil yield

Oil content was significantly affected by nitrogen (N) and phosphorus (P) fertilization ($P < 0.01$), whereas the effects of year (Y), $Y \times N$, $Y \times P$, $N \times P$, and $Y \times N \times P$ interactions were not significant (Table 3). The absence of a significant year effect indicates that oil concentration remained relatively stable across the two growing seasons. Nitrogen application reduced oil content, with the highest values recorded at 40 and 80 kg N ha⁻¹ and the lowest at 120 kg N ha⁻¹ (Table 5). In contrast, phosphorus fertilization significantly increased oil content, with the highest values obtained at 60 and 80 kg P ha⁻¹. The reduction in oil content at higher nitrogen rates is commonly attributed to changes in carbon partitioning during seed development. Increased nitrogen availability promotes protein synthesis, thereby reducing the proportion of assimilates allocated to lipid accumulation. Conversely, phosphorus plays an important role in energy transfer and metabolic processes involved in fatty acid synthesis, contributing to improved oil accumulation in developing seeds. The absence of significant interaction effects further indicates that nitrogen and phosphorus influenced oil concentration independently.

These findings agree with those of Berti et al. (2009), who reported that excessive nitrogen fertilization reduced flax oil concentration, whereas phosphorus application improved oil accumulation. Similar responses have also been reported by Kassaye et al. (2018), indicating that balanced phosphorus nutrition enhances oil biosynthesis without altering the overall response pattern to nitrogen fertilization.

3.8. Oil yield

Oil yield was significantly influenced by year (Y), nitrogen (N), phosphorus (P), and the $N \times P$ interaction ($P < 0.01$), whereas the $Y \times N$, $Y \times P$, and $Y \times N \times P$ interactions were not significant (Table 3). Mean oil yield was significantly higher in 2023 than in 2024 (Table 5), reflecting the more favorable environmental conditions during the first growing season. Nitrogen application markedly increased oil yield from 40 to 80 kg N ha⁻¹, whereas no further significant increase was obtained with 120 kg N ha⁻¹. Likewise, phosphorus application significantly improved oil yield, with the highest mean value recorded at 60 kg P ha⁻¹, although it did not differ significantly from that obtained at 80 kg P ha⁻¹ (Table 5). The significant $N \times P$ interaction indicated that oil yield depended on the combined application of both nutrients, with the highest values obtained under the 80 kg N ha⁻¹ $\times$ 60 kg P ha⁻¹ treatment (Figure 8A).

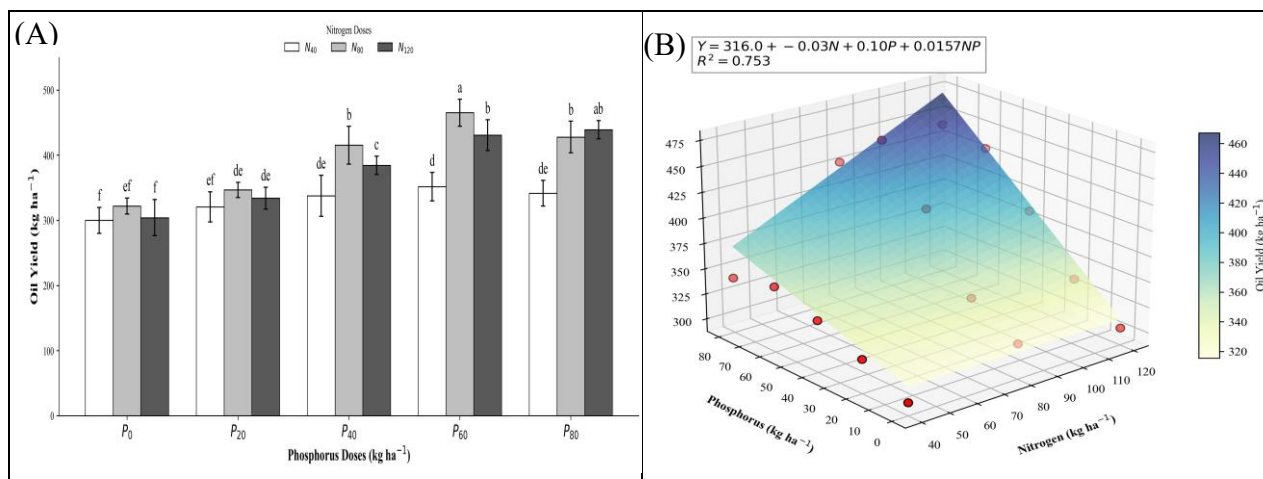


Figure 8. Interaction effects of nitrogen (N) and phosphorus (P) doses on oil yield (kg ha⁻¹); (A) Interaction of N and P levels with mean comparisons. Vertical lines above bars indicate standard error ($\pm$ SE). Means followed by the same letter are not significantly different at $P < 0.05$ according to the LSD test. (B) 3D response surface plot of oil yield with the corresponding regression equation and coefficient of determination (R^2).

The three-dimensional response surface analysis further illustrated the combined effects of nitrogen and phosphorus on oil yield (Figure 8B). The regression model explained a large proportion of the variation in oil yield, indicating a good agreement between the observed and predicted values. The response surface showed that balanced nitrogen and phosphorus fertilization enhanced oil production more effectively than increasing either nutrient individually. Oil yield is determined by the combined effects of seed yield and oil concentration. Although higher nitrogen rates slightly reduced oil content, the substantial increase in seed yield compensated for this reduction, resulting in greater oil yield at moderate nitrogen application. However, increasing the nitrogen rate from 80 to 120 kg ha⁻¹ did not provide additional benefits because the decline in oil concentration offset the limited improvement in seed production. Similarly, phosphorus application increased both seed yield and oil concentration, leading to maximum oil yield at 60 kg P ha⁻¹. These results

indicate that balanced fertilization is more important than excessive nutrient application for maximizing oil production under rainfed conditions.

The present findings are in agreement with those of Berti et al. (2009), Rahimi et al. (2011), Dordas (2011), Kassaye et al. (2018), and Patel et al. (2023), who reported that moderate nitrogen combined with adequate phosphorus maximizes oil yield in flax through simultaneous improvements in seed productivity and oil accumulation.

4. CONCLUSION

This two-year field study demonstrated that balanced nitrogen and phosphorus fertilization plays a crucial role in improving the growth, yield, and oil productivity of linseed under rainfed conditions. Nitrogen and phosphorus significantly enhanced most agronomic and yield-related traits, although excessive nitrogen application did not provide additional benefits. The combined application of 80 kg N ha⁻¹ and 60 kg P ha⁻¹ consistently produced the highest seed and oil yields by promoting capsule formation and improving seed development, while maintaining satisfactory oil content. Increasing nitrogen to 120 kg ha⁻¹ resulted in little or no further improvement in yield and was associated with a reduction in oil concentration.

The response surface analysis confirmed that balanced nutrient management was more effective than increasing the application rate of either nutrient alone. This finding is broadly consistent with other oilseed flax studies conducted under semi-arid conditions, where a balanced combination of nitrogen and phosphorus (e.g., 150 kg N ha⁻¹ with 75 kg P₂O₅ ha⁻¹) likewise outperformed high-nitrogen-alone treatments in maximizing grain yield (Liu et al., 2020). The results indicate that 80 kg N ha⁻¹ combined with 60 kg P ha⁻¹ represents the optimum fertilization strategy for linseed production under the semi-arid, rainfed conditions of Central Anatolia. This fertilization regime can improve productivity while avoiding unnecessary fertilizer inputs, thereby contributing to more efficient, economical, and environmentally sustainable flax production. Future studies should evaluate these nutrient rates under different soil types and climatic conditions and assess their long-term effects on soil fertility and nutrient use efficiency.

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