

Check for  
updates

## Research Article

# Can Sowing Date and Phosphorus Management Enhance Linseed Productivity in Pothwar Region?

Ali Hakim Chaudhary<sup>1</sup>, Ghulam Qadir<sup>1</sup>, Mukhtar Ahmad<sup>1</sup>, Muhammad Aqeel Aslam<sup>2</sup>, Rifat hayat<sup>3</sup>, Sahir Hmeed Khattak<sup>2</sup>, Ihsan Ullah<sup>2</sup>, Saida Komal<sup>4</sup>, Esha Yaseen<sup>1,2</sup>, Abdul Ahad Aziz<sup>1</sup>

<sup>1</sup>Department of Agronomy, PMAS Arid Agriculture University Rawalpindi, Pakistan.

<sup>2</sup>Oilseeds Research Program, Crop sciences institute, National Agricultural Research Centre, Park Road Islamabad 45500 Pakistan.

<sup>3</sup>Institute of Soil and Environmental Sciences, PMAS Arid Agriculture University Rawalpindi, Pakistan.

<sup>4</sup>Department of Agronomy, University of Poonch, Rawlakot, AJK, Pakistan.

## ABSTRACT

Linseed (*Linum usitatissimum* L.) is a nutraceutical-rich oilseed crop with strong adaptability but remains underexploited in low-input systems such as Pakistan's Pothwar Plateau. This study evaluated the effects of phosphorus fertilization and sowing dates on linseed phenology, yield traits, and oil quality over two seasons (2023–2025) at NARC, Islamabad. A split-plot design included four sowing dates (SD1–SD4) and six phosphorus levels (0–250 kg ha<sup>-1</sup> DAP). Early sowing (SD1) combined with 150 kg ha<sup>-1</sup> P significantly improved capsules per plant, seed yield, 1000-seed weight, oil content, and phenological development. Seed yield increased by up to 7.6% under SD1–P150 compared with the control, supported by enhanced oil biosynthesis and favorable soil moisture dynamics. Yield exhibited a positive linear association with soil moisture across replications. The results highlight the importance of optimizing phosphorus input and sowing windows to maximize linseed productivity and promote sustainable oilseed production in semi-arid rainfed areas.

**Keywords:** Linseed (*Linum usitatissimum* L.); Sowing dates; Phosphorus fertilization; Phenology; Seed yield; Oil content; Rainfed agriculture.



## Correspondence

Muhammad Aqeel Aslam  
aqeel7016@parc.gov.pk

## Article History

Received: August 19, 2025

Accepted: December 05, 2025

Published: December 30, 2025



**Copyright:** © 2024 by the authors.  
**Licensee:** Roots Press,  
Rawalpindi, Pakistan.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license:

<https://creativecommons.org/licenses/by/4.0>

## INTRODUCTION

Linseed (*Linum usitatissimum* L.) is a primitive cold-season oilseed crop that has expanded back to great international focus as a result of its outstanding nutritional content, industrial relevance, and suitability in sustainable agriculture (Paliwal et al., 2023; Aslam et al., 2017a). Linseed is a botanical member of the *Linaceae* family of plants, where both its seeds, which contain oil, and stalks, which are used as fibers, are cultivated (Katoch & Bhatia, 2021). According to the literature sources, its seeds have about 40-45 percent oil, 20-25 percent protein, and 28 percent dietary fiber (Katoch & Bhatia, 2021; Oso & Ashafa, 2021), and especially a high level of alpha-linolenic acid (ALA, C18:3n-3), an essential omega-3 fatty acid, promoting cardiovascular and neurological health (Pandohee, 2022). The lignans that are potent phytoestrogens with chemo preventive capacity, and anticancer and antioxidant effects are also abundant in linseed (Stepień et al., 2025; Alam et al. 2025) and tocopherols, orbitides, and phenolics that can be used as functional foods (Sarma et al., 2024). It is abundantly used as animal feed in its defatted meal as well as textile and composite industries in its fibers (Adorian et al., 2022). Linseed is also considered a strategic crop to climate-resilient and resource-efficient agriculture,

especially in semi-arid areas, because, due to its low water and nutrients requirements, it is commonly cultivated in marginal lands (Rossi et al., 2022; Aslam et al., 2017b).

Linseed has a long history as a minor crop mainly grown on marginal land under rain fed condition in Pakistan (Khan et al., 2024). It has a very high nutritional and industrial potential, but the production of this crop has been proposed because it is hindered by the lack of more productive varieties, seed systems, inadequate extension services, and poor agronomic practices (Payasi et al., 2024). Nevertheless, the recent dietary changes towards functional foods revived the interest to the cultivation of linseed along with the ability of the farm to utilize it in low-input conditions. Since Pakistan solely depends on the import of edible oil, the cultivation of oilseeds locally such as those of linseed can lead to better food and nutritional security, diversification of cropping, and economic wealth in rural areas (Hussain et al., 2023).

Pothwar Plateau, located in northeastern Pakistan, is one of the key agro-ecological regions with high potential of rainfed production of oilseed crops (Naz et al., 2023). In terms of geography, the area is spread over Islamabad, Rawalpindi, Chakwal, Attock, and Jhelum districts and has around 1.01 million hectares (Tahir & Khaliq, 2018). It is high-relief with rugged topography, shallow and heterogeneous soil, and two modes of rainfall distribution (Raza & Khalid, 2022). The precipitation occurs annually, ~250 mm in the southern Salt Range regions and reaches more than 1,500 mm in the north (Islamabad), is focalized during the monsoon (July-September) and slightly increased in winter (January-February) (Batool et al., 2023). Temperature regimes have a high variability since they are normally above 40–45°C in the summers (June-July) and below-zero in the winters (December–January) (Ejaz et al., 2023), which places wide temperature amplitude that induces changes in crop phenology, moisture retention, and nutrient dynamics. The soils of the region are loamy to Clay-loam, moderately alkaline (pH of 7.5 to 8.5), and in general both low in organic matter and bioavailable phosphorus (Aziz et al., 2021; Waheed et al., 2025). The combination of these edaphic constraints, uncertain rainfall and growing interannual variability of the climate has become a major constraint to agricultural productivity (Mehmood et al., 2021a,b; Kamruzzaman et al., 2024). Therefore, attaining a high degree of agronomic practices and especially selection time and application of nutrients will be important in enhancing crop performance in this agro-ecosystem which is very delicate.

Phosphorus (P) is one of the requisite macronutrients that take the center stage in optimizing the growth of crops, especially the rainfed-grown ones (Panigrahi et al., 2024). Phosphorus (P) is one of the requisite macronutrients that take the center stage in optimizing the growth of crops, especially the rainfed-grown ones (Xie et al., 2022). An experiment conducted in Pakistan (Faisalabad) demonstrated that seed yield in response to increase in phosphorus rate of application significantly increased (from ~958 to ~1,190 kg ha<sup>-1</sup>) and number of capsules per plant and oil content were significantly improved at higher rates of phosphorus application particularly in high yielding cultivar LS-49 (Sameer et al., 2021). Rainfed conditions implying good responsiveness of linseed to combined nitrogen and phosphorus fertilization were observed by other regional trials as well (Zafar et al., 2020).

The other important factor that affects the productivity of linseed is the sowing date which determines the matching of the crop growth with the prevailing climatic conditions (Rossi et al., 2022). Many experiments (e.g., at Banaras Hindu University, UP, India) have shown that a delay on sowing after mid-November increasingly reduces the height of the plant, branch number, accumulation of dry matter, seed production (from 16.4 q ha<sup>-1</sup> at 14 Nov to 11.6 q ha<sup>-1</sup> at 14 Dec), oil amount, and harvest index (Singh, 2013). In Jharkhand (2020-22), it was reported that sowing on 18 Nov produced best capsule number (approximately 34.7 per plant), test weight and seed yield on most of the varieties sown, compared to those planted on 8 Dec, 18 Dec and 4 Jan (Alam et al., 2025). Early sowing in late-October or first-week November accompanied by narrow planting geometry (e.g., 22.5 cm x 5 cm) ideal in both economic and yield terms was practiced in the Indian mid hill zones (Raj & Gupta, 2020). Seed sowing practiced in the agro ecological setting of Pakistan is usually between late October to mid-November in a rainfed environment in order to utilize the left-over soil moisture and also to avert end of season heat, as documented also, in Apni Kheti recommendations.

In as much as phosphorus fertilization and sowing date, separately have their independent effects on the growth of linseed and its yield, interaction effects of the two factors in semi-arid, moisture limited environments have not been well investigated. An experiment in Egypt with Sakha-5 flax demonstrated that factorial combined trials with sowing dates and phosphorus rate had a huge role in seed yield and oil content production of the flax plant. (Hemeid, 2020). Likewise, a more contemporary and large scale experiment in Tanzania (though in cotton) also pointed to a high interaction effect between early sowing (Nov/Dec) and moderate P application (20-60 kg P ha<sup>-1</sup>) in enhancing the rise of yield relative to late sowing (Aslam et al., 2018,2021; Tlatlaa et al., 2024). Nevertheless, similar linseed specific

interactions in Pothwar of Pakistan are empirically poor.

This research was thus conducted to determine the cumulative effect of phosphorus level of application and sowing dates on the growth, yield parameters, and oil quality of linseed in a rainfed condition. The experiment will be carried out over two crop seasons at the National Agricultural Research Centre (NARC), Islamabad with the objectives being (i) to determine the optimum phosphorus requirements of linseed production in phosphorus deficient soils, (ii) to determine the best sowing periods to obtain optimal yields, and (iii) to determine the interaction effect between phosphorus application and sowing date. The results are intended to guide evidence-based agronomic prescriptions to the linseed intensification in the semi-arid agro-ecosystems, specifically the climatically vulnerable and resource limited ones.

## MATERIALS AND METHODS

### Experimental Site and Climatic Context

The experiment was done as a field study during two consecutive winter years (2023-24 and 2024-25) at experimental fields of Oilseed Research Program, National Agricultural Research Centre (NARC), Islamabad, Pakistan (33.6701° N, 73.1261° E). The experimental location is found in the Pothwar Plateau which is a typical semi-arid agro-ecological region with undulating and shallow soils which receive erratic rainfall pattern. The soil of the studied place can be characterized as loamy and with moderate alkalinity (pH 7.5-8.4) as well as containing low amounts of organic carbon and available phosphorus.

Weather records of the 2 seasons were obtained at the NARC weather station. The average daily temperature varied between 11.57°C and 12.85°C with the maximum temperatures varying between 27.48°C and 28.42°C and the minimum temperatures as low as 7.62°C especially in the later sowings. Climatic conditions of the growing season were typical of Pothwar region, which has cooler growing conditions and varied rainfall affecting the availability of soil moisture and development of crops.

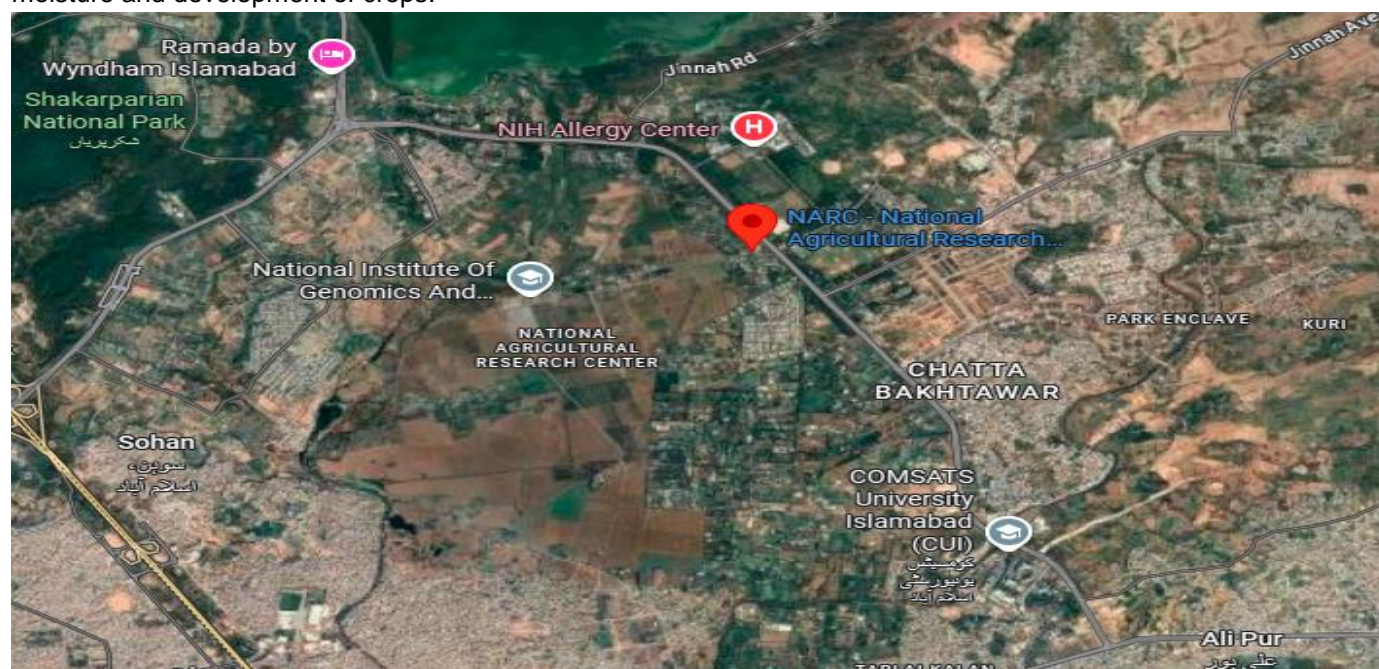


Figure 1. Geographical location of the experimental site at the Oilseed Research Program, National Agricultural Research Centre (NARC), Islamabad, Pakistan (33.6701° N, 73.1261° E). The site lies within the semi-arid Pothwar Plateau, representative of rainfed agro-ecological conditions in northeastern Pakistan.

### Experimental Design and Treatments

In the study, the split-plot design was used in a randomized complete block design (RCBD) with three replications to ascertain the interactive effects of treatment of phosphorus fertilization and sowing dates on growth, yield, and oil quality on linseed production to administer under rainfed condition. Sowing date was to be set as main-plot factor and the rates of the application of phosphorus were to be placed under sub-plots. This factorial structure allowed main effect and interaction analysis in the aspects of temporal and nutritional management strategies. Four sowing date

treatments were established based on the regional agro-climatic calendar, representing a gradient from early to delayed planting (Table 2).

Table 1. Mean, maximum, minimum, and average temperature (degree Celsius) at NARC, Islamabad during 2023-25 and 2024-25 under four sowing dates.

Maximum Temperature			Minimum Temperature		Mean Temperature	
Baseline	28.75		8.89		12.55	
Years	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
SD1	27.48	28.42	8.56	8.18	11.85	12.35
SD2	28.41	27.85	8.75	8.54	12.55	12.85
SD3	27.85	28.13	7.85	7.62	12.35	11.85
SD4	28.18	28.02	7.75	7.85	11.57	12.56

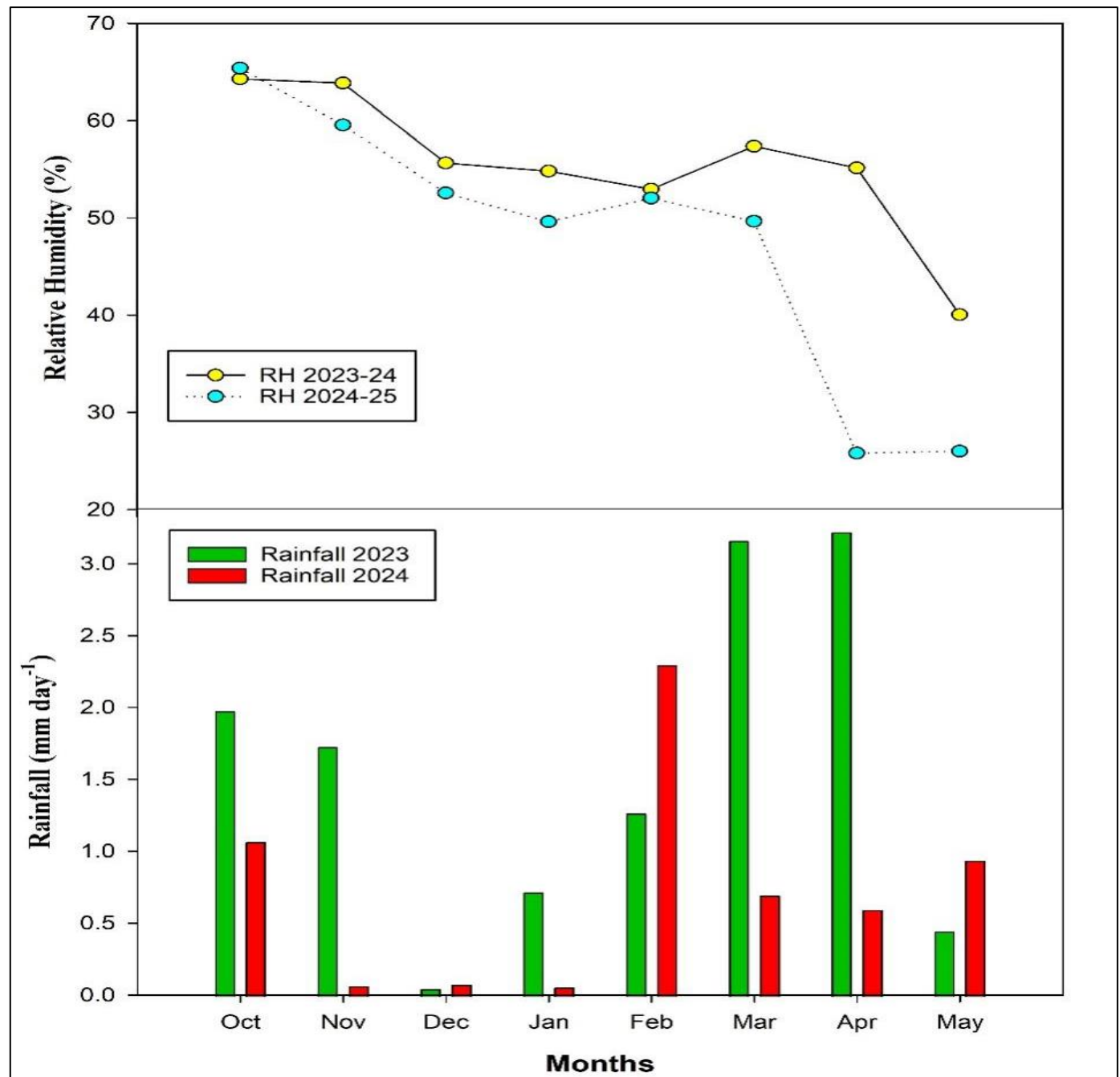


Figure 2. Mean rainfall ( $\text{mm day}^{-1}$ ) and relative humidity (%) at Islamabad during 2023-25 and 2024-25.

Table 2. Sowing Date Treatments for Linseed Based on Regional Agro-Climatic Calendar.

Sowing Date Code	Sowing Date (2023-24)	Sowing Date (2024-25)
SD1	26-Oct-2023	6-Nov-2024
SD2	15-Nov-2023	21-Nov-2024
SD3	03-Dec-2023	11-Dec-2024
SD4	22-Dec-2023	27-Dec-2024

Such sowing windows were chosen to reflect the usual range of planting dates that would occur in the Pothwar plateau and SD1 marked the most favorable sowing time and SD4 marked the least feasible date to plant under the prevailing field conditions. Phosphorus was applied in the form of diammonium phosphate (DAP; 18% N, 46% P<sub>2</sub>O<sub>5</sub>) at six levels to assess the dose-response relationship across sowing dates (Table 3).

Table 3. Phosphorus Fertilization Treatments and Corresponding DAP Application Rates for Linseed.

Treatments	Phosphorus Application Code	DAP Quantity (kg ha <sup>-1</sup> )
T1	P0	0
T2	P50	50
T3	P100	100
T4	P150	150
T5	P200	200
T6	P250	250

There were four phosphorus subplots per main plot and dimensions of the individual subplots were 5 m x 1.5 m. The rows of main and subplots maintained a buffer of 2 meters and 1 meter respectively in order to reduce cross-contamination of nutrients and moisture. There were 72 treatment combinations (4 sowing dates x 6 phosphorus levels x 3 replications) to be carried out.

The phosphorus treatments were applied uniformly on sowing just as a base dose to offer the nutrient availability on early occasions. The seeds were sown manually on a line spacing of 30 cm and intra-row spacing of about 10 cm with a hand drill. Standard agricultural processes were carried out as follows; manual weeding, manual thinning and pest monitoring in an identical way in all the treatments to reduce any non-treatment variation.

This experimental protocol allowed conducting a powerful assessment of individual and combined effects of sowing date and phosphorus nutrition on linseed performance, which allowed comparing and analyzing time and management of agronomic regime statistically valid interactions.

#### **Crop Management and Fertilizer Application**

Manual sowing of linseed seeds of a locally adapted variety was done at a row spacing of 30 cm with the use of a hand drill. To obtain a uniform nutrient availability, the DAP fertilizer was used by spreading over the seedlings at base cover at the time of sowing. No further application of nitrogen was done because the experimental plots had previously been cultivated with groundnut hence the introduction of residual nitrogen due to biological nitrogen fixation. Agronomic general cultivation measures such as hand weeding and pests' surveillance were applied on all the treatments in similar ways.

#### **Data Collection on Morphological and Yield Parameters**

Growth related data were recorded from ten randomly selected plants per subplot. The parameters included Plant height, number of seed capsule<sup>-1</sup>, Oil Content percentage, 1000 Seed weight and Seed yield.

#### **Statistical Analysis**

Data were subjected to analysis of variance (ANOVA) using statistical Package R to determine the effects of phosphorus levels, sowing dates, and their interaction on all measured traits. Where significant treatment effects were detected, means were compared using the Least Significant Difference (LSD) test at a 5% probability level. Pearson's correlation coefficients were computed to assess the relationships between soil moisture levels and seed yield components.

## **RESULTS**

### **Plant Height**

Plant height (PH) measured at six phenological stages (PH1–PH6) was significantly influenced by the interaction of phosphorus application and sowing date across both growing seasons ( $P < 0.05$ ). The highest average plant height was

consistently observed under SD1 × P150, where the final stage (PH6) reached 87.5 cm, (Figure 3-4) representing an increase of 42.3% compared to the lowest-performing treatment combination (SD4 × P50, 60.9 cm). This trend demonstrates the critical role of early sowing and optimal phosphorus supply in promoting vertical biomass accumulation. Across all treatments, earlier sowing (SD1) led to greater plant height, with values declining progressively from SD1 > SD2 > SD3 > SD4. For instance, Treatment 4 showed a gradual decline from 87.5 cm in SD1 to 63.1 cm in SD4, signifying a 27.9% reduction due to delayed sowing. Similarly, phosphorus-deficient treatments (e.g., P0 & P50) consistently recorded lower heights across all sowing dates, indicating that phosphorus supplementation plays a pivotal role in enhancing stem elongation and canopy development.

The year-to-year comparison revealed taller plants during the 2023–24 season, attributed to more favorable climatic conditions during the vegetative growth period, including lower vapor pressure deficits and more consistent soil moisture availability. Treatments receiving moderate to high phosphorus (P150 TO P250) particularly benefitted from this environmental advantage.

These results highlight that both sowing date and phosphorus nutrition significantly modulate linseed plant height, and their interactive effects are particularly pronounced under rainfed agro-ecosystems such as the Pothwar Plateau. The optimal combination of early sowing and adequate phosphorus (P150 & P200) proved most effective in maximizing plant stature and potentially biomass yield.

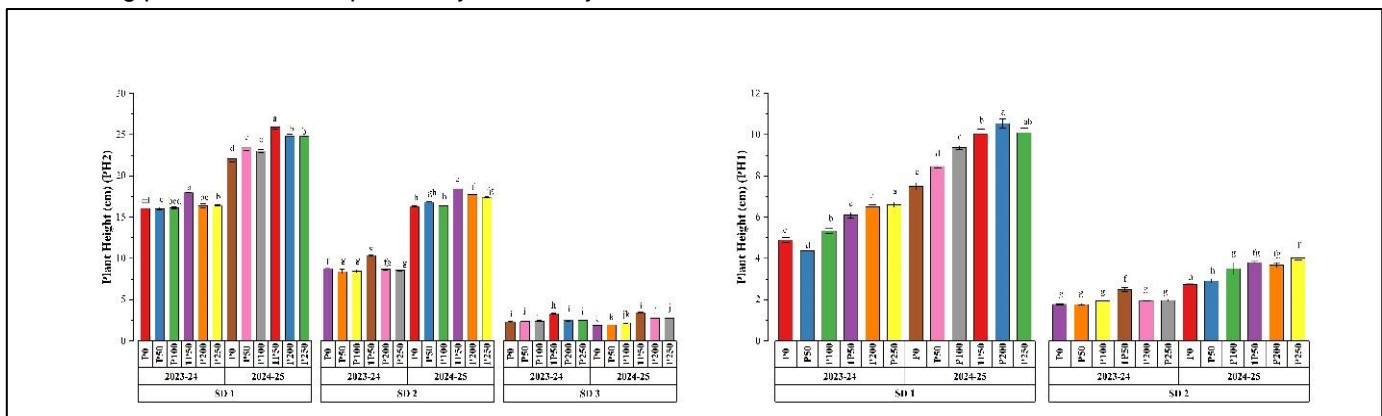


Figure 3. Plant Height 1&2 of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25).

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among sowing date × treatments ( $p < 0.05$ ) based on the Least Significance Difference (LSD) test. Each treatment was replicated three times ( $n=3$ )

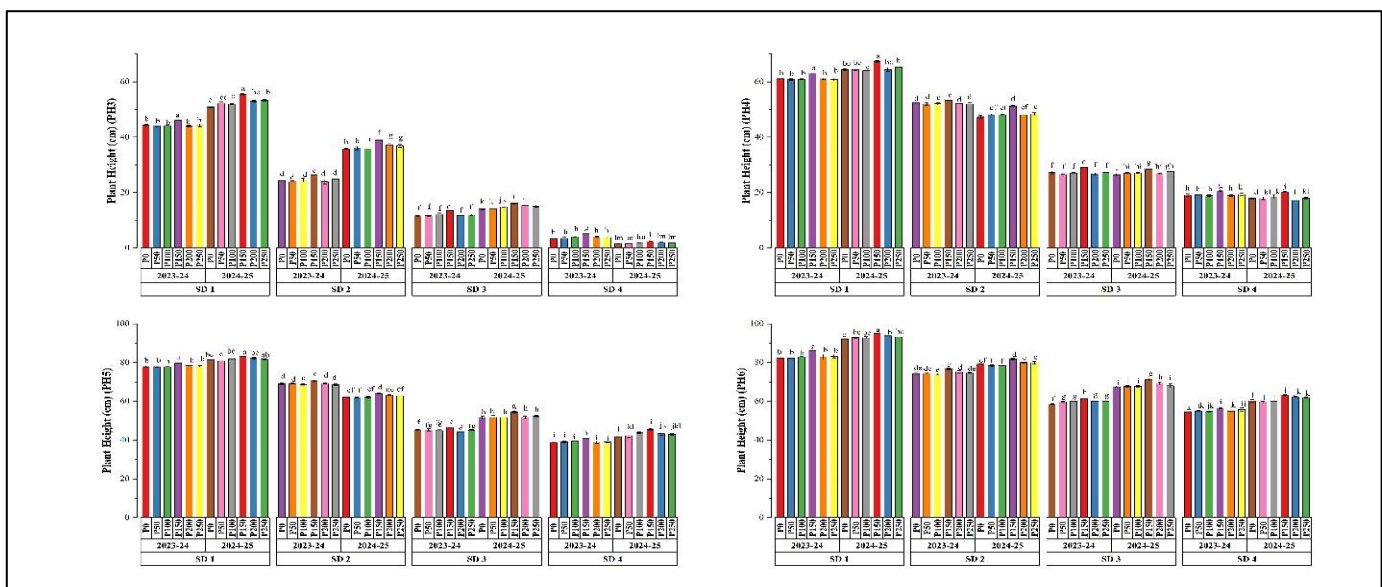


Figure 4. Plant Height 3-6 of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25)

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among

sowing date \* treatments ( $p < 0.05$ ) based on the (LSD) test. Each treatment was replicated three times ( $n = 3$ )

**Number of Seeds per Capsule**

The average number of seeds per capsule exhibited pronounced sensitivity to both sowing date and phosphorus application, revealing a distinct interactive response pattern. The maximum seed count per capsule was observed under SD1 x P150 (9.58 seeds capsule<sup>-1</sup>), whereas the minimum value was noted under SD4 x P250 (3.67 seeds capsule<sup>-1</sup>), representing a reduction of 61.7% relative to the highest treatment combination.

Phosphorus application, particularly at 150 kg ha<sup>-1</sup> (P150), resulted in consistently higher seed numbers across all sowing windows, highlighting its pivotal role in reproductive efficiency (Figure 5). Under SD1 conditions, P150 enhanced the seed count by 16% over the control (P0), while improvements of 0.6%, 10.4%, and 20.4% were observed under SD2, SD3, and SD4, respectively, when compared to their respective controls. This trend underscores the importance of moderate phosphorus supplementation for optimizing ovule fertilization and seed setting.

From a sowing date perspective, early sowing (SD1) led to significantly better seed development, with an average of 8.5 seeds capsule<sup>-1</sup> across treatments, followed by SD2 (6.9), SD3 (5.6), and SD4 (4.2). The consistent decline in seed count with delayed sowing is likely attributed to suboptimal thermal regimes and shortened reproductive durations that negatively impacted fertilization and seed filling processes.

These findings affirm that timely sowing in combination with optimal phosphorus input—especially at 150 kg ha<sup>-1</sup>—is essential to enhance sink capacity and reproductive efficiency in linseed.

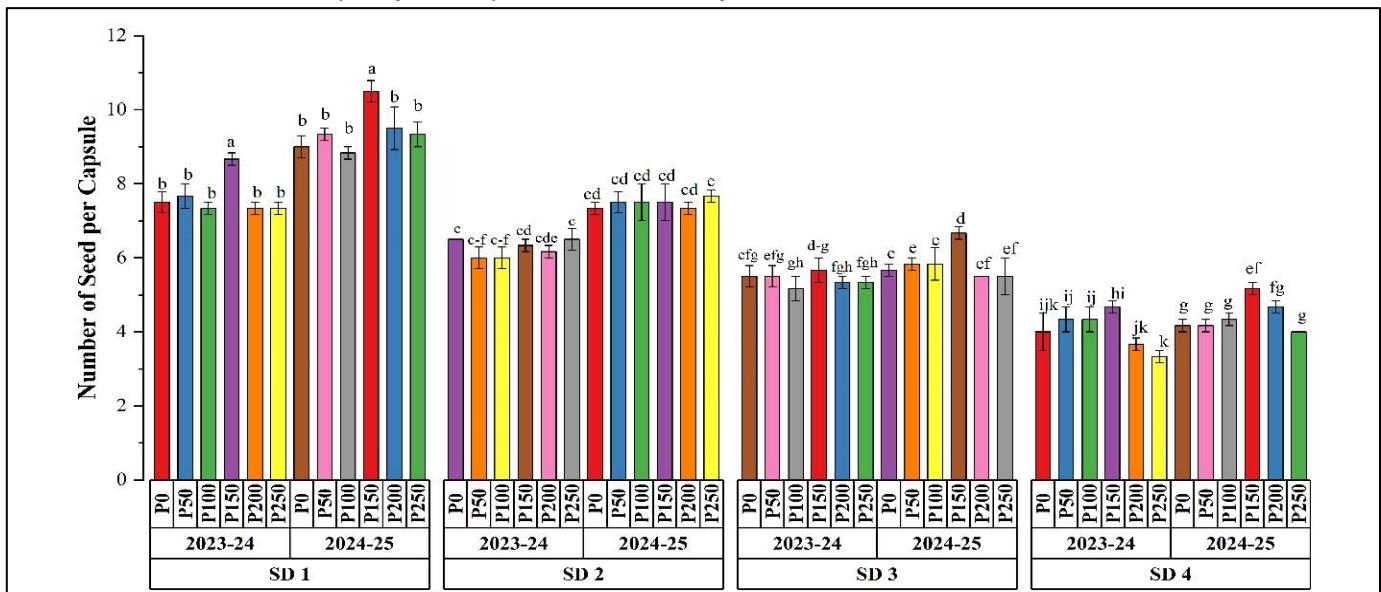


Figure 5. Number of seed per capsule of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25).

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among sowing date \* treatments ( $p < 0.05$ ) based on the Least Significance Difference (LSD) test. Each treatment was replicated three times ( $n = 3$ )

**Oil Content (%)**

Oil content in linseed was significantly modulated by both sowing dates and phosphorus levels, exhibiting clear trends across the treatment combinations. The highest oil concentration was obtained under SD1 x P150 (37.92%), reflecting optimal physiological conditions for lipid biosynthesis. In contrast, the lowest oil percentage (23.64%) was recorded in SD4 x P0, showing a sharp 37.4% reduction compared to the top-performing treatment.

Phosphorus application at 150 kg ha<sup>-1</sup> markedly improved oil synthesis across all sowing windows. For example, under SD1, P150 enhanced oil content by 3.99% over P0 (Figure 6). Similarly, increases of 1.4%, 2.5%, and 11.8% were recorded under SD2, SD3, and SD4, respectively, when comparing P150 to their respective controls. These outcomes affirm the role of moderate phosphorus levels in enhancing metabolic allocation toward oil biosynthesis, particularly when environmental conditions are favorable.

Across the sowing dates, oil content declined steadily with delayed planting. The average oil percentages under SD1, SD2, SD3, and SD4 were 36.57%, 32.38%, 27.73%, and 24.42%, respectively, indicating that early sowing provides

critical climatic advantages such as cooler post-anthesis temperatures and longer grain-filling duration—factors known to favor oil accumulation in linseed.

Interestingly, while P250 often mirrored the performance of P150 under SD1, its effectiveness was notably diminished under later sowings, suggesting diminishing returns or possible nutrient imbalances at excessive application rates. These findings confirm that early sowing combined with a balanced phosphorus dose (especially P150) creates an ideal physiological environment for maximizing oil yield in linseed.

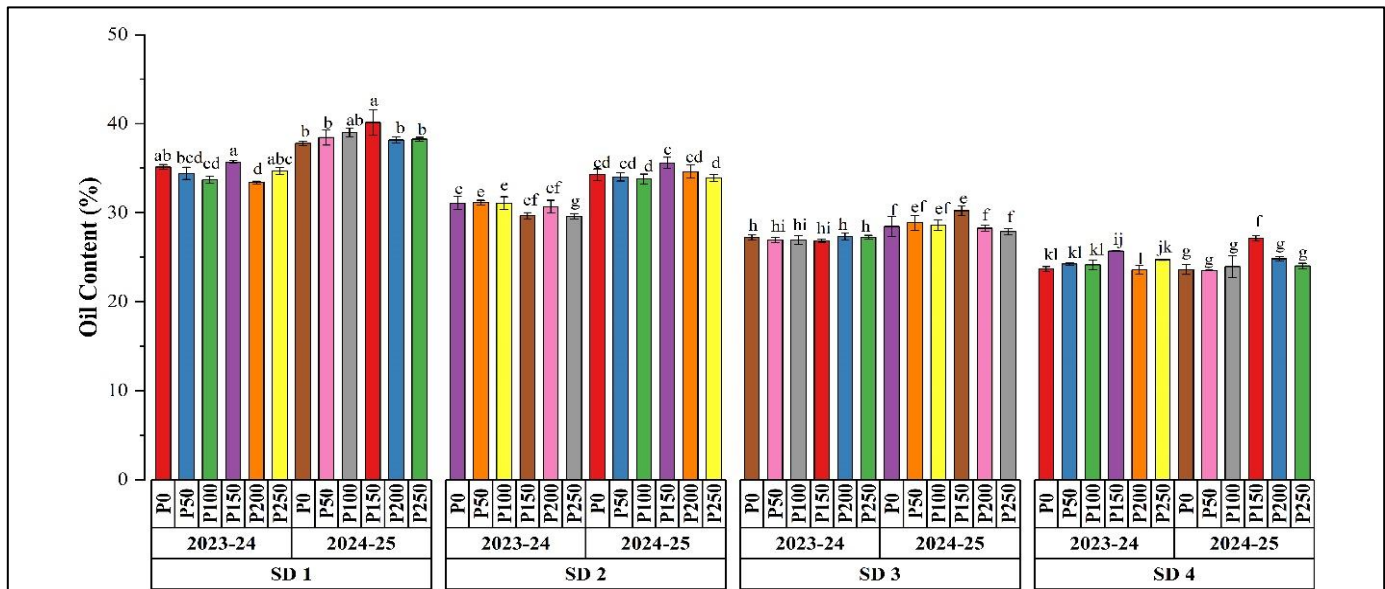


Figure 6. Oil content (%) of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25).

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among sowing date \* treatments ( $p < 0.05$ ) based on the Least Significance Difference (LSD) test. Each treatment was replicated three times ( $n=3$ )

### 1000-Seed Weight (g)

The weight of 1000 seeds, a key indicator of seed quality and grain filling efficiency, was significantly affected by both sowing date and phosphorus application. The maximum 1000-seed weight was recorded under SD1 × P150 (7.50 g), whereas the lowest value was observed under SD4 × P200 (3.02 g), indicating a 59.7% reduction attributable to late sowing and nutrient stress.

Application of 150 kg P ha<sup>-1</sup> (P150) consistently led to improved seed weight across all sowing dates. Compared to the control (P0), P150 enhanced 1000-seed weight by 10.6%, 10.0%, 14.8%, and 14.0% under SD1, SD2, SD3, and SD4, respectively (Fig 7). This pattern reflects improved assimilate partitioning and longer grain-filling durations facilitated by sufficient phosphorus supply.

When comparing sowing dates, SD1 produced the heaviest seeds, with an average of 6.76 g, followed by SD2 (5.37 g), SD3 (4.05 g), and SD4 (3.18 g). The decline in seed mass with delayed sowing was likely due to higher terminal temperatures and a shortened grain-filling phase, which constrained dry matter accumulation in seeds.

Notably, treatments beyond P150 (i.e., P200 and P250) did not confer further advantages and, in some cases, reduced seed weight, suggesting a potential threshold beyond which phosphorus may no longer positively influence seed development. These results underscore the importance of synchronized sowing time and moderate phosphorus application for optimizing seed development and final grain weight in linseed.

### Seed Yield (g m<sup>-2</sup>)

Seed yield was significantly influenced by both sowing date and phosphorus application, with noticeable differences across treatment combinations. The maximum seed yield was obtained under SD1 × P150 (902.41 g m<sup>-2</sup>), while the minimum yield (636.29 g m<sup>-2</sup>) was recorded under SD4 × P200, representing a decline of 29.5% compared to the best-performing treatment.

Among phosphorus levels, the application of 150 kg ha<sup>-1</sup> (P150) consistently resulted in higher seed yields across all sowing dates. When compared to the P0 control, P150 led to yield increases of 5.9% in SD1, 4.7% in SD2, 4.6% in SD3, and 1.9% in SD4 (Fig 8). These results suggest that phosphorus application at 150 kg ha<sup>-1</sup> is optimal for

promoting reproductive efficiency and assimilate allocation to developing seeds.

In terms of sowing date performance, seed yield declined progressively with delayed planting. Averaged across phosphorus treatments, SD1 recorded the highest mean yield (869.22 g m<sup>-2</sup>), followed by SD2 (791.38 g m<sup>-2</sup>), SD3 (720.29 g m<sup>-2</sup>), and SD4 (652.02 g m<sup>-2</sup>). This downward trend is likely a result of late-season sowings encountering suboptimal thermal regimes and reduced vegetative biomass, thereby limiting reproductive output.

While P200 and P250 exhibited moderate improvements over control in early sowings, their marginal benefits diminished under later sowings. These findings indicate that a strategic alignment of early sowing and phosphorus at 150 kg ha<sup>-1</sup> is crucial for maximizing seed productivity in linseed

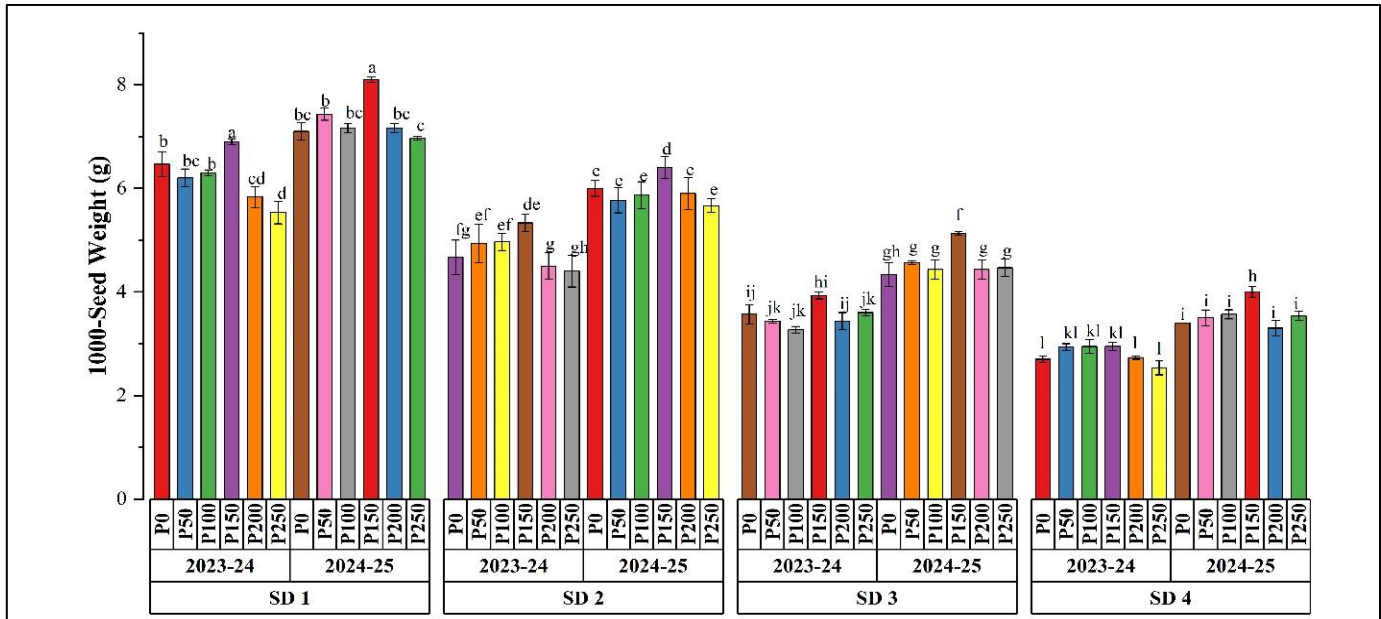


Figure 7. 1000-Seed weight (g) of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25).

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among sowing date \* treatments (p<0.05) based on the Least Significance Difference (LSD) test. Each treatment was replicated three times (n=3)

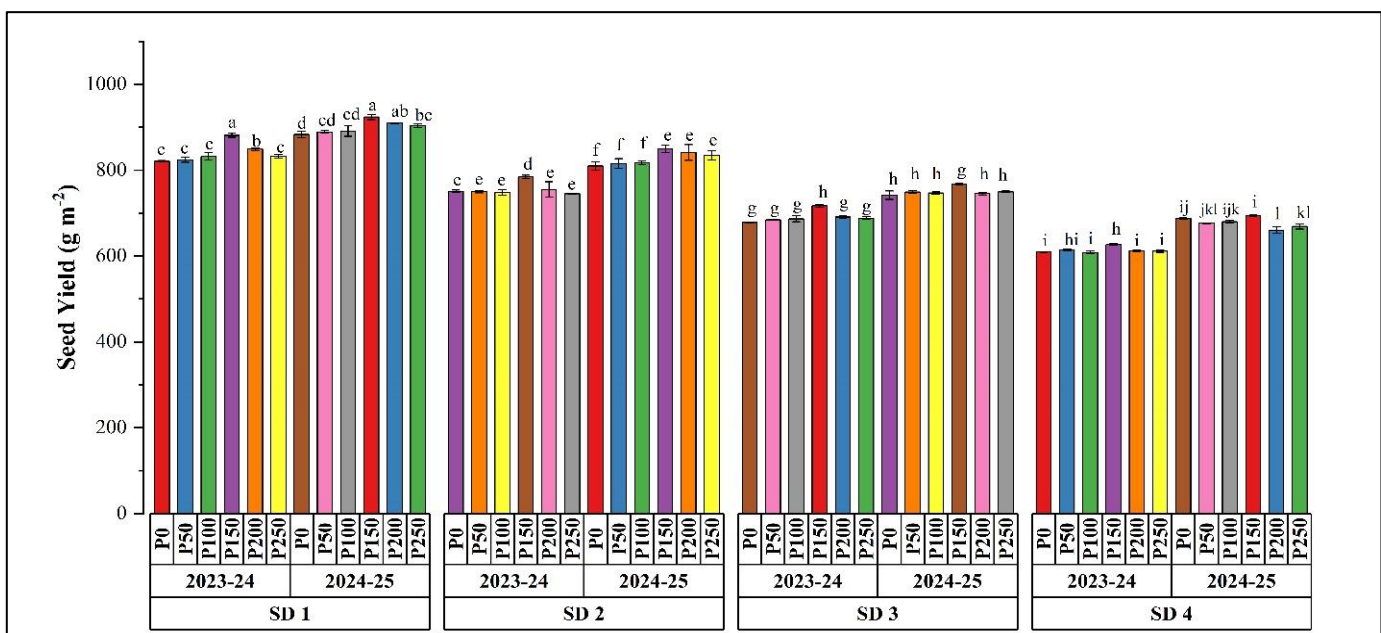


Figure 8. Seed yield (g m<sup>-2</sup>) of Line seed under different sowing dates and treatments across two cropping seasons (2023-24 and 2024-25).

Note: Bars represent mean values with standard error. Different letters above bars denote significant differences among sowing date \* treatments ( $p < 0.05$ ) based on the Least Significance Difference (LSD) test. Each treatment was replicated three times ( $n=3$ )

## DISCUSSION

### Synergistic Effects of Sowing Date and Phosphorus on Crop Growth and Yield

The results confirm a significant interaction in the combination of early sowing (SD1) and moderate phosphorus (P150) to maximize linseed agronomic performance in rainfed environment. High yield and yield components resulted under SD1 x P150 and can be justified by the earlier reports that illustrate that, early sowing ensures that the plant growth is in tune with the conditions during post monsoon moisture, lesser thermal constraints that makes the plants more advantageous thereby providing more fertile conditions (Prakash et al., 2015; SHRIRAM, 2022). Likewise, moderate application of phosphorus has significantly increased the height of the plant, the number of branches and capsules, seed weight and oil content- which remain stagnant or down-played once the application rate exceeds P150 as observed in the case of our experiment (Kassaye et al., 2018; Ullah et al. 2025; Muhammad et al., 2020).

Delays in sowing (SD3 and SD4) substantially condensed the phenological trajectory of the crop and lowered the number of days between the crop emergence and crop harvest to about 50-60 days. This rapid growth rate resembles those observed globally which is that late season sowing subjects' linseed to high temperatures hence reducing time in vegetative and reproductive stages and curtailing assimilates accrual (Aleka, 2023; He et al., 2024). The resulting yield penalties are driven by impaired floral initiation, capsule formation, seed filling, and oil deposition (Goutam et al.).

P150 combined with early sowing resulted in the highest oil content (37.9 percent), which indicated the optimal post-anthesis temperatures as well as long seed filling periods. According to literature, cooler conditions during grain filling conditions are conducive to the biosynthesis and accumulation of lipids (Paliwal et al., 2023; Sharma & Samota, 2024). In addition, adequate phosphorus availability helps in ATP dependent metabolic pathways and this contributes to effectively assimilate translocation and biosynthesis of oil (He et al., 2024; Xie et al., 2022). We identified decreasing returns or even oil percentage decline with higher P levels (P200-P250) which confirms other results that too much phosphorus could disrupt hormonal balances or trigger luxury consumption without positive effects on the yields (Payasi et al., 2024).

Though the water was not directly modeled, moderate phosphorus application increased the canopy development and yield, indicating better use of moisture-suggested by the studies that have presented and reported the phosphorus-enhanced root proliferation and the increased water extraction conditioned by the moisture-limited conditions (Kang et al., 2014; Kim & Li, 2016). The responses that lead to yield stability entail these adaptive responses particularly when soil moisture begins to decline drastically in late sowings.

The best phosphorus rate ( $150 \text{ kg ha}^{-1}$ ) is equivalent to the recommended P 2 O 5 rates ( $40 \text{ } 60 \text{ kg ha}^{-1}$ ) internationally, adapted to the local soil stratigraphy and residual fertility (Muhammad et al., 2020). Nevertheless, there are international trials (China, Europe) that found peak seed and oil production at low P rates ( $80 \text{ } 120 \text{ kg ha}^{-1}$ ) in controlled moisture environments which suggests site-specific P response (He et al., 2024). The causes of such differences are the variability of soil baseline fertility, structure, climate, and cultivar.

## CONCLUSION

The results of this study indicate that both sowing date and phosphorus management significantly influence the growth, phenology, and yield of linseed under the semi-arid, rainfed conditions of the Pothwar Plateau. Early sowing (late October to early November) consistently promoted vegetative growth, capsule development, seed filling, and oil accumulation, benefiting from favorable temperature regimes and improved soil moisture. Among the phosphorus treatments,  $150 \text{ kg ha}^{-1}$  emerged as the optimal dose for enhancing yield components and oil quality. The observed correlation between seed yield and soil moisture underscores the importance of integrating nutrient management with water conservation strategies. These findings suggest that linseed productivity in Pothwar can be maximized by adopting early sowing combined with moderate phosphorus application. To further enhance sustainability and resource-use efficiency, it is recommended to implement moisture retention practices, select responsive cultivars, and strengthen field advisory services. Future research should focus on genotype–environment–management interactions and employ modern monitoring tools to support precision-based decision-making and long-term improvement of linseed cultivation systems.

## AUTHOR CONTRIBUTIONS

A.H. Chaudhary, S.H.Khattak and S. Komal, executed the study; G. Qadir and M.A. Aslam conceptualized the study; M. Ahmad and R. hayat, analyzed the study; I. Ullah provided the land for experiment; E. Yaseen and A.A Aziz did proof reading.

## COMPETING OF INTEREST

The authors declare no competing interests.

## REFERENCES

- Adorian, T. J., Pianesso, D., Bender, A. B. B., Speroni, C. S., Mombach, P. I., Kowalski, É. A., & da Silva, L. P. (2022). Fractionation of linseed and obtaining ingredients rich in protein and fibers: Alternatives for animal feed. *Journal of the Science of Food and Agriculture*, 102(4), 1514-1521.
- Alam, M. P., Sulochna, & Pandey, S. K. (2025). EFFECT OF DATE OF SOWING ON YIELD ATTRIBUTES, YIELD AND ECONOMICS OF LINSEED VARIETIES UNDER CHOTA NAGPUR PLATEAU REGION OF JHARKHAND INDIA. *Plant Archives*, 25(1). <https://doi.org/https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.1.364>
- Aleka, A. B. (2023). YIELD AND OIL CONTENTS OF LINSEED (*Linum usitatissimum* L.) VARIETIES AS INFLUENCED BY SOWING DATES SEED AND NPS FERTILIZER RATES IN HORO GUDURU WOLLEGA DISTRICT, WESTERN ETHIOPIA [Haramaya University].
- Alam, B., I. Ullah, F. Ullah, I.U. Khan, M.A. Aslam, G. Zahid, S. Begum, A. Errum, F. Amin, R. Akram, M. Murtaza, F. Jabeen, E. Yaseen, G.M. Ali and S.H. Khattak (2025). Morphological and yield characterization of different wheat genotypes. *J. Agric. Vet. Sci.*, 4(2): 151–157.
- Aslam, M.A., M. Ahmed, C.O. Stöckle, S.S. Higgins, F.U. Hassan and R. Hayat (2017). Can growing degree days and photoperiod predict spring wheat phenology? *Front. Environ. Sci.*, 5: 57. DOI: 10.3389/fenvs.2017.00057.
- Aslam, M.A., M. Ahmed, F.U. Hassan and R. Hayat (2017). Modeling nitrogen use efficiency under changing climate. In: *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability* (M. Ahmed and C.O. Stöckle, eds.). Springer International Publishing, Switzerland, pp. 71–90.
- Aslam, M.A., M. Ahmed, F.U. Hassan, O. Afzal, M.Z. Mehmood, G. Qadir, M. Asif, S. Komal and T. Hussain (2021). Impact of temperature fluctuations on plant morphological and physiological traits. In: *Building Climate Resilience in Agriculture* (Jatoi et al., eds.). Springer, Cham, pp. 25–52. ISBN 978-3-030-79408-8. DOI: 10.1007/978-3-030-79408-8.
- Aslam, M.A., M. Ahmed, F.U. Hassan, R. Hayat and S. Ahmad (2018). Quantification of impact of sowing dates on productivity of rainfed wheat. *Sci. Tech. Dev.*, 37(1): 28–35.
- Aziz, H., Siddique, M., Ahmed, H., Iqbal, M., & Hameed, M. A. (2021). Indexing plant available sulfur content in the major oil seed producing districts of Pothohar, Pakistan. *Soil & Environment*, 40(2).
- Batool, M., Toqeer, M., & Shah, M. H. (2023). Assessment of water quality, trace metal pollution, source apportionment and health risks in the groundwater of Chakwal, Pakistan. *Environmental Geochemistry and Health*, 45(7), 4327-4352.
- Ejaz, R., Chaudhary, K. M., Ashraf, I., & Tahir, M. (2023). ANALYSIS OF CONSTRAINING FACTORS REGARDING ADOPTION OF SOIL AND WATER CONSERVATION PRACTICES IN THE POTHOHAR, PUNJAB. *Journal of Agricultural Research (JAR)*. 61(2), 161-167.
- Goutam, P. K., Maurya, A. K., & Chauhan, D. Morphological Traits, Agronomical Practices and Value of Linseed Crop.
- He, N., Huang, F., Luo, D., Liu, Z., Han, M., Zhao, Z., & Sun, X. (2024). Oilseed flax cultivation: optimizing phosphorus use for enhanced growth and soil health. *Frontiers in Plant Science*, 15, 1432875.
- Hemeid, M. M. (2020). Effect of sowing date and phosphorus fertilizer rates on yield and yield components of sakha 5 flax cultivar. *Alexandria Science Exchange Journal*, 41(July-September), 341-351.
- Hussain, M., Wahab, A., Ahmad, U., & Arshad, Z. (2023). Current scenario of oilseeds in Pakistan. *Trends Biotech Plant Sci*, 1(1), 29-36.
- Irshad, S., ur Rehman, H., Wahid, M. A., Saleem, M. F., Basra, S. M. A., & Saeed, M. T. (2016). Influence of phosphorus application on growth, yield and oil quality of linola. *Journal of Plant Nutrition*, 39(6), 856-865.
- Kamruzzaman, M., Biswas, J. C., Islam, H. T., & Hossain, A. Z. (2024). Interannual climate variability and its impacts on major crop productivity. In *Climate Change and Soil-Water-Plant Nexus: Agriculture and Environment* (pp. 297-329). Springer.
- Kang, L., Yue, S., & Li, S. (2014). Effects of phosphorus application in different soil layers on root growth, yield, and water-use efficiency of winter wheat grown under semi-arid conditions. *Journal of Integrative Agriculture*, 13(9), 2028-2039.

- Kassaye, K. T., Tirfe, A. A., Yilm, W. A., Haile, D. H., Teto, A. M., & Weldegebriel, A. T. (2018). Influence of phosphorus application on yield, yield components, and quality of linseed. *Journal of Plant Nutrition*, 41(19), 2525-2535.
- Katoch, M., & Bhatia, N. S. (2021). Linseed and its basic composition. *International Journal of Advances in Agricultural Science and Technology*, 8(6), 10-26.
- Khan, M. N., Malik, A. M., & Khan, F. (2024). Performance and instability of oilseed crops in Pakistan. *Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences*, 61(1), 77-87.
- Kim, H.-J., & Li, X. (2016). Effects of phosphorus on shoot and root growth, partitioning, and phosphorus utilization efficiency in Lantana. *HortScience*, 51(8), 1001-1009.
- Muhammad, H., Ahmad, A., & Tahir, M. (2020). Response of different phosphorus levels and application methods on the growth and quality of linseed crop. *Biol. Clin. Sci. Res. J*, 19.
- Mehmood, M.Z., Afzal, O., Ahmed, M., Qadir, G., Kheir, A.M.S., Aslam, M.A., Din, A.M.U., Khan, I., Hassan, M.J., Meraj, T.A., Raza, M.A. and Ahmad, S. (2021). Can sulphur improve the nutrient uptake, partitioning, and seed yield of sesame? *Arabian Journal of Geosciences*, 14: 865.
- Mehmood, M.Z., Ahmed, M., Afzal, O., Aslam, M.A., Arfeen, R.Z.U., Qadir, G., Komal, S., Shahid, M.A., Awan, A.A., Awale, M.A., Sameen, A., Kalsoom, T., Nasim, W., Hassan, F.U. and Ahmad, S. (2021). Internet of Things (IoT) and sensors technologies in smart agriculture: Applications, opportunities, and current trends. In: *Building Climate Resilience in Agriculture* (Jatoi et al., eds.). Chapter 21. Springer International Publishing, Switzerland. ISBN 978-3-030-79408-8, DOI: 10.1007/978-3-030-79408-8.
- Mehmood, M.Z., Qadir, G., Afzal, O., Din, A.M., Raza, M.A., Khan, I., Hassan, M.J., Awan, S.A., Ahmad, S., Ansar, M., Aslam, M.A. and Ahmed, M. (2021). Paclobutrazol improves sesame yield by increasing dry matter accumulation and reducing seed shattering under rainfed conditions. *International Journal of Plant Production*, 15: 337–349.
- Naz, I., Ijaz, S., Ansar, M., & Khan, K. (2023). Changes in soil enzymatic activity associated with conservation agriculture in the rainfed pothwar plateau of Pakistan. *Applied Ecology & Environmental Research*, 21(3).
- Oso, A. A., & Ashafa, A. O. (2021). Nutritional composition of grain and seed proteins. In *Grain and seed proteins functionality*. IntechOpen.
- Paliwal, S., Tripathi, M. K., Tiwari, S., Tripathi, N., Payasi, D. K., Tiwari, P. N., Singh, K., Yadav, R. K., Asati, R., & Chauhan, S. (2023). Molecular advances to combat different biotic and abiotic stresses in linseed (*Linum usitatissimum* L.): A comprehensive review. *Genes*, 14(7), 1461.
- Pandohee, J. (2022). Alpha-linolenic acid. In *Nutraceuticals and Health Care* (pp. 279-288). Elsevier.
- Panigrahi, C. K., Jena, N., & Charitha, K. (2024). The Role of Phosphorus in Root Development and Crop Yield. *Soil Fertility and Plant Nutrition*, 21.
- Payasi, D. K., Garg, D., & Payasi, S. (2024). Preharvesting processing of linseed crop. In *Linseed* (pp. 21-45). Elsevier.
- Prakash, G., Singh, R., Singh, A., & Singh, K. (2015). Growth, yield, nutrient uptake and quality of linseed (*Linum usitatissimum* L.) varieties as affected by varying sowing dates. *Environment and Ecology*, 33(1A), 271-274.
- Rahman, A., Ali, N., Anjum, M. M., Jalal, F., Khan, B., Khan, G. R., & Ali, S. (2023). Increasing Flax Crop Performance and Oil Content with Phosphorus and Foliar Zinc Supplementations. *Gesunde Pflanzen*, 75(6), 2773-2783.
- Raj, R., & Gupta, D. (2020). Effect of sowing dates and planting geometry on yield attributes, yield and economics of linseed under the north hill zone of Chhattisgarh. *Int. J. Curr. Microbiol. App. Sci*, 9(10), 3749-3755.
- Raza, I., & Khalid, P. (2022). An Application of Remote Sensing/GIS to map groundwater potential zone for Hydrogeophysical Prospecting in Potwar Plateau, Pakistan.
- Rossi, A., Clemente, C., Tavarini, S., & Angelini, L. G. (2022). Variety and sowing date affect seed yield and chemical composition of linseed grown under organic production system in a semiarid mediterranean environment. *Agronomy*, 13(1), 45.
- Sameer, S., Singh, V., Tiwari, D., & George, S. G. (2021). Effect of Nitrogen and Phosphorus levels on growth and yield of Linseed (*Linum usitatissimum* L.). *Pharma Innovation Journal*, 10(10), 1833-1836.
- Sarma, S. D., Begum, T., & Lal, M. (2024). Application of linseed in cosmetic and personal care products development. In *Linseed* (pp. 193-203). Elsevier.
- Sharma, M., & Samota, M. K. (2024). Metabolic engineering of linseed crop for enhancing production yield. In *Linseed* (pp. 107-117). Elsevier.
- SHRIRAM, P. S. (2022). DROUGHT TOLERANCE STUDIES IN DIFFERENT GENOTYPES OF LINSEED UNDER RAINFED CONDITION DR. PANJABRAO DESHMUKH KRISHI VIDYAPEETH].
- Singh, R. (2013). *Effect of Dates of Sowing on Growth, Yield and Quality of Linseed (Linum usitatissimum L.) Varieties* Ph. D. Thesis, Banaras Hindu University Varanasi].
- Stepień, A. E., Trojniak, J., & Tabarkiewicz, J. (2025). Anti-Oxidant and Anti-Cancer Properties of Flaxseed. *International Journal of Molecular Sciences*, 26(3), 1226.

- Tahir, M., & Khaliq, T. (2018). Land use in Pakistan. In *Developing Sustainable Agriculture in Pakistan* (pp. 33-57). CRC Press.
- Tlatlaa, J. S., Tryphone, G. M., & Nassary, E. K. (2024). Impact of sowing date and level of phosphorus application on economic returns in cotton [Original Research]. *Frontiers in Plant Science*, Volume 15 - 2024. <https://doi.org/10.3389/fpls.2024.1402731>
- Ullah, S., Arif, S.M., Aslam, M.A., Khattak, S.H., Begum, S., Ali, G.M., Murtaza, M. and Jamil, M. (2025). Assessment of various herbicides for weed management and their impact on wheat yield components in rice-wheat cropping system in Punjab, Pakistan. *Plant Protection*, 9(1): 173–179.
- Waheed, A., Hussain, A., Hussain, N., Kousar, S., Iqbal, H. I., Arif, M., Gul, N., Ali, S., Rahim, M., & Ahmad, B. (2025). Assessment of Soil Micronutrient Variability and Its Impact on Crop Productivity in District Jhelum, Pakistan. *Pak-Euro Journal of Medical and Life Sciences*, 8(2), 269-278.
- Xie, Y., Li, Y., Qi, Y., Wang, L., Zhao, W., Li, W., Dang, Z., Zhang, J., Wang, X., & Zhang, Y. (2022). Effects of phosphorus supply on seed yield and quality in flax. *Agronomy*, 12(12), 3225.
- Zafar, A., Sarwar, G., Sarfraz, M., Manzoor, M. Z., Muhammad, S., & Murtaza, G. (2020). Dose optimization of NPK fertilizers for growing linseed crop under saline sodic soil environment. *Pakistan Journal of Agricultural Research*, 33(2), 344-350.