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Comparative performance of Chinese and indigenous flaxseed (*Linum usitatissimum* l.) genotypes under NPK and boron nutrition in southern Pakistan

Allah Wadhayo Gandahi[1], Zhao Wei[2*], Adul Ghaffar Shar[3], Aftab Ali Shah[1], Muhammad Saleem Sarki[1], Hajra Khan[4], Wang Limin[2], Qi Yanni[2], Xie Yapping[2]

[1] Department of Soil Science, Sindh Agriculture University, Tandojam 70060, Pakistan
[2] Crop Research Institute, Gansu Academy of Agricultural Sciences, China
[3] Xi'an Fanyi University, Taiyigong, Changan, Shaanxi, China
[4] Oil Seed Research Institute, Agriculture Research Centre, Tandojam 70060, Pakistan
* Corresponding author's e-mail: 308214921@qq.com

ABSTRACT

A field experiment was conducted to evaluate the performance of three Chinese flaxseed (*Linum usitatissimum* L.) genotypes (Longya-10, Longya-14, Longxuan-1,) against local check Ilsi-90 under varying levels of NPK and boron fertilization in the agro-climatic conditions of Sindh, Pakistan. The study followed a factorial randomized complete block design with three replications and five fertilizer treatments: Five fertilizer treatments were applied: F_1 (control) with 0–0–0 NPK + 0.0 kg B ha^{-1}, F_2 with 50–30–20 NPK + 0.5 kg B ha^{-1}, F_3 with 75–45–35 NPK + 1.0 kg B ha^{-1}, F_4 with 100–60–50 NPK + 1.5 kg B ha^{-1}, and F_5 with 120–75–50 NPK + 2.0 kg B ha^{-1}. Data were collected on agronomic traits (plant height, branches per plant, capsules per plant, 1000-seed weight, grain yield, and oil content), as well as nutrient concentrations in leaves and seeds (N, P, K, and B). The results revealed that the combined application of 100–60–50 NPK + 1.5 kg B ha^{-1}, especially in the genotype Longya-14, significantly improved all measured parameters. Longya-14 consistently recorded the highest plant height (78.5 cm), branching (17.0), capsules per plant (12.0), seed weight (7.5 g), grain yield (1089.3 kg ha^{-1}), and oil content (40.12%), along with superior concentrations of N, P, and K in both leaf and seed tissues. Significant treatment × variety interactions were observed for seed potassium and boron content and for leaf phosphorus, potassium, and boron concentrations. These results indicate that balanced NPK fertilization with boron, in combination with nutrient-responsive genotypes like Longya-14, can enhance flaxseed performance and seed nutritional quality under field conditions.

Keywords: flaxseed, NPK, boron, seed nutrient content, leaf nutrient concentration, genotypic response.

INTRODUCTION

Flaxseed (*Linum usitatissimum* L.) is one of the oldest cultivated oilseed crops, belonging to the family Linaceae. Globally, it holds significant economic and nutritional value due to its multifaceted utility in the production of oil, fiber, and functional food ingredients. Originally native to the Mediterranean and West Asian regions, flaxseed has successfully adapted to a variety of temperate and subtropical climates. The oil derived from flaxseed is extensively used in food, pharmaceutical, cosmetic, and industrial applications, while its fiber finds use in textile manufacturing, composite materials, and biodegradable products. Furthermore, flax seeds are ground and utilized to produce linseed meal and oil. Oil is used to make paints, varnishes, printing ink, oil cloth, and soap because it dries quickly in the air (Abdelmasieh et al., 2023).

In Pakistan, flaxseed is primarily cultivated for oil extraction. The oil cake left after processing is used as animal feed and organic fertilizer, while the fiber is utilized in the production of ropes, cloth, and paper. Despite its nutritional and industrial importance, flaxseed cultivation in Pakistan has witnessed a significant decline in recent years. According to official statistics (GoP, 2022), the cultivated area and production in the country dropped to 1,919 hectares and 1.372 tonnes respectively in 2020–21, with Sindh contributing 1,886 hectares and 1,351 tones. New, enhanced, high-yielding and disease resistant varieties must take the place of the outdated ones in farmer fields (Zeng et al., 2015; Mahmoud et al., 2022; Laghari et al., 2024) indicated that the new promising strain (S.651) had the highest percentage of total fiber. According to Elsorady et al. (2022), the new flax strain (S.651) had the highest technical length value, whilst the flax genotypes Giza 12 and Giza 11 provided the maximum straw yield per plant and straw yield per hectare. S.651 also contained the most fiber and moisture of any strain. Furthermore, the flaxseed Sakha 5 genotype had the most oil content, while the flaxseed Sakha 3 genotype had the least. Pakistan flaxseed productivity (692 kg/ha) is much behind that of Germany (1,500 kg/ha), Canada (1,385 kg/ha), Ethiopia (1065 kg/ha) and China (1,000 kg/ha). This necessitates the introduction of improved, high-yielding, and stress-tolerant flaxseed varieties to replace traditional, low-yielding cultivars still used by local farmers.

In this context, three exotic Chinese flaxseed genotypes – Longya-10, Longya-14, and Longxuan-1 – were evaluated against the local check variety Ilsi-90. These Chinese genotypes were selected based on their reported agronomic advantages, such as high oil content, superior seed yield, and better adaptability to drought and low-input conditions. The Longya series, in particular, has shown consistent performance in semi-arid regions of China and is regarded for its resilience under water-limited environments. Compared to local varieties like Ilsi-90, which are still cultivated in parts of Sindh but exhibit low productivity and limited stress resistance, these introduced genotypes offer improved genetic potential. The inclusion of the local check in this study allows for a meaningful comparison to assess the relative advantage and adaptability of the Chinese lines under local agro-climatic conditions.

Soil fertility is a key determinant of crop productivity, and balanced nutrient management is fundamental to realizing the genetic potential of any crop. For flaxseed, the macronutrients along with the micronutrient boron, play critical roles in physiological, biochemical, and reproductive development. Deficiencies in these nutrients not only reduce growth and biomass accumulation but also impair seed yield and oil content. Nitrogen is vital for vegetative growth and protein synthesis. In flaxseed, a balanced nitrogen supply enhances plant height, capsule formation, seed size, and yield. Over 90% of soils in Sindh are deficient in nitrogen, making its proper management essential for improving flaxseed productivity in the region. Phosphorus is indispensable for root development, flowering, seed formation, and energy transfer within the plant. It enhances seed setting, oil synthesis, and physiological maturity. Most Pakistani soils, especially in Sindh, are naturally deficient in phosphorus, underscoring the importance of phosphorus fertilization in flaxseed cultivation. Potassium improves plant vigor, stress tolerance, disease resistance, and seed quality. Potassium deficiency, which affects about 40% of Sindh's soils, contributes to reduced productivity. The application of potassium is particularly crucial under water-deficient or saline conditions (Al-obady and Shaker, 2022). Boron although required in trace amounts, is critical for cell wall development, pollen viability, flower retention, and seed formation. Boron deficiency leads to flower abortion, poor capsule development, and reduced oil quality. Given the low availability of boron in sandy and calcareous soils common in many parts of Sindh its supplementation is necessary to improve seed yield and enhance oil composition.

Despite the recognized importance of N, P, K, and B, there remains a lack of comprehensive studies evaluating their individual and combined effects on flaxseed under the specific agro-climatic conditions of Sindh. Furthermore, genotype-specific nutrient responses have not been adequately explored, although research such as that by Sahito et al. (2022) has shown that different flaxseed varieties respond differently to environmental and nutrient inputs. Among various genotypes studied in Pakistan, performance variation has been noted in traits like plant height, capsule production, seed yield, and oil content, indicating that genotype × nutrient interactions play a crucial role in determining final productivity. This study was therefore undertaken to evaluate the performance of three Chinese flaxseed genotypes in comparison with a local check

(Ilsi-90), and to assess their response to balanced macronutrient and boron application under the nutrient-deficient soils of Sindh.

MATERIALS AND METHODS

Experimental site and design

A field experiment was conducted at the Oil Seed Section, Agricultural Research Centre (ARC), Tandojam. The experiment was laid out in a randomized complete block design (RCBD) with a factorial arrangement comprising three replications.

Experimental treatments

The study consisted of two factors:

- Factor A (flaxseed hybrids):
  V_1 = LONGYA-10
  V_2 = LONGYA-14
  V_3 = LONGXUAN-1
  V_4 = ILSI-90 (Local Check)
- Factor B (NPK + boron levels, all values in kg ha^{-1}):
  F_1 = 0-0-0 NPK + 0.0 B
  F_2 = 50-30-20 NPK + 0.5 B
  F_3 = 75-45-35 NPK + 1.0 B
  F_4 = 100-60-50 NPK + 1.5 B
  F_5 = 120-75-50 NPK + 2.0 B

Plant material

Seeds of flaxseed hybrids (V_1–V_3) were imported from the Gansu Academy of Agricultural Sciences, People's Republic of China, while the local check (V_4) was sourced domestically.

The selected nutrient treatments were designed to represent graduated levels of combined macronutrients (NPK) and boron (B) to evaluate their integrated effect on flaxseed growth, yield, and nutrient uptake. The increasing levels of boron were aligned proportionally with the incremental NPK doses to reflect a practical fertilization gradient, rather than isolating factorial effects of individual nutrients.

Fertilizer application

Phosphorus was applied using single super phosphate (SSP), potassium using sulphate of potash (SOP), and boron using Borax at the time of final seedbed preparation. Urea was used as a nitrogen source and applied in three equal splits as per treatment.

Soil analysis

Composite soil samples were collected from each plot before sowing and after harvest. Analyses included:

- Total nitrogen (N) by Kjeldahl method of Bremner and Mulvaney (1982).
- Available phosphorus (P) and potassium (K) by AB-DTPA extraction.
- Available B was determined by hot water extraction method and was measured colorimetrically using azomethine-H (Bingham, 1982).

Plant analysis

Leaf and seed samples were collected at maturity. Nutrient analyses included:

- Nitrogen (N) by Kjeldahl method, phosphorus and potassium by wet digestion.
- Boron in plant tissue and seed was determined by dry ashing followed by azomethine-H colorimetric (Benton, 2001).

Agronomic observations

Plant height (cm) measured from the plant base to the apex using a measuring scale.

- Branches plant^{-1} – counted manually at maturity.
- Capsules plant^{-1} – counted manually.
- Seeds capsule^{-1} – seeds from randomly selected capsules were counted manually.
- 1000-seed weight (g) – a sample of 1000 seeds were weighed using an electronic balance.
- Seed oil content (%) – determined using the Soxhlet extraction method.

After threshing, the seeds were separated from the straw and weighed per plot area. The seed yield was first calculated in kg m^{-2}, then converted into tons per hectare (t ha^{-1}) using the following formula:

$$Seed\ yield\ (t\ ha^{-1}) = Seed\ yield\ (kg\ m^{-2}) \times 10 \quad (1)$$

Statistical analysis

The data were subjected to analysis of variance (ANOVA) using Statistix 8.1 software.

(Analytical Software, 2005). Treatment means were compared using least significant difference (LSD) at a 5% probability level ($p < 0.05$) (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Agronomic performance of flaxseed varieties as affected by fertilizer treatments

The analysis of variance revealed that fertilizer treatments (T), flaxseed varieties (V), and their interactions (T × V) had a significant ($P < 0.05$) impact on all measured agronomic traits except for the number of branches and capsules per plant, which showed non-significant interaction effects. These findings are summarized in Table 1.

Among the five fertilizer regimes tested, the treatment 100–60–50 NPK + 1.5 kg ha^{-1} B consistently resulted in the highest mean values for growth and yield traits across all varieties. The interaction between this treatment and Longya-14 (V2) was especially pronounced, with the variety recording the tallest plants (78.5 cm), greatest number of branches per plant (17.0), maximum capsules per plant (12.0), and highest 1000-seed weight (7.5 g). This treatment combination also resulted in the maximum grain yield (1089.3 kg ha^{-1}) and oil content (40.12%), significantly outperforming the control and other nutrient levels.

The significant varietal response to nutrient treatment indicates genotypic differences in nutrient use efficiency. The higher yield in Longya-14 under balanced fertilization suggests its superior genetic potential for resource conversion and oil accumulation under optimal nutrient supply.

A significant increase in phenological traits was recorded in plants treated with the full package of blended fertilizer (NPKB). This may be explained by the nutrients' synergistic effects since N is one of the main elements that restrict the growth of plants. An adequate supply of N also encourages the formation of chlorophyll, which in turn raises photosynthetic activity and boosts vegetative growth and taller plants. Furthermore, K is necessary for controlling stomata, which controls the entry of raw materials for photosynthesis, and water regulation. Phosphorus is necessary for the development of shoots and roots, where metabolism is high and cell division is rapid (Vale et al., 2011). Balanced availability of nitrogen, phosphorus, and potassium, which are essential for cell division, elongation, and vegetative development, while boron contributed to cell wall structure and elongation. The experimental results are in line with those of Kumar et al. (2016), Chopra and Badiyala (2016), Kurrey and Singh (2019) and Shivanand et al. (2025). These results are also consistent with findings by Yadav et al. (2020) which emphasize the role of N, P, and K in photosynthesis, energy metabolism, and physiological function. Branching was also enhanced by fertilizer application, although the genotype × fertilizer interaction was not statistically significant. Longya-14 still recorded the highest number of branches, suggesting a genetic predisposition supported by boron-enhanced lateral bud activation (Sahu et al., 2024). Capsule number per plant, a direct yield component, reached its peak under 100–60–50 NPK + 1.5 B, likely due to improved pollen viability and reproductive organ development supported by boron (Darule et al., 2024). Seed weight and seed index were significantly influenced by both genotype and fertilization, with Longya-14 under optimal nutrient supply achieving the highest seed index, possibly due to more efficient assimilating partitioning and seed filling. Finally, grain yield increased significantly with optimized fertilization, a reflection of the cumulative effects of improved vegetative and reproductive performance. Oil content also responded positively to nutrient application, with the highest values recorded under 75–45–35 and 100–60–50 NPK + B treatments. While varietal differences in oil content were not statistically significant, Longya-14 consistently produced higher oil levels, likely due to enhanced lipid biosynthesis under nutrient-sufficient conditions (Ehrensing, 2008). The results emphasize the significance of nutrient management in enhancing linseed yield, specifically highlighting the pivotal role of NPKB fertilizer in optimizing production. This finding aligns with nutrient efficiency principles, suggesting targeted nutrient applications can maximize crop output. Such insights advance current studies by elucidating the interaction between specific nutrients and yield components (Zhang et al., 2021).

Plant leaf N, P, K and B content of flaxseed varieties as affected by fertilizer treatments

Results shown in Table 2 revealed that Leaf nutrient concentrations of N, P, K, and B in flaxseed were significantly influenced by fertilizer

Table 1. Effect of fertilizer treatments on agronomic traits of flaxseed varieties

Fertilizer treatments (kg ha^{-1})	Plant height (cm)	Number of branches $plant^{-1}$	Number of capsules $plant^{-1}$	1000-seed index (g)	Grain yield (kg ha^{-1})	Oil content (%)
Control	27.3 D	3.25 D	3.0 E	1.83 C	786.04 BC	36.153 C
50-30-20 NPK+0.5 B	57.3 C	10.5 C	5.9 CD	3.33 B	768.98 C	27.651 B
75-45-35 NPK +1.0 B	68.3 B	11.04 C	6.9 BC	3.98 B	811.34 BC	39.198 A
100-60-50 NPK +1.5 B	72.3 A	15.83 A	9.1 A	5.13 A	936.43 A	39.233 A
120-75-50 NPK+2.0 B	67.5 B	13.21 B	7.5 B	3.93 B	886.57 AB	38.533 AB
LSD (0.05)	3.9127	3.8598	1.1197	0.4199	115.54	1.1057
Varieties						
Longya-10	60.9 B	10.1 B	6.1 BC	2.94 C	672.79 C	38.027 A
Longya-14	64.2 A	13.2 A	8.1 A	5.14 A	971.94 A	38.642 A
Lonxuan-1	58.8 C	10.4 C	6.6 B	3.66 B	894.04 AB	38.134 A
Ilsi-90	50.3 D	9.4 C	5.2 C	2.8 C	812.73 B	37.812 A
LSD (0.05)	3.4996	3.4523	1.0014	0.3756	103.34	0.9889
Significance Treatments (T)	**	**	**	**	**	**
Varieties (V)	**	Ns	**	**	**	Ns
T X V	**	Ns	Ns	**	Ns	Ns

Note: ** – significant at p = 0.05, NS = non-significant, abc – means followed by common letter are similar at 5% probability level.

treatments, genotypic variation, and their interactions in some cases. Among the treatments, application of 100–60–50 NPK + 1.5 kg ha^{-1} B consistently resulted in the highest leaf nutrient concentrations, with values of 0.81% N, 0.6842% P, 0.71% K, and 10.45 mg kg^{-1} B. These values were significantly higher than those observed in the control treatment, which recorded 0.252% N, 0.6842% P, 0.318% K, and 8.62 mg kg^{-1} B, demonstrating the profound impact of balanced fertilization on nutrient uptake and internal nutrient accumulation in the vegetative tissues of flaxseed. The increasing trend in nutrient concentration with increasing levels of applied NPK and B confirms the synergistic role of macronutrients and micronutrients in promoting effective nutrient assimilation. However, it was evident that beyond the optimum level (i.e., 100–60–50 NPK + 1.5 B), further increase to 120–75–50 NPK + 2.0 B did not result in statistically significant improvement in nutrient concentrations (Table 2). This suggests that there is a nutrient saturation point beyond which plant uptake efficiency does not increase proportionally, possibly due to physiological thresholds or nutrient antagonism. Regarding varietal response, Longya-14 (V2) demonstrated the highest nutrient concentrations in leaf tissues, with 0.73% N, 0.748% P, 0.66% K, and 9.60 mg kg^{-1} B. This was followed by Lonxuan-1 and Longya-10, while Ilsi-90 (V4) recorded the lowest values, particularly for nitrogen (0.33%), phosphorus (0.486%), and potassium (0.41%). Interestingly, the highest boron concentration in leaves (10.9 mg kg^{-1}) was observed in Ilsi-90, but only under the 100–60–50 NPK + 1.5 B treatment. This unique response suggests that while Ilsi-90 may be less efficient in uptake of major nutrients, it may have a higher affinity for boron under certain conditions. Statistical analysis revealed that the main effects of both fertilizer treatment (T) and variety (V) were highly significant ($P < 0.001$) for all nutrients. The T × V interaction was also significant for phosphorus, potassium, and boron, but not for nitrogen, indicating that genotypic differences played a larger role in the accumulation of P, K, and B, while N uptake was uniformly influenced by fertilization across all genotypes. This interaction effect emphasizes the importance of matching fertilizer management with genotype-specific nutrient demand for optimized leaf nutrition. Physiologically, higher concentrations of leaf N, P, and K are directly associated with enhanced chlorophyll content, energy transfer, and osmotic regulation, all of which are crucial during the vegetative growth phase. Elevated boron levels, on the other hand, are known to improve cell wall stability, membrane function, and carbohydrate translocation – functions vital

Table 2. Leaf nutrient content of flaxseed varieties under fertilizer treatments

Fertilizer treatments (kg ha^{-1})	Leaf N	Leaf P	Leaf K	Leaf B
	(%)			(mg kg^{-1})
Control	0.252 C	0.6842 C	0.318 DE	8.62 CD
50-30-20 NPK+0.5 B	0.64 B	0.6075 B	0.38 D	8.80 C
75-45-35 NPK +1.0 B	0.67 B	0.6258 AB	0.53 BC	9.70 B
100-60-50 NPK +1.5 B	0.81 A	0.6842 A	0.71 A	10.45 A
120-75-50 NPK+2.0 B	0.67 B	0.6117 B	0.59 B	9.67 B
LSD (0.05)	0.0915	0.0653	0.0455	0.0558
Varieties				
Longya-10	0.68 B	0.5347 C	0.47 C	9.35 BC
Longya-14	0.73 A	0.748 A	0.66 A	9.60 A
Lonxuan-1	0.68 B	0.594 B	0.50 B	9.43 B
Ilsi-90	0.33 C	0.486 C	0.41 CD	9.42 B
LSD (0.05)	0.0818	0.0584	0.0407	0.0499
Significance treatments (T)	**	**	**	**
Varieties (V)	**	**	**	**
T X V	Ns	**	**	**

Note: ** – significant at p = 0.05, NS – non-significant, abc – means followed by common letter are similar at 5% probability level.

for reproductive development. The improved leaf nutrient status under balanced NPK + B application, especially in Longya-14, likely contributed to the superior yield components and seed quality observed in this variety in related results. Enhanced nutrient concentrations under optimal fertilizer conditions likely contributed to better physiological functioning, such as improved chlorophyll biosynthesis, enzyme activation, and reproductive readiness. These observations align with earlier studies that emphasize the close link between leaf nutrient status and vegetative vigor, which ultimately affects yield potential (Klimek-Kopyra et al., 2022).

Seed Nutrient (N,P,K and B) content in flaxseed varieties as affected by fertilizer treatments

Seed nutrient content in flaxseed was significantly influenced by fertilizer treatments, varieties, and their interactions for specific nutrients. Application of NPK along with boron substantially improved the accumulation of nitrogen (N), phosphorus (P), potassium (K), and boron (B) in seeds compared to the control. The fertilizer treatment of 100–60–50 NPK + 1.5 kg ha^{-1} B consistently resulted in the highest seed nutrient concentrations, with values reaching 3.91% N, 1.56% P, 0.67% K, and 10.45 mg kg^{-1} B, all statistically superior to other treatments. This indicates that a balanced supply of macronutrients, particularly when supplemented with boron, plays a critical role in enhancing nutrient translocation into reproductive organs such as seeds. Although a further increase in nutrient level to 120–75–50 NPK + 2.0 B maintained high values, it did not lead to significant additional improvement, suggesting that 100–60–50 NPK + 1.5 B represents the optimum dose for nutrient enrichment in flaxseed. Varietal differences were also pronounced. Among the four genotypes, Longya-14 stood out with significantly higher seed phosphorus (1.51%), potassium (0.60%), and boron content (9.59 mg kg^{-1}), and a relatively higher nitrogen content (3.72%), indicating its superior genetic potential for nutrient uptake and efficient partitioning into seeds. In contrast, Ilsi-90 consistently recorded the lowest seed nutrient values, reflecting its limited responsiveness to nutrient application. Interaction effects between treatments and varieties were non-significant for nitrogen and phosphorus, suggesting consistent varietal responses to these nutrients across treatments. However, significant T × V interactions for potassium and boron suggest that seed enrichment with these nutrients is more dependent on specific genotype-treatment combinations. These findings highlight the importance

Table 3. Seed nutrient content in flaxseed varieties as affected by fertilizer treatments

Fertilizer treatments (kg ha^{-1})	Seed N	Seed P	Seed K	Seed B
	(%)			mg kg^{-1}
Control	2.26 E	0.85 E	0.29 E	8.62 CD
50-30-20 NPK+0.5 B	3.48 ABCD	1.22 ABCD	0.52 BCD	8.80 C
75-45-35 NPK +1.0 B	3.61 ABC	1.40 AB	0.55 BC	9.70 B
100-60-50 NPK +1.5 B	3.91 A	1.56 A	0.67 A	10.45 A
120-75-50 NPK+2.0 B	3.75 AB	1.30 ABC	0.57 B	9.67 B
LSD (0.05)	0.3470	0.1091	0.0424	0.1954
Varieties				
Longya-10	3.40 B	1.22 ABC	0.48 C	9.34 BC
Longya-14	3.72 A	1.51 A	0.60 A	9.59 A
Lonxuan-1	3.40 B	1.25 AB	0.52 B	9.43 B
Ilsi-90	3.10 BC	1.07 ABCD	0.47 CD	9.43 B
LSD (0.05)	0.3103	0.0975	0.0380	0.1748
Significance treatments (T)	**	**	**	**
Varieties (V)	**	**	**	**
T X V	Ns	Ns	**	**

Note: ** – significant at p = 0.05, NS = non-significant, abc – means followed by common letter are similar at 5% probability level.

of both optimized fertilizer application and genotype selection in improving seed nutritional quality. In particular, the combination of Longya-14 and 100–60–50 NPK + 1.5 B emerges as the most promising strategy for producing nutrient-rich flaxseed under field conditions.

The findings of this study, which demonstrate significant improvements in seed nitrogen, phosphorus, potassium, and boron content in flaxseed varieties following the application of 100–60–50 NPK + 1.5 kg ha^{-1} B, are in agreement with several previous studies. Jankauskienė et al. (2003) reported similar nutrient concentrations in flaxseed, with seed N, P, K, and B values aligning closely with those observed under optimal fertilization in the present study. The positive response of seed phosphorus content to P application also supports the work of Xie et al. (2013), who highlighted phosphorus's critical role in capsule formation, seed weight, and phosphorus use efficiency. Likewise Abdel-Bakry et al. (2015) and Almas et al. (2023) demonstrated that the combined application of potassium and micronutrients such as boron enhanced yield components, including branching and 1000-seed weight, similar to the synergistic effect noted in our Longya-14 genotype. Bungla et al. (2021) and Khan et al. (2023) further corroborated that boron levels around 1.5 kg ha^{-1} optimize seed boron content and yield in linseed, indicating that higher boron doses may not offer additional benefits – consistent with the plateauing effect seen at 2.0 kg ha^{-1} B in our study. These findings reinforce the conclusion that balanced macronutrient application, particularly when supplemented with boron, significantly enhances nutrient partitioning into flaxseed. However, it is worth noting that some field-based extension recommendations, such as those by the North Dakota State University (NDSU, 2022), suggest more conservative fertilizer use in flax based on soil test results, which may differ from controlled experimental conditions. Overall, our results are strongly supported by both experimental and field literature, emphasizing the importance of genotype-specific nutrient management for improving seed nutritional quality in flax.

CONCLUSIONS

The present study demonstrates that flaxseed growth, yield, and seed quality were significantly enhanced by balanced application of NPK in combination with boron. The fertilizer treatment of 100–60–50 NPK + 1.5 kg ha^{-1} B proved to be the most effective across all measured agronomic and physiological parameters. This treatment led to significant improvements in plant height, branching, capsule number, seed weight, and oil content. It also resulted in higher leaf and seed nutrient concentrations of nitrogen, phosphorus, potassium, and boron. Among the genotypes tested, Longya-14 consistently exhibited the highest performance, reflecting its strong genetic potential and nutrient responsiveness. Significant interactions between treatment and variety for certain nutrient parameters suggest the need for genotype-specific nutrient strategies to maximize crop productivity. These findings confirm that the selection of responsive genotypes like Longya-14, when combined with appropriate fertilization regimes, can substantially improve both yield and seed nutritional value of flaxseed in Pakistan's field conditions.

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