International Journal of Agriculture and Biosciences 2025 14(6): 1261-1270.
https://doi.org/10.47278/journal.ijab/2025.141

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Foliar Fertilization Enhances Oil Flax Yield and Quality in Semi-arid Rainfed Zones

Almagul Malimbayeva [1], Batyrgali Amangaliyev [1], Erbol Zhusupbekov [1], Zhuldyz Oshakbayeva [2], Akerke Soltanayeva [1], Aina Sagimbayeva [1], Karlyga Rustemova [1] and Maksat Batyrbek [1,*]

[1]Kazakh Research Institute of Agriculture and Plant Growing, Almalybak village 040909, Karasai district, Almaty region, Kazakhstan
[2]Kostanay Engineering and Economics University named after M. Dulatov, Kostanay, Kazakhstan
*Corresponding author: batyrbek-maksat@bk.ru; maksat.batyrbek@outlook.com

ABSTRACT

The effectiveness of micronutrients, complex fertilizers with chelated trace elements, and biofertilizers in oil flax cultivation under rainfed conditions in southeastern Kazakhstan remains underexplored. This study aimed to evaluate the impact of foliar fertilization using tank mixes of macro- and micronutrients, complex fertilizers (brands: 13-40-13, 12-12-36, 3-11-38), and the biofertilizer Terra Sorb Complex on the productivity and seed quality of oil flax. Field experiments were conducted on light chestnut soils in the Almaty region during favorable weather conditions with adequate soil moisture and moderate temperatures. Results showed that treatments involving four foliar applications of a tank mix containing MACRO+MICRO elements and NPK fertilizers with chelated elements significantly increased seed count per capsule by 2.1seeds compared to the control. The highest 1000-seed weight (7.2g) was achieved with three or four foliar applications of macro- and micronutrient tank mixes or complex fertilizers with chelated elements, combined with pre-sowing biofertilizer treatment. The maximum seed yield (0.89t/ha) was observed with four foliar applications of MACRO+MICRO elements or NPK fertilizers with chelated elements, representing a 19.2% increase over the control. Additionally, fat content in seeds reached 42.0%, and protein content peaked at 28.4% with foliar treatments. These findings highlight the potential of foliar fertilization to enhance oil flax productivity and seed quality under rainfed conditions.

Keywords: Oil flax, Micronutrient, Crop foliar fertilization, Seed yield, Seed quality.

Article History
Article # 25-299
Received: 23-May-25
Revised: 12-Jun-25
Accepted: 09-Jul-25
Online First: 31-Aug-25

INTRODUCTION

The cultivation of flax has expanded in response to the rising demand for flax-based products. Modern flax cultivars contain up to 50% oil in their seeds, although the biological maximum of 60% has yet to be reached. Globally, oil flax is cultivated on approximately 2.5 to 3.2 million hectares, producing an estimated 1.9 to 2.7 million tons of seeds (Amangaliev et al., 2023). In modern agriculture, achieving high and sustainable yields of crops requires more than just the application of mineral fertilizers (Zafar et al., 2025). It also necessitates the use of micronutrients, complex fertilizers containing chelated forms of microelements, biofertilizers, and other supplements. One of the most effective and simple methods of applying micronutrients is pre-sowing seed treatment. This method provides plants with microelements at the very beginning of their growth, stimulating physiological and biochemical processes in germinating seeds. For this purpose, salts of microelements are commonly used (Bobrenko et al., 2020; Gopalsamy et al., 2025).

Modern micronutrients are highly soluble in water, have prolonged effects, and can be used in combination with plant protection agents. By supplying plants with essential nutrients and boosting their immunity, these products are environmentally friendly and easy to use (Bora, 2022; Trukhachev et al., 2023; Zuma et al., 2023). Currently, microelements in agriculture are primarily applied in the form of chelates. Chelated compounds facilitate the absorption of microelements by plants, as their structure and properties are similar to those naturally occurring in living organisms. The organic shell of the chelate can penetrate the waxy coating of a leaf and

Cite this Article as: Malimbayeva A, Amangaliyev B, Zhusupbekov E, Oshakbayeva Z, Soltanayeva A, Sagimbayeva A, Rustemova K and Batyrbek M, 2025. Foliar fertilization enhances oil flax yield and quality in semi-arid rainfed zones. International Journal of Agriculture and Biosciences 14(6): 1261-1270. https://doi.org/10.47278/journal.ijab/2025.141

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deliver nutrients directly to the plant, unlike inorganic elements, which cannot as easily bypass the protective barrier (Madhupriyaa et al., 2024; Feizi et al., 2025). Research by scientists and practical agricultural experience have shown that water-soluble complex fertilizers and biological fertilizers positively influence crop yields (Lamlom et al., 2023). Creating optimal nutritional conditions for plants throughout the growing season requires the proper combination of base fertilizers and supplementary feedings (Saquee et al., 2023). The foundation of complex fertilizers (NPK) consists of simple water-soluble salts in various combinations to meet the needs of plants during different stages of growth and development. The action of foliar fertilizers in non-root feedings is based on the rapid incorporation of essential nutrients into metabolism, influencing major metabolic processes independently of the root system. The significant yield increase is associated with improved root absorption of nutrients by 10-15% (Liu, et al., 2020; Ganguly et al., 2021; Zharkikh et al., 2025).

Tank mixtures of water-soluble simple and complex fertilizers are prepared considering the crop's nutrient requirements at specific stages of organogenesis. The set of nutrients is adjusted based on the biological needs of the crop during critical periods of growth and development. These mixtures can be used alongside pesticides, reducing their stress-inducing effects on plants without compromising their efficacy. By mixing various types and forms of fertilizers in tank solutions, it is possible to influence the content of proteins, sugars, and fats in the reproductive organs of plants (Dhaliwal et al., 2023; Khan et al., 2024). Biofertilizers or organic bioproducts (based on seaweed, vermicompost, etc.) are specialized anti-stress fertilizers with high concentrations of various amino acids. Their application helps plants overcome stressful situations, stimulates metabolism and nutrient absorption, and significantly improves yield and quality of agricultural products even under unfavorable environmental conditions (Karthik and Jayasri, 2023).

According to Dolgopolova et al. (2022), foliar feeding does not replace the main fertilizer application but can serve as the only viable additional source of mineral nutrients in some cases. Leaves quickly absorb nitrogen, phosphorus, potassium, magnesium, and microelements, which are either directly incorporated into the synthesis of organic substances or transported to other plant organs for intracellular metabolism. This process positively influences key physiological activities. Foliar feeding has been widely adopted in the production practices of various crops across diverse climatic regions in Europe, Australia, United States of America, Canada, China, and Russia. The effectiveness of foliar feeding, depending on its precision during the critical phase of field crops, can increase yields by 11-18% or more (Lafond et al., 2003; Cui et al., 2022; Amangaliev et al., 2023; Stavropoulos et al., 2023).

In the agricultural practices of Kazakhstan, traditional simple and complex fertilizers such as superphosphate, Monoammonium phosphate (MAP), ammonium nitrate, urea, and potassium chloride are commonly used for oil flax. These fertilizers contain nutrients in salt form, are poorly soluble, and often precipitate, resulting in plant absorption rates of only 30-35%.

A promising direction in intensive farming for crop cultivation is the introduction of innovative fertilizers, such as complex fertilizers with chelated forms of microelements, the preparation of balanced nutrient tank mixtures with water-soluble fertilizers, and organic biofertilizers. The objective of this study is to evaluate the effectiveness of traditional and innovative fertilizer applications, including seed treatment and foliar feeding, on the growth, yield, and quality indicators of oil flax under rainfed conditions in the semi-arid southeastern region of Kazakhstan.

MATERIALS & METHODS

The experimental research was conducted in 2024 on an experimental field of the Soil Science and Agrochemistry Laboratory of the Kazakh Research Institute of Agriculture and Plant Growing (43°13′N, 76°41′E, 740m asl) (Fig. 1), focusing on oil flax crops.

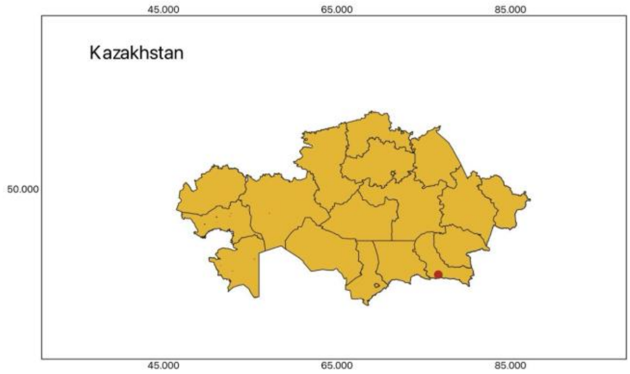

Fig. 1: Map of research area.

The soil of the rainfed plot is represented by light chestnut soil with a medium loamy composition and a moderately thick humus horizon (0-46cm), formed from loess-like loams and clays. The soil in the experimental plot contains a low amount of total humus in the arable layer, ranging from 1.60% to 1.90%. The total nitrogen content is 0.15%, total phosphorus is 0.21%, and total potassium is 1.67%. The reaction of the soil in the arable horizon is slightly to moderately alkaline, with pH values ranging from 7.8 to 8.2. The experiment was structured spatially and temporally with three replicates, 13 treatments: I-Control (without fertilizers), II-N60P60K60, III-N60P60K60 (background) + Seed Treatment–, IV-Background + 3 Foliar Treatments with Tank Mixture of Macro + Micronutrients, V-Background + 4 Foliar Treatments with Tank Mixture of Macro + Micronutrients, VI-Background + 3 Foliar Treatments with Biofertilizer, VII-Background + 4 Foliar Treatments with Biofertilizer, VIII-Background + 3 Foliar Treatments with NPK and Micronutrients (brands: 13-40-13; 12-12-36), IX -Background + 4 Foliar Treatments with NPK and Micronutrients (brands: 13-40-13; 12-12-36; 3-11-38), X-Background + 3 Foliar Treatments with Macro + Micronutrients + Biofertilizer, XI-Background + 4 Foliar Treatments with Macro + Micronutrients + Biofertilizer, XII-Background + 3 Foliar

Treatments with NPK and Micronutrients + Biofertilizer, XIII-Background + 4 Foliar Treatments with NPK and Micronutrients + Biofertilizer. The arrangement of the plots was systematic, and treatments within replicates were randomized. The area of each experimental plot was 25m². The predecessor crop for oil flax was spring barley. Sowing was carried out at optimal dates (April 1–5) using an Agromaster seeder at a seeding rate of 40 $kg.ha^{-1}$. The seed sowing depth was 2–3cm. The experiment included various types, forms, methods, and timings of fertilizer application:

Mineral fertilizers: Urea (N-46%), Monoammonium phosphate (MAP) (N-12%, P-52%), and potassium sulfate (K-50%) were applied in spring before sowing during cultivation. Monoammonium phosphate (N-12%, P-52%) and potassium sulfate (K-50%) were also applied in autumn during primary soil preparation (plowing to a depth of 20–22cm) at a rate of 60kg of active substance per hectare.

Biofertilizer: Terra Sorb Complex was used, containing free amino acids 20.0%, organic nitrogen 5%, total nitrogen 5.5%, boron 1.5%, manganese 0.1%, copper 0.25%, zinc 0.1%, iron 1%, magnesium 0.8%, molybdenum 0.001%, total organic matter 25%. The biofertilizer was applied during pre-sowing seed treatment at a rate of $4.5Lt^{-1}$ and as foliar feeding at a dose of $2Lha^{-1}$ at the following growth phases: 5–6 leaf stage early "fir tree" phase, 8–9 leaf stage "Fir tree" phase, budding phase, flowering phase.

A tank mixture consisting of the following macro and micronutrients was used for foliar feeding during various growth stages: Urea (N - 46.2%), $5kgha^{-1}$. Magnesium sulfate (Mg - 16%, SO_3 - 32%), 1 kg ha^{-1}. Monopotassium phosphate (P_2O_5 - 52%, K_2O - 34%) or Potassium sulfate (K_2O - 51%, SO_4 - 45%), $1kgha^{-1}$. Bortrac 150 (B - 11%, N - 4.7% + adjuvants) and Zintrac 700 (Zn - 40%, N - 1% + adjuvants), $0.1kgha^{-1}$. This mixture was applied during the following growth phases: 5–6 leaf stage early "fir tree" phase, 8–9 leaf stage "Fir tree" phase, budding phase, flowering phase.

Chelated complex fertilizers (brands: 13-40-13, 12-12-36, 3-11-38) were applied via foliar feeding at a rate of $2kgha^{-1}$ during the specified growth stages. To control weed infestations in oil flax crops, herbicide application was conducted during the "fir tree" phase using a tank mixture of Samurai Super ($0.54kgha^{-1}$) and Herbitox ($0.54Lha^{-1}$). The yield of oil flax was determined according to Arslanoglu et al. (2022). Quality parameters of plant samples were analyzed in the laboratory for technological grain evaluation. Protein content was measured using the Kjeldahl method and infrared spectroscopy (FOSS), while fat content was determined using infrared spectroscopy. Statistical analysis was conducted to assess the reliability of the obtained results. The experimental results were analyzed by SPSS software generally accepted method comparing variations between different treatments (Gerber and Green, 2012). The analysis of essential nutrients nitrogen determined by Keldal method (Goyal et al., 2022), while phosphorus and potassium were determined by Michigan method in modification of the Central Research Institute of Agrochemical Services for Agriculture State Standard 26205-91. Exchangeable potassium was calculated on a flame photometer following State Standard 26205-91 (Batyrbek et al., 2022).

This year, favorable meteorological conditions were observed for the growth of oil flax (Fig. 2). In April, a significant amount of precipitation, 111.3mm, or 100.6% of the long-term average, was recorded, accompanied by an average monthly air temperature of 12.8°C. These conditions positively influenced the uniform emergence of seedlings and the subsequent growth and development of oil flax plants during the post-emergence period. May was warm, with an average air temperature of 17.6°C, and frequent rains of varying intensity. Total precipitation for the month was 121mm, exceeding the long-term average by 123.1%.

Fig. 2: Oil flax research field.

In June, there was a noticeable increase in air temperature 3.3°C above the long-term average. However, precipitation during this month was minimal, at only 18.0mm. Despite the low rainfall, sufficient soil moisture remained in the one-meter soil layer due to the May rains.

In early July, most of the precipitation occurred, totaling 57.0mm, which was consistent with the long-term average. During the second ten-day period of July, precipitation decreased to 27.4mm, and the air temperature rose to 24.0°C. These conditions facilitated the full ripening of oil flax plants by the beginning of the third ten-day period in July (Fig. 3).

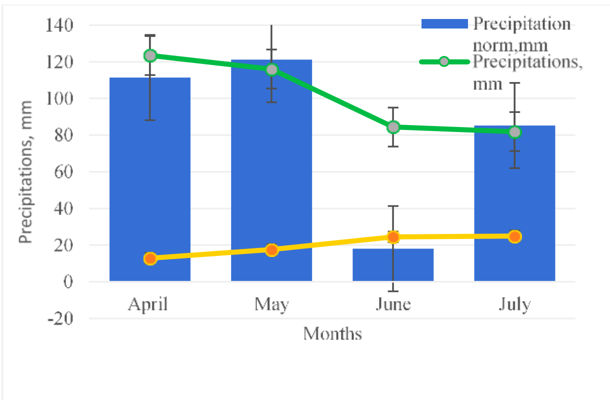

Fig. 3: Weather Conditions during the Vegetation Period of Oil Flax.

RESULTS

Humus Contents in Soil

The results demonstrated significant variations in labile humus, total humus content, and soil humus levels across different growth stages under various fertilization treatments (Fig. 4). Labile humus content ranged from 1.52mgkg^{-1} to 1.86mgkg^{-1} across treatments. The highest value was recorded in treatment XI (1.86±0.09mgkg^{-1}), while the lowest was observed in the control (1.52±0.06mgkg^{-1}). Other treatments with foliar fertilization, particularly X (1.71±0.1mgkg^{-1}) and XII (1.68±0.08mgkg^{-1}), also demonstrated higher labile humus levels compared to the control. Total humus content varied significantly, with the highest values recorded in treatments I and IV (1730mgkg^{-1}), while the lowest were observed in treatments V and VII (1330mgkg^{-1}). At the shoot formation stage, treatment IV (1560±95mgkg^{-1}) exhibited the highest humus content, whereas treatment VII (1255±105mgkg^{-1}) had the lowest. A similar trend was observed at the budding stage, where treatment IV (1480±151mgkg^{-1}) and XIII (1480±105mgkg^{-1}) maintained significantly higher humus content than the control (1250±105mgkg^{-1}). Before harvest, total humus content remained highest in treatments IV and XIII (1480±151mgkg^{-1} – 1480±105mgkg^{-}mg kg^{1}), whereas treatments V, VII, and VIII exhibited the lowest values (1120±72 – 1130±115mgkg^{-}kg^{1}).

Nitrate Nitrogen, Mobile Phosphorus and Exchangeable Potassium Changes

The study revealed significant variations in nitrate nitrogen, mobile phosphorus, and exchangeable potassium levels in the soil across different treatments and growth stages (Fig. 5).

For nitrate nitrogen, the highest concentrations were observed at the shoots stage, with values ranging from 23±3mgkg^{-1} in the control (I) to 42±6mgkg^{-1} in treatment VI. As plant growth progressed, nitrate nitrogen levels declined across all treatments, reaching their lowest levels before harvesting (11±2mgkg^{-1} in the control and 24±6mgkg^{-1} in treatment VI). Treatments with foliar fertilization, particularly those including macro and micronutrients, demonstrated significantly higher nitrate nitrogen availability compared to the control. Mobile phosphorus content also exhibited treatment-dependent variations. At the shoots stage, concentrations ranged from 23±4mgkg^{-1} in the control to 40±6mgkg^{-1} in treatment VII. By the budding stage, phosphorus levels increased in most treatments, with the highest values recorded in treatments IX (36±6mgkg^{-1}) and VIII (35±4mgkg^{-1}). However, at the harvesting stage, phosphorus levels declined, with the lowest in the control (17±3mgkg^{-1}) and the highest in treatment IX (32±5mgkg^{-1}). Treatments with repeated foliar fertilization demonstrated better phosphorus retention in the soil. Regarding exchangeable potassium, the control treatment consistently showed the lowest values throughout the growth stages. At the shoots stage, potassium ranged from 271±10mgkg^{-1} (control) to 340±13 mg kg^{-1} (treatment VI). At the budding stage, potassium content remained highest in treatments VIII (298±12mgkg^{-1}) and IX (301±9mgkg^{-1}), while the control recorded the lowest value (243±12mgkg^{-1}). By the harvesting stage, potassium levels declined in all treatments, with the lowest in the control (212±11mgkg^{-1}) and the highest in treatment VIII (280±6mgkg^{-1}).

Effect of Foliar Fertilization on Plant Density, the Number of Capsules per Plant, the Number of Seeds per Capsule and 1000 Seed Weight

Favorable soil moisture conditions during the vegetation period of oil flax, combined with the application of tank mixtures of macro and micronutrients, complex fertilizers with chelated micronutrient forms, the biological fertilizer Terra Sorb Complex, and mineral fertilizers, positively influenced the formation of the main indicators of yield structure elements.

The experiment revealed significant variations in plant density, the number of capsules per plant, the number of seeds per capsule, and 1000 seed weight among different fertilization treatments. Plant density was lowest in the control treatment (244±8.5plants/m^2), while the highest values were observed in treatments V (296±8.2plants/m^2) and IX (296±5.0plants/m^2), both of which included foliar fertilization. In general, treatments that incorporated foliar applications of macro- and micronutrients demonstrated increased plant density compared to the control. A similar trend was observed for the number of capsules per plant, where the control had the lowest value (9.1±0.7), and the highest number was recorded in treatment V (17.9±0.7).

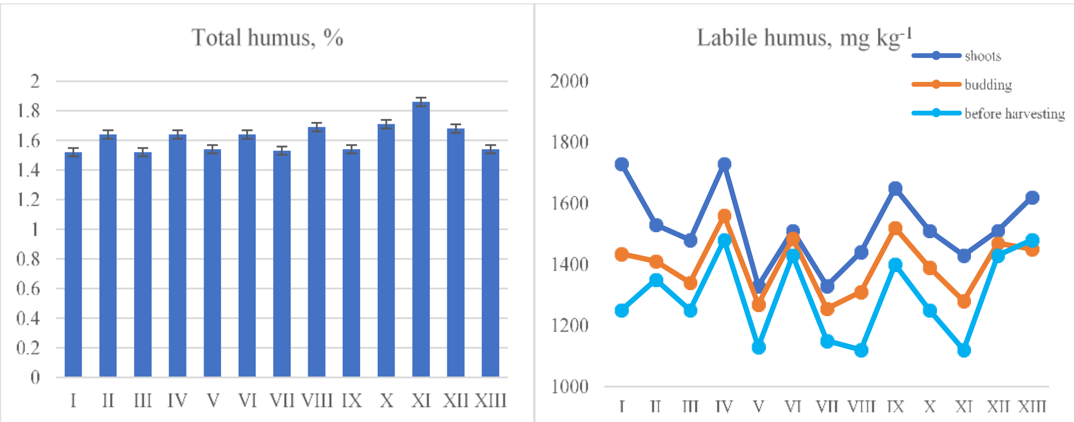

Fig. 4: Total and labile humus changes.

Table 1: Influence of foliar application on plant growth and yield components

Treatments	Plant Density (plants/m²)	Capsules/plant	Seeds/capsule	1000 Seed Weight (g)
I	244±8.5b	9.1±0.7g	5.1±0.8b	6.0±0.7a
II	250±4.6b	10.2±0.5g	5.5±0.8ab	7.0±1.1a
III	252±8.2b	10.6±0.9g	5.6±1.0ab	7.0±0.8a
IV	292±7.5a	16.8±1.4ab	7.0±1.0a	7.2±1.1a
V	296±8.2a	17.9±0.7a	7.2±0.7a	7.2±1.0a
VI	254±7.2b	12.5±0.7f	5.7±0.9ab	7.0±0.9a
VII	257±4.6b	13.3±1.0ef	5.8±1.0ab	7.0±0.5a
VIII	292±10.5a	16.1±1.0bc	6.9±0.8a	7.2±1.0a
IX	296±5.0a	17.2±1.3ab	7.2±0.8a	7.2±0.9a
X	284±8.2a	14.4±0.8de	5.9±0.9ab	7.1±0.8a
XI	285±6.6a	14.9±0.3cd	6.0±0.8ab	7.1±0.7a
XII	287±8.5a	15.0±0.8cd	6.5±1.1ab	7.0±1.0a
XIII	289±5.6a	15.7±1.0bcd	6.2±0.9ab	7.0±0.8a

Values (mean±SD) bearing different letters in a column indicate significant (P<0.05) difference.

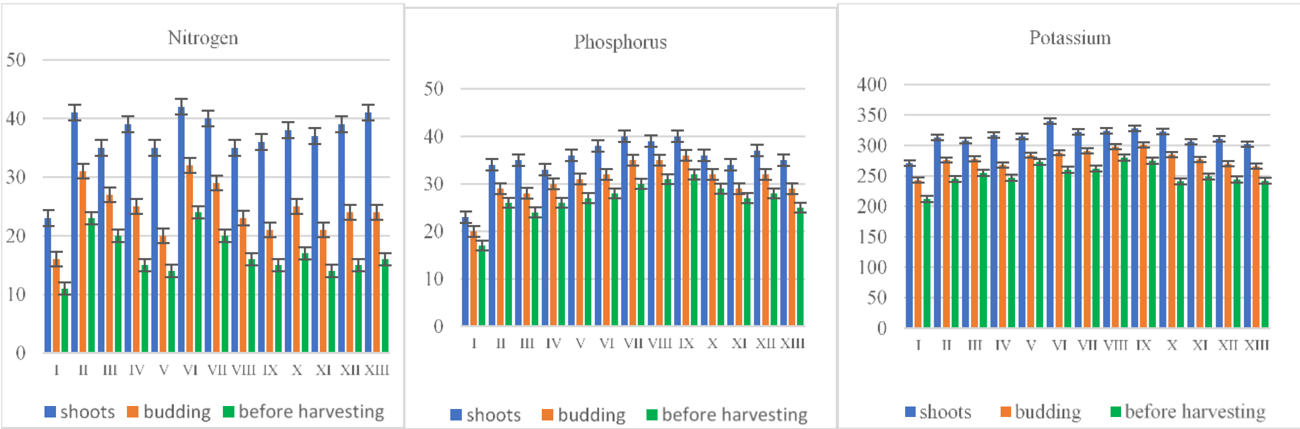

Fig. 5: Nitrate nitrogen, mobile phosphorus, and exchangeable potassium changes during the vegetation period of oilseed flax.

Treatments incorporating multiple foliar applications, particularly VIII (16.1±1.0) and IX (17.2±1.3), significantly outperformed the control, highlighting the beneficial effects of foliar fertilization on reproductive development. The number of seeds per capsule followed a comparable pattern, with the lowest value in the control (5.1±0.8) and the highest values in treatments V and IX (7.2±0.7 – 7.2±0.8). Notably, treatments with four foliar applications tended to produce more seeds per capsule compared to those with only three applications, emphasizing the importance of repeated foliar nutrition. Regarding seed quality, the 1000 seed weight exhibited slight variations across treatments. The lowest weight was recorded in the control (6.0±0.7g), while the highest values were found in treatments IV-V and VIII-IX. Although differences were not always statistically significant, the results suggest that foliar fertilization, particularly with macro- and micronutrients, contributes to improved seed weight. Overall, the findings indicate that foliar fertilization enhances key yield components of oil flax, with treatments V and IX showing the most pronounced improvements. Additionally, biofertilizer-based treatments (X-XIII) also demonstrated positive effects, suggesting their potential role in improving yield and quality under semi-arid rainfed conditions. (Table 1).

Effect of Foliar Fertilization on Quality and Quantity of Oilseed Flax

The application of foliar fertilization significantly influenced oil flax yield, fat content, and protein levels. The lowest yield was recorded in the control treatment (0.72±0.01tha^{-1}), while the highest yield was observed in treatments V, IX, X, and XIII (0.89tha^{-1}), demonstrating a 19.2% increase compared to the control. In general, treatments incorporating foliar fertilization showed substantial yield improvements, with higher increases in treatments that included macro- and micronutrients, biofertilizers, and multiple foliar applications. The fat content varied among treatments, ranging from 39.8±1.01% (control) to 42.0±0.70% (treatment IX). Treatment IX, which included four foliar applications of NPK and micronutrients, exhibited the highest fat percentage, significantly exceeding the control. Other treatments with multiple foliar applications (V, VIII, X, and XI) also demonstrated increased fat content (41.1–41.5%), confirming the beneficial effects of foliar nutrition on oil accumulation in flax seeds.

The protein content showed minor fluctuations across treatments, with values ranging from 27.0±1.08% (control) to 28.4±0.85% (treatment V). However, statistical analysis indicated that differences between treatments were not always significant (P>0.05), suggesting that while foliar fertilization can enhance protein levels, other factors such as soil conditions and genetic variability may also play a role. The results highlight that foliar fertilization improves both yield and oil quality of oil flax, particularly when applied in multiple treatments with a combination of macro- and micronutrients. Treatments V and IX exhibited the most pronounced improvements, making them the most effective foliar fertilization strategies under semi-arid rainfed conditions. (Table 2).

Table 2: Impact of foliar application on yield and seed quality parameters

Treatments	Yield (tha^{-1})	Compare to control (tkg^{-1})	Oil (%)	Protein (%)
I	0.72±0.01e	-	39.8±1.01c	27.0±1.08a
II	0.75±0.02de	4.0	40.1±0.95bc	27.3±0.75a
III	0.78±0.01d	7.7	40.2±0.75bc	27.4±0.82a
IV	0.83±0.02bc	13.3	41.0±0.60abc	28.3±0.82a
V	0.89±0.01a	19.2	41.1±0.82abc	28.4±0.85a
VI	0.81±0.01c	11.2	40.7±0.92abc	27.5±1.25a
VII	0.83±0.00bc	13.3	40.8±1.11abc	27.5±0.92a
VIII	0.86±0.02ab	16.3	41.5±0.95ab	27.7±0.95a
IX	0.89±0.02a	19.2	42.0±0.70a	27.9±0.75a
X	0.89±0.02a	19.2	41.2±0.75abc	28.1±0.40a
XI	0.86±0.02ab	16.3	41.3±0.53abc	28.2±0.62a
XII	0.86±0.01ab	16.3	40.9±0.36abc	27.6±0.92a
XIII	0.89±0.02a	19.2	41.0±0.46abc	27.7±0.82a

Values (mean±SD) bearing different letters in a column indicate significant ($P<0.05$) difference.

DISCUSSION

Foliar Application on Soil Health

The observed variations in both labile and total humus contents across different fertilization treatments underscore the critical influence of nutrient management strategies on soil organic matter dynamics. Labile humus, a sensitive indicator of soil biological activity and nutrient availability, showed marked improvement under foliar fertilization treatments, particularly treatment XI (1.86±0.09mgkg^{-1}), which significantly outperformed the control (1.52±0.06mgkg^{-1}). This finding aligns with previous studies highlighting that foliar application of micronutrients can stimulate root exudation and microbial activity, thereby enhancing the formation of labile organic compounds (Bana et al., 2022). Similarly, the total humus content exhibited distinct differences, with the highest values recorded in treatments I and IV (1730mgkg^{-1}), indicating the cumulative benefit of both basal and foliar fertilization regimes on long-term organic matter stabilization. Treatment IV consistently maintained elevated humus levels across all growth stages, suggesting its superior efficacy in promoting organic matter accumulation. This may be attributed to the synergistic effects of applied nutrients enhancing plant biomass return and microbial decomposition processes (Lal, 2015; Han et al., 2016).

Notably, the reduction in humus content in treatments V, VII, and VIII (ranging from 1120±72 to 1130±115mgkg^{-1}) suggests a potential imbalance or insufficiency in nutrient supply, which may have constrained microbial activity and organic matter turnover. These observations support earlier reports that suboptimal fertilization not only limits crop productivity but also depletes soil carbon pools over time (Srinivasarao et al., 2019). Recent studies further emphasize the role of foliar fertilization in enhancing soil biological properties. For instance, Tastanbekova et al. (2024) demonstrated that integrating foliar fertilization with compost and soil fertilizers significantly improved soil microbial biomass and enzymatic activities, leading to enhanced soil health and productivity under greenhouse conditions. Such findings corroborate the positive impact of foliar applications on soil biological dynamics.

Overall, these results demonstrate that targeted fertilization especially combinations involving foliar application can effectively enhance both labile and total humus content in soil, thereby contributing to improved soil health and sustainability in semi-arid agroecosystems.

Foliar Application and Soil Macronutrient Dynamics

The study revealed notable temporal and treatment-dependent fluctuations in soil nutrient availability, particularly for nitrate nitrogen (NO_3^--N), mobile phosphorus (P), and exchangeable potassium (K^+). These dynamics are indicative of the strong influence of foliar fertilization strategies on nutrient cycling and retention during crop growth stages.

Nitrate nitrogen levels peaked during the shoot formation stage, consistent with the early vegetative demand for nitrogen. The highest concentrations were found in treatment VI (42±6mgkg^{-1}), significantly surpassing the control (23±3mgkg^{-1}), suggesting enhanced nitrogen mineralization or reduced leaching under foliar nutrient supplementation. As plant development advanced, nitrate levels declined across all treatments, reaching their lowest before harvest. This trend is well-documented, as nitrogen is highly mobile in soil and rapidly taken up during active plant growth phases (Li et al., 2024; Zhang et al., 2024). Treatments combining macro and micronutrients via foliar application appeared to prolong nitrate availability, likely due to improved nutrient use efficiency and reduced volatilization losses (Alotaibi et al., 2023).

Mobile phosphorus content showed a similar pattern, with increased concentrations during early growth stages and a general decline towards harvest. Treatments with foliar fertilization, particularly VIII and IX, demonstrated higher P levels throughout the season compared to the control. This may be due to the role of foliar P in reducing phosphorus fixation in the soil and enhancing root exudation, which mobilizes sparingly soluble P forms (Rafiullah et al., 2021). The sustained phosphorus availability in these treatments suggests improved internal nutrient cycling and possibly higher mycorrhizal activity promoted by foliar feeding (Etesami et al., 2021).

Exchangeable potassium, crucial for water regulation and stress tolerance, consistently exhibited the lowest values in the control treatment. In contrast, foliar-fed treatments, especially VI, VIII, and IX, maintained significantly higher K levels. The increase in K availability may be attributed to the synergy between soil and foliar K inputs, which can stimulate microbial mineralization and improve soil K buffering capacity (Ishfaq et al., 2023). Despite a general decline toward the harvesting stage, treatments with repeated foliar applications showed slower depletion rates, suggesting better nutrient retention and possibly reduced plant uptake saturation or leaching loss (He et al., 2022). Collectively, these findings highlight the effectiveness of foliar fertilization in enhancing and maintaining essential macronutrient levels in soil, which is crucial for sustaining crop productivity and soil fertility in rainfed systems.

Influence of Foliar Fertilization on Yield Components of Oil Flax

The present study demonstrated that foliar fertilization significantly improved key yield structure components of oil flax, including plant density, the number of capsules per plant, the number of seeds per capsule, and 1000 seed weight. These findings are consistent with previous research highlighting the benefits of foliar nutrient application in enhancing growth and productivity under semi-arid and nutrient-limited conditions (Niu et al., 2021; Xu et al., 2023).

The increased plant density in treatments V and IX (296plants/m^2), compared to the control (244plants/m^2), suggests that foliar fertilization supports better seedling establishment and survival. Enhanced nutrient availability through foliar feeding, particularly when macro- and micronutrients are combined, may have supported early growth and plant vigor (Babu et al., 2022). The positive response in density aligns with the view that balanced nutrient supply during early growth stages can increase stand uniformity and resilience in stress-prone environments (Dass et al., 2022). Capsule formation, a critical yield-determining factor, was also strongly influenced by foliar nutrition. Treatments V, VIII, and IX, which involved multiple foliar applications, significantly increased the number of capsules per plant (up to 17.9 vs. 9.1 in the control). This aligns with findings by Meriño-Gergichevich et al. (2021), who reported that foliar-applied micronutrients, such as zinc and boron, stimulate flowering and fruit setting processes by enhancing enzymatic activity and hormonal balance.

Similarly, the number of seeds per capsule increased notably with foliar treatments, particularly in treatments V and IX, each recording 7.2 seeds per capsule compared to 5.1 in the control. The beneficial effect of repeated foliar fertilization could be attributed to improved nutrient assimilation during the reproductive phase, which enhances seed formation and filling (Mitra et al., 2023). Although the 1,000 seed weight showed modest differences among treatments, higher weights observed in treatments IV, V, VIII, and IX suggest that foliar feeding may also positively influence seed development. Previous studies have shown that nutrient supplementation, especially involving chelated micronutrients and biostimulants, can enhance assimilate translocation to seeds, resulting in higher weight and improved seed quality (El Sayed et al., 2024).

Biofertilizer treatments (X–XIII), which included Terra Sorb Complex, also contributed positively to plant density and yield components, although not always to the same extent as mineral-based foliar treatments. The role of biofertilizers in improving nutrient uptake efficiency and stimulating plant metabolism under water-limited conditions has been increasingly recognized (Rouphael and Colla, 2020; Liao et al., 2025). Overall, the findings of this study confirm that foliar fertilization, particularly when applied in multiple stages and in combination with macro- and micronutrients, enhances the structural yield components of oil flax. Treatments V and IX were identified as the most effective, underlining their potential for optimizing flax productivity in semi-arid, rainfed environments.

Foliar Nutrient Management Strategies to Boost Oil Flax Performance in Rainfed Environment

The findings of this study demonstrate that foliar fertilization significantly enhances both the yield and quality parameters of oil flax grown under semi-arid rainfed conditions. The notable increase in seed yield, particularly in treatments V, IX, X, and XIII (up to 19.2% higher than the control), aligns with previous research showing that foliar application of nutrients can compensate for soil nutrient limitations, especially in water-limited environments (Fernández and Ebert, 2005; Ishfaq et al., 2022). The enhanced productivity in these treatments can be attributed to the synergistic effect of macro- and micronutrients, which are essential for metabolic processes, photosynthesis, and seed development (Pahalvi et al., 2021).

The improvement in oil content, with treatment IX exhibiting the highest fat percentage (42.0%), reinforces the role of balanced nutrient application in promoting lipid biosynthesis in oilseed crops. Foliar application of NPK along with micronutrients such as zinc and boron likely stimulated enzymatic activities involved in fatty acid synthesis (Dhaliwal et al., 2022). This finding is consistent with Premalatha et al. (2023), who reported increased oil content in oilseed crops following repeated foliar fertilization with both macro- and micronutrients. Treatments V, VIII, X, and XI, which also received multiple nutrient sprays, showed similarly elevated fat levels, further supporting the importance of repeated applications in maximizing nutrient uptake and utilization (Rahman et al., 2020).

Although the protein content varied slightly across treatments, with the highest value recorded in treatment V (28.4%), the differences were not statistically significant ($p > 0.05$). This suggests that while foliar fertilization may have a modest impact on protein synthesis, other factors such as genotype, environmental stress, and soil nutrient reserves may exert a greater influence (Crista et al., 2023). Nevertheless, the trend toward higher protein content in treated plots supports findings from Cordeiro et al. (2022), who indicated that biofertilizers and foliar nutrients can enhance nitrogen metabolism and amino acid formation. Recent research further supports these findings. For instance, Rahman et al. (2023) demonstrated that foliar application of phosphorus and zinc significantly increased oil content and yield in flax, highlighting the importance of these nutrients in oilseed crop production. Similarly, a study by Tastanbekova et al. (2024) found that integrating foliar fertilization with compost and soil fertilizers. Overall, the study confirms that foliar fertilization particularly when applied in multiple treatments combining macro- and micronutrients can be an effective agronomic strategy to enhance both yield and oil quality of oil flax in dryland agriculture. Treatments V and IX emerged as the most effective approaches, corroborating the benefits of integrated nutrient management through foliar feeding, as emphasized in earlier studies (Ashenafi et al., 2025).

Conclusions

Experimental results demonstrated that foliar fertilization with various formulations and application methods significantly improved key agronomic traits, yield, and seed quality of oilseed flax. The highest plant stand density (296plants/m²) was achieved in treatments involving four foliar applications of a tank mix of macro- and micronutrients or NPK with micronutrients (brands: 13-40-13; 12-12-36; 3-11-38). These values were 52plants/m² higher than the control. In contrast, the lowest plant survival (250plants/m²) was recorded in plots where only mineral fertilizers (N60P60K60) were applied, indicating the limitations of mineral fertilization alone. Among foliar treatments, the highest number of pods per plant (17.9) was observed in the treatment involving four foliar applications of macro- and micronutrients, combined with mineral fertilization and pre-sowing seed treatment with the biofertilizer Terra Sorb Complex. This treatment resulted in an increase of 8.8 pods per plant compared to the control. Conversely, the lowest number of pods was recorded in the mineral fertilizer-only treatment and the unfertilized control, with increases of just 1.1 and 1.5 pods per plant, respectively. The greatest number of seeds per pod (7.2) was recorded in treatments that received four foliar applications of macro- and micronutrients or NPK with micronutrients, in combination with mineral fertilizers and pre-sowing biofertilizer treatment. This represented a significant improvement over the control (5.1 seeds per pod). Other fertilization strategies resulted in seed counts of 5.5 to 7.0 per pod, exceeding the control by 0.4 to 1.9 seeds. Foliar fertilization, combined with mineral fertilizers and biofertilizer seed treatment, resulted in a 1000-seed weight of 7.0–7.2g, surpassing the control by 1.0–1.2g. These findings highlight the positive impact of foliar feeding on seed development. The highest seed yield ($0.89tha^{-1}$) was obtained from treatments involving: Four foliar applications of a tank mix of macro- and micronutrients, four foliar applications of chelated micronutrient-containing fertilizers (brands: 40-13-40; 12-12-36; 3-11-38), three foliar applications of macro- and micronutrients combined with biofertilizers, four foliar applications of a complex fertilizer and biofertilizer. These treatments, applied on the background of mineral fertilizers and pre-sowing biofertilizer treatment, resulted in a yield increase of $0.17tha^{-1}$ (19.2%) compared to the control. Foliar fertilization also improved technological seed quality. Treatments involving foliar feeding, mineral fertilizers, and pre-sowing biofertilizer application resulted in a fat content of 40.7–42.0%, surpassing the control by 0.9–2.2% and mineral fertilizer-only treatments by 0.5–1.9%.

The highest protein content (28.4%) was achieved in treatments that included four foliar applications of macro- and micronutrients on the background of mineral fertilizers and pre-sowing biofertilizer treatment. Other fertilization strategies resulted in protein contents ranging from 27.3–28.3%, exceeding the control by 0.3–1.3%. Soil nutrient dynamics were also positively influenced by foliar fertilization. Treatments with macro- and micronutrient applications improved nitrate nitrogen, mobile phosphorus, and exchangeable potassium availability throughout the growing season, supporting plant nutrient uptake and overall physiological performance. Overall, these findings confirm that foliar fertilization, when combined with mineral fertilizers and pre-sowing biofertilizer treatment, enhances yield components, seed productivity, and technological quality of oilseed flax under semi-arid conditions. This approach presents an effective strategy for optimizing nutrient use efficiency and improving flax production.

DECLARATIONS

Funding: This article was published as part of project #AP23486266 "Developing effective methods for applying traditional and innovative fertilizers for oilseed flax under dryland conditions in southeastern Kazakhstan" funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Acknowledgement: We acknowledge the institutional support and resources that made this work possible.

Conflict of Interest: None

Data Availability: All the data is available in the article.

Ethics Statement: Field experiments were conducted with institute permission in compliance with all relevant guidelines and without involving humans, animals, or endangered species.

Author's Contribution: Almagul Malimbayeva: Conceptualized and designed the study and collected data, methodology, review, and editing. Maksat Batyrbek: Conceptualization, methodology, data curation, writing-review, and editing. Batyrgali Amangaliyev: Conceptualization, methodology, writing. Erbol Zhusupbekov: Methodology and writing. Akerke Soltanayeva: Data curation. Zhuldyz Oshakbaeva: Methodology and literature review. Aina Sagimbayeva: Literature review. Karlyga Rustemova: Literature review. All authors have read, reviewed, and approved the final manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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