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Effect of foliar application of micronutrients and biofertilizers on growth, yield and quality of linseed (*Linum usitatissimum* L.) under irrigated conditions

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Abstract

A field experiment was conducted to evaluate the effect of foliar application of micronutrients and bio-fertilizers on growth and yield attributes of linseed (*Linum usitatissimum* L.). The experiment was laid out in a randomized block design with twelve treatments comprising foliar sprays of ZnSO₄ (0.5%), borax (0.2%) and FeSO₄ (0.5%) combined with seed inoculation of *Azotobacter* and phosphate solubilizing bacteria (PSB). The results revealed that micronutrient application along with bio-fertilizer inoculation significantly improved growth and yield attributes of linseed. The treatment ZnSO₄ 0.5% + PSB (T₆) recorded the highest plant height (93.20 cm), branches per plant (7.40), dry matter accumulation (13.80 g plant⁻¹) and leaf area index (2.82) at harvest. Yield attributes were also significantly improved under this treatment, recording the maximum number of capsules per plant (67.30), seeds per capsule (9.60) and test weight (8.50 g). Control treatments consistently recorded the lowest values for all parameters. The improved performance under micronutrient and bio-fertilizer treatments may be attributed to enhanced nutrient availability, improved photosynthetic efficiency and better physiological processes in plants. The study indicates that integration of foliar micronutrients with bio-fertilizer seed inoculation is an effective strategy to enhance growth and yield attributes of linseed under field conditions.

Keywords: Linseed, micronutrients, biofertilizers, azotobacter, Phosphate solubilizing bacteria (PSB)

1. Introduction

Linseed (flaxseed) is a versatile oilseed crop grown for edible and industrial oil, fiber and high-value nutraceutical uses. Seeds contain ~40% oil, 21-28% protein, abundant dietary fiber and minerals, and are especially rich in α -linolenic acid (ALA, omega-3) and lignans, underpinning their “superfood” status and use in functional foods and health products (Kausar et al., 2023; Biradar et al., 2023; Kaur et al., 2023; Zanwar et al., 2023; Žuk et al., 2015) [3, 13, 14, 30, 31]. Linseed oil is used in paints, varnishes and inks, while seedcake serves as protein-rich livestock feed and organic manure (Biradar et al., 2023; Žuk et al., 2015) [3, 31].

Despite this potential, linseed yields remain low in many regions because it is often grown on marginal soils with low and unbalanced fertility and minimal inputs (Singh et al., 2025; Kathane et al., 2025; Biradar et al., 2023) [3, 12, 22]. Nutrient deficiencies especially of nitrogen, phosphorus and key micronutrients significantly reduce plant height, capsules per plant, seed yield and oil content (Ashenafi et al., 2025; G et al., 2025; Alam et al., 2021; Singh et al., 2020; Rastogi et al., 2014) [1, 2, 9, 21, 23].

Micronutrients such as zinc (Zn), boron (B), and iron (Fe) are critical for enzyme activation, chlorophyll synthesis, pollen viability, carbohydrate metabolism and grain filling (Singh et al., 2025; G et al., 2025; Alam et al., 2021; Singh et al., 2020; Rastogi et al., 2014) [1, 9, 21, 22, 23]. Foliar or soil application of ZnSO₄ and borax at appropriate stages (often around 45 DAS) consistently increases plant height, dry matter, capsules per plant, seeds per capsule, 1000-seed weight, seed yield, oil content and economic returns compared with untreated controls (Singh et al., 2025; G et al., 2025; Alam et al., 2021; Singh et al., 2020; Rastogi et al., 2014) [1, 9, 21, 22, 23]. Balanced multi-nutrient fertilization (NPKS + Zn + B) can raise seed yield above 2.2 t ha⁻¹ and improve oil content and fatty-acid profile (Ashenafi et al., 2025; G et al., 2025; Alam et al., 2021; Singh et al., 2020; Rastogi et al., 2014) [1, 2, 9, 21, 23]. Bio-fertilizers such as *Azotobacter* and Phosphate-Solubilizing Bacteria (PSB) enhance biological nitrogen fixation, solubilize soil P and often mobilize micronutrients, leading to higher plant height, branches, dry matter and yield attributes in linseed (Kathane et al., 2025;

Sood et al., 2020; Jalal et al., 2024) [11, 12, 26]. Dual inoculation with *Azotobacter* + PSB, especially when combined with organic manures or mineral fertilization, improves nutrient uptake, stand vigor and seed yield relative to uninoculated control plots (Kathane et al., 2025; Sood et al., 2020; Jalal et al., 2024) [11, 12, 26]. Keeping in view the above facts, the present study was undertaken to evaluate the impact of foliar application of micronutrients and bio-fertilizers on the growth and yield performance of linseed (*Linum usitatissimum* L.) under field conditions.

2. Material and Methods

2.1 Experimental site and soil characteristics

A field experiment was conducted during the Rabi season of 2025-2026 at the Agriculture Instructional Farm, Career Point University, Kota, Rajasthan, India. The experimental site is located in the semi-arid agro-climatic zone of south-eastern Rajasthan, characterized by hot summers, mild winters, and low to moderate rainfall. The soil of the experimental field was sandy loam in texture, well-drained and nearly levelled, ensuring uniform distribution of irrigation water and nutrients. Prior to sowing, the field was prepared through ploughing, harrowing and levelling to obtain a fine tilth suitable for linseed cultivation.

2.2 Experimental crop and variety

Linseed (*Linum usitatissimum* L.), an important rabi oilseed crop known for its high oil content and industrial significance, was used as the experimental crop. A high-yielding variety recommended for the region was selected for the study. The crop was grown following standard agronomic practices recommended for linseed cultivation in the region.

2.3 Experimental design and treatments

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with three replications. The treatments consisted of two experimental factors, namely micronutrient foliar spray and bio-fertilizer seed inoculation.

2.3.1 Factor A comprised four levels of micronutrient foliar spray

- A₁: Control (water spray)
- A₂: ZnSO₄ @ 0.5% at flowering stage
- A₃: Borax @ 0.2% at flowering stage
- A₄: FeSO₄ @ 0.5% at flowering stage

2.3.2 Factor B consisted of three levels of bio-fertilizer application:

- B₁: Control (no bio-fertilizer)
- B₂: Seed inoculation with *Azotobacter*
- B₃: Seed inoculation with PSB (phosphate solubilizing bacteria)

The combination of these factors resulted in 12 treatment combinations (4 × 3), which were randomly allocated within each replication.

2.4 Crop management practices

The experimental field was prepared with two cross ploughings followed by harrowing and levelling to obtain a well-prepared seedbed. The layout of the experiment was

marked according to the experimental design prior to sowing. Seeds were inoculated with *Azotobacter* and Phosphate Solubilizing Bacteria (PSB) according to the treatment requirements. The required quantity of bio-fertilizer culture was mixed with a small quantity of water to form a slurry and uniformly coated on the seeds. The inoculated seeds were shade dried for approximately 30 minutes before sowing.

Sowing was carried out manually during the rabi season using healthy and certified seeds, maintaining recommended row spacing for linseed. The recommended dose of fertilizers was applied uniformly to all plots as basal application at the time of sowing. Other agronomic practices such as irrigation, weeding, and plant protection measures were followed uniformly for all treatments. Foliar application of micronutrients was performed at the flowering stage using a knapsack sprayer fitted with a flat-fan nozzle. The spray solutions were freshly prepared and applied uniformly to ensure proper coverage of the crop foliage.

2.5 Data collection

Observations on crop growth were recorded periodically to evaluate the effect of treatments. Initial plant population was recorded 20 Days After Sowing (DAS) by counting the number of plants within a one square meter area randomly selected in each plot. Plant height was measured from the ground surface to the tip of the main stem at 30, 60, 90 DAS and at harvest from five randomly selected plants in each plot. The number of branches per plant was recorded from the same plants at these stages and the mean value was calculated.

Dry matter accumulation was determined by uprooting five plants at 30, 60, 90 DAS and at harvest. The plants were cleaned, dried under sunlight and then oven dried at 65 ± 5°C until constant weight, and the dry weight was expressed as g plant⁻¹. Leaf Area Index (LAI) was measured at different growth stages using a leaf area meter and calculated as the ratio of total leaf area to the corresponding ground area.

At harvest, the number of capsules per plant was counted from five randomly selected plants in each plot and the mean value was expressed as capsules per plant. For seeds per capsule, ten mature capsules were randomly selected from each plot, opened and the seeds were counted to obtain the average number of seeds per capsule. Test weight was determined by weighing 1000 well-filled seeds from each treatment using an electronic balance and expressed as 1000-seed weight (g).

2.6 Data analysis

The recorded data on growth, yield and quality parameters were statistically analyzed using analysis of variance (ANOVA) appropriate for a Factorial Randomized Block Design. The significance of micronutrient treatments, bio-fertilizer treatments and their interaction effects was tested at the 5% level of probability. When the F-test was found significant, treatment means were compared using the Critical Difference (CD) at P = 0.05. Standard error of mean (SEm) was also calculated to assess experimental variability.

3. Results

3.1 Growth parameters

The data presented in Fig. 1 indicate that the initial plant population of linseed was not significantly influenced by the foliar application of micronutrients and bio-fertilizers. The plant population ranged from 285 to 302 plants m^{-2} across different treatments. The highest initial plant population (302 plants m^{-2}) was recorded under T₆ (ZnSO₄ 0.5% + seed inoculation with PSB), followed by T₉ (299 plants m^{-2}) and T₅ (298 plants m^{-2}). The lowest plant population (285 plants m^{-2}) was observed under T₁ (Control).

The data regarding plant height of linseed at different growth stages are presented in Fig. 2. Plant height increased progressively with crop growth from 30 DAS to harvest under all treatments, and significant differences among treatments were observed at all growth stages. At 30 DAS, plant height ranged from 18.40 cm to 24.10 cm. The maximum plant height (24.10 cm) was recorded under T₆ (ZnSO₄ 0.5% + PSB), while the minimum (18.40 cm) was observed under T₁ (Control). At 60 DAS, plant height varied from 42.30 cm to 56.80 cm. The tallest plants (56.80 cm) were recorded under T₆, followed by T₉ (54.00 cm) and T₅ (53.40 cm). The lowest plant height (42.30 cm) was recorded under T₁ (Control). At 90 DAS, plant height ranged from 63.50 cm to 82.60 cm. The maximum plant height (82.60 cm) was observed under T₆, followed by T₉ (79.40 cm) and T₅ (78.30 cm), whereas the minimum plant height (63.50 cm) was recorded under T₁ (Control). At harvest, plant height varied between 72.10 cm and 93.20 cm. The maximum plant height (93.20 cm) was recorded under T₆, followed by T₉ (89.70 cm) and T₅ (88.50 cm). The minimum plant height (72.10 cm) was observed under T₁ (Control).

The data presented in Fig. 2 revealed that the number of branches per plant increased progressively with crop growth from 30 DAS to harvest, and the treatments significantly influenced branching. At 30 DAS, the number of branches per plant ranged from 1.80 to 2.70. The maximum number of branches (2.70) was recorded under T₆ (ZnSO₄ 0.5% + PSB), while the minimum (1.80) was observed under T₁ (Control). At 60 DAS, the number of branches varied from 3.20 to 5.00. The highest number of branches (5.00) was recorded under T₆, followed by T₉ (4.70) and T₅ (4.60). The lowest number (3.20) was observed under T₁ (Control). At 90 DAS, the number of branches ranged from 4.10 to 6.80. The maximum number (6.80) was recorded under T₆, followed by T₉ (6.40) and T₅ (6.20), whereas the minimum (4.10) was recorded under T₁ (Control). At harvest, the number of branches ranged from 4.80 to 7.40. The maximum number of branches (7.40) was recorded under T₆, followed by T₉ (7.00) and T₅ (6.80). The minimum number (4.80) was recorded under T₁ (Control).

The data on dry matter accumulation of linseed at different growth stages are presented in Fig. 2. Dry matter accumulation increased progressively with crop growth from 30 DAS to harvest under all treatments, and significant differences among treatments were observed. At 30 DAS, dry matter accumulation ranged from 1.25 g $plant^{-1}$ to 2.05 g $plant^{-1}$. The highest dry matter (2.05 g $plant^{-1}$) was recorded under T₆ (ZnSO₄ 0.5% + PSB), while the lowest (1.25 g $plant^{-1}$) was recorded under T₁ (Control). At 60 DAS, dry

matter ranged from 3.85 g $plant^{-1}$ to 6.42 g $plant^{-1}$. The maximum dry matter (6.42 g $plant^{-1}$) was recorded under T₆, followed by T₉ (6.05 g $plant^{-1}$) and T₅ (5.78 g $plant^{-1}$). The minimum value (3.85 g $plant^{-1}$) was recorded under T₁ (Control). At 90 DAS, dry matter accumulation ranged from 6.75 g $plant^{-1}$ to 11.80 g $plant^{-1}$. The highest dry matter (11.80 g $plant^{-1}$) was recorded under T₆, followed by T₉ (11.10 g $plant^{-1}$) and T₅ (10.55 g $plant^{-1}$). The lowest value (6.75 g $plant^{-1}$) was recorded under T₁ (Control). At harvest, dry matter accumulation ranged from 8.60 g $plant^{-1}$ to 13.80 g $plant^{-1}$. The maximum dry matter (13.80 g $plant^{-1}$) was recorded under T₆, followed by T₉ (13.10 g $plant^{-1}$) and T₅ (12.60 g $plant^{-1}$), whereas the minimum (8.60 g $plant^{-1}$) was recorded under T₁ (Control).

The data on leaf area index of linseed at different growth stages are presented in Fig. 2. The treatments significantly influenced leaf area index at all growth stages. At 30 DAS, the leaf area index ranged from 0.78 to 1.32. The highest LAI (1.32) was recorded under T₆ (ZnSO₄ 0.5% + PSB), while the lowest (0.78) was recorded under T₁ (Control). At 60 DAS, the leaf area index ranged from 1.85 to 3.05. The maximum LAI (3.05) was recorded under T₆, followed by T₉ (2.90) and T₅ (2.72). The minimum (1.85) was observed under T₁ (Control). At 90 DAS, the leaf area index varied from 2.10 to 3.62. The highest LAI (3.62) was recorded under T₆, followed by T₉ (3.40) and T₅ (3.28). The lowest LAI (2.10) was recorded under T₁ (Control). At harvest, the leaf area index ranged from 1.72 to 2.82. The maximum LAI (2.82) was recorded under T₆, followed by T₉ (2.65) and T₅ (2.55). The minimum (1.72) was observed under T₁ (Control).

3.2 Yield attributes

The data presented in Fig. 2 revealed that the number of capsules per plant, number of seeds per capsule and test weight was significantly influenced by the foliar application of micronutrients and bio-fertilizers.

The number of capsules per plant ranged from 42.60 to 67.30 across treatments. The maximum number of capsules (67.30) was recorded under T₆ (ZnSO₄ 0.5% + PSB), followed by T₉ (63.50) and T₅ (61.80). The minimum number (42.60) was recorded under T₁ (Control). The number of seeds per capsule ranged from 7.20 to 9.60. The maximum number of seeds (9.60) was recorded under T₆ (ZnSO₄ 0.5% + PSB), followed by T₉ (9.05) and T₅ (8.95). The minimum number (7.20) was recorded under T₁ (Control). The test weight ranged from 6.40 g to 8.50 g among treatments. The maximum test weight (8.50 g) was recorded under T₆ (ZnSO₄ 0.5% + PSB), followed by T₉ (8.10 g) and T₅ (7.95 g). The minimum test weight (6.40 g) was recorded under T₁ (Control).

4. Discussion

Foliar micronutrients and PSB did not affect crop establishment, as plant population varied only slightly (285-302 plants m^{-2}) and non-significantly among treatments. Similar non-significant effects of Zn and B on plant stand have been reported in linseed and other micronutrient studies (Alam et al., 2021; Verma et al., 2021) [1, 28]. This suggests that emergence was governed mainly by seedbed conditions and seed quality rather than foliar/bio-fertilizer

treatments. The results obtained in the present investigation clearly indicate that treatment T6 (ZnSO₄ 0.5% + PSB) consistently produced superior growth performance compared with other treatments. This treatment recorded the highest plant height, number of branches per plant, dry matter accumulation, and leaf area index at different growth stages. The treatments T9 (Borax 0.2% + PSB) and T5 (ZnSO₄ 0.5% + Azotobacter) also exhibited comparatively higher values for these parameters and remained the next best treatments after T6.

The improvement in growth parameters under the application of micronutrients and biofertilizers observed in the present study is consistent with earlier reports in linseed. Several studies have documented that the application of zinc and boron, either alone or in combination with biofertilizers such as Azotobacter and phosphate-solubilizing bacteria, significantly enhances plant height, branching, and dry matter accumulation in linseed (Kathane et al., 2025; G et al., 2025; Alam et al., 2021; Meena et al., 2024; Kotadiya et al., 2023; Singh et al., 2020; Verma et al., 2021) [1, 9, 12, 15, 18, 23, 28]. The beneficial effects of zinc are mainly associated with its involvement in enzyme activation, chlorophyll synthesis, and auxin metabolism, which collectively promote cell division, cell elongation, and overall vegetative growth (Singh et al., 2025; G et al., 2025; Dhaliwal et al., 2022) [8, 9, 22]. Similarly, seed inoculation with phosphate-solubilizing bacteria and other biofertilizers improves phosphorus availability in the rhizosphere, enhances root growth, and contributes to biological nitrogen fixation. These processes lead to improved nutrient uptake, higher biomass production, and increased branching in linseed (Kathane et al., 2025; Mucharla et al., 2025; Kumar & Bara, 2024; Singh et al., 2021) [12, 16, 19, 24].

Comparable findings have been reported in several studies on linseed, where micronutrient application and biofertilizer inoculation significantly improved vegetative growth, yield attributes, and seed yield compared with control treatments. Increased plant height, number of branches, and dry matter accumulation have been observed with the application of zinc, boron, farmyard manure, vermicompost, PSB, or Azotobacter (Kathane et al., 2025; G et al., 2025; Alam et al., 2021; Meena et al., 2024; Kotadiya et al., 2023; Singh et al., 2020; Verma et al., 2021) [1, 9, 12, 15, 18, 23, 28]. Likewise, yield attributes and seed yield of linseed have been reported to increase significantly with the application of zinc, boron, nano-zinc, and biofertilizers (Kathane et al., 2025; G et al., 2025; Alam et al., 2021; Meena et al., 2024; Kotadiya et al., 2023; Singh et al., 2020; Dhaliwal et al., 2022; Singh et al., 2024; Pandao & Sajid, 2023) [1, 8, 9, 12, 15, 18, 23, 25].

The present study revealed a significant improvement in yield attributes of linseed under treatment T6 (ZnSO₄ 0.5% + seed inoculation with PSB), indicating that foliar application of micronutrients in conjunction with biofertilizers enhanced reproductive efficiency and seed development. The increase in number of capsules per plant, number of seeds per capsule, and test weight under this treatment suggests a favorable influence on flowering, fertilization, and seed filling processes.

A marked increase in the number of capsules per plant was observed under T6 (67.3) compared with the control (42.6), indicating improved flower retention and pod setting.

Similar increases in capsule or pod number following foliar application of zinc, boron, and combined nutrient sprays have been reported in linseed and other oilseed and legume crops (Meena et al., 2024; Singh et al., 2025; Dass et al., 2022; Gondal et al., 2023) [7, 10, 18, 22]. Zinc plays a crucial role in auxin metabolism, enzyme activation, and photosynthetic efficiency, while phosphate-solubilizing bacteria enhance phosphorus availability and root growth, thereby improving assimilate supply to developing reproductive organs (Cheng et al., 2023; Kathane et al., 2025; Dasila et al., 2023; Luo et al., 2024) [4, 6, 12, 17].

The number of seeds per capsule also increased significantly under T6 (9.6) compared with the control (7.2), suggesting improved pollen viability, fertilization, and reduced ovule or seed abortion. Earlier reviews and experimental studies on linseed have demonstrated that zinc and boron are essential for proper pollen function, fertilization, and seed set, resulting in higher grain number per capsule (Singh et al., 2025; Culpan and Arslan, 2024) [5, 22]. Comparable responses, in terms of increased seeds per pod following foliar micronutrient application and biofertilizer inoculation, have also been documented in soybean, pinto bean, and linseed (Dass et al., 2022; Taghvaei et al., 2025; Kathane et al., 2025; Gondal et al., 2023; Singh et al., 2021) [7, 10, 12, 24, 27].

Similarly, the higher test weight recorded under T6 (8.5 g) compared with the control (6.4 g) reflects improved seed filling and efficient translocation of photosynthates during the grain-filling period. Previous studies have reported that foliar application of zinc or iron, along with biofertilizer or organic nutrient management practices, significantly increased 1000-seed weight in linseed and flax (Xie et al., 2025; Kathane et al., 2025; Kotadiya et al., 2023; Gondal et al., 2023; Singh et al., 2021) [10, 12, 15, 24, 29]. The enhanced leaf area index, dry matter accumulation, and branching observed under micronutrient and biofertilizer treatments likely contributed to a stronger source capacity, which, combined with improved nutrient availability under ZnSO₄ and PSB application, resulted in the development of bolder and heavier seeds (Singh et al., 2025; Meena et al., 2024; Kathane et al., 2025; Kotadiya et al., 2023; Gondal et al., 2023) [10, 12, 15, 18, 22].

Overall, the findings are in agreement with earlier reports indicating that foliar application of micronutrients such as zinc, boron, and iron, along with biofertilizer inoculation, significantly improves yield components of linseed. Increased capsule number per plant has been widely associated with the application of micronutrients and biofertilizers or organic nutrient sources (Xie et al., 2025; Dass et al., 2022; Singh et al., 2025; Meena et al., 2024; Kathane et al., 2025; Kotadiya et al., 2023; Gondal et al., 2023) [7, 10, 12, 15, 18, 22, 29]. Likewise, improvements in the number of seeds per capsule have been linked with better pollination and seed set under micronutrient and microbial treatments (Dass et al., 2022; Singh et al., 2025; Culpan and Arslan, 2024; Kathane et al., 2025; Taghvaei et al., 2025; Gondal et al., 2023; Singh et al., 2021) [7, 10, 12, 18, 22, 24, 27]. Enhanced test weight has also been consistently reported with foliar zinc or iron application and biofertilizer use in linseed and related crops (Xie et al., 2025; Singh et al., 2025; Kathane et al., 2025; Kotadiya et al., 2023; Gondal et al., 2023; Singh et al., 2021) [10, 12, 15, 22, 24, 29].

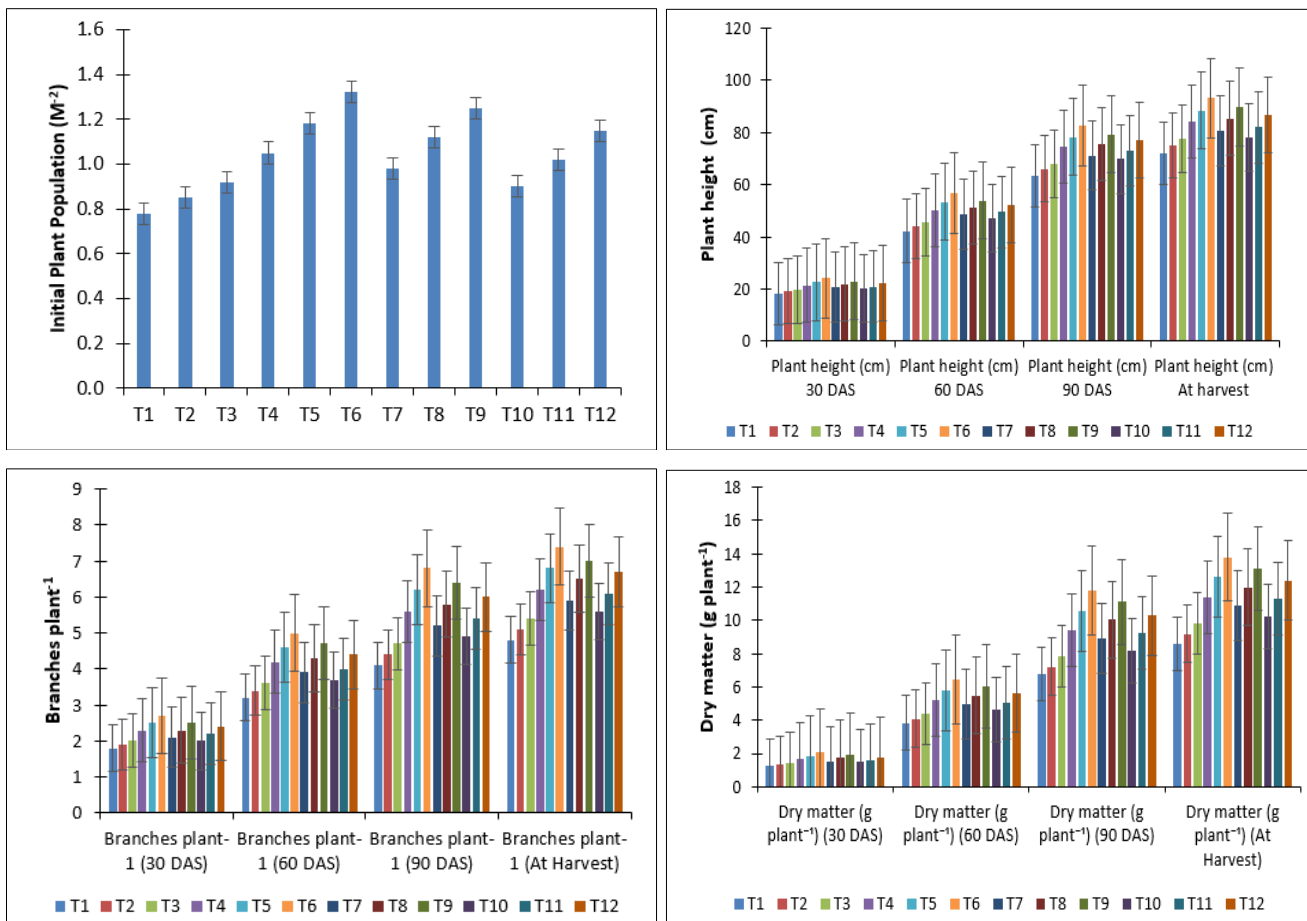


Fig 1: Impact of foliar micronutrient and bio-fertilizer application on growth parameters of linseeds

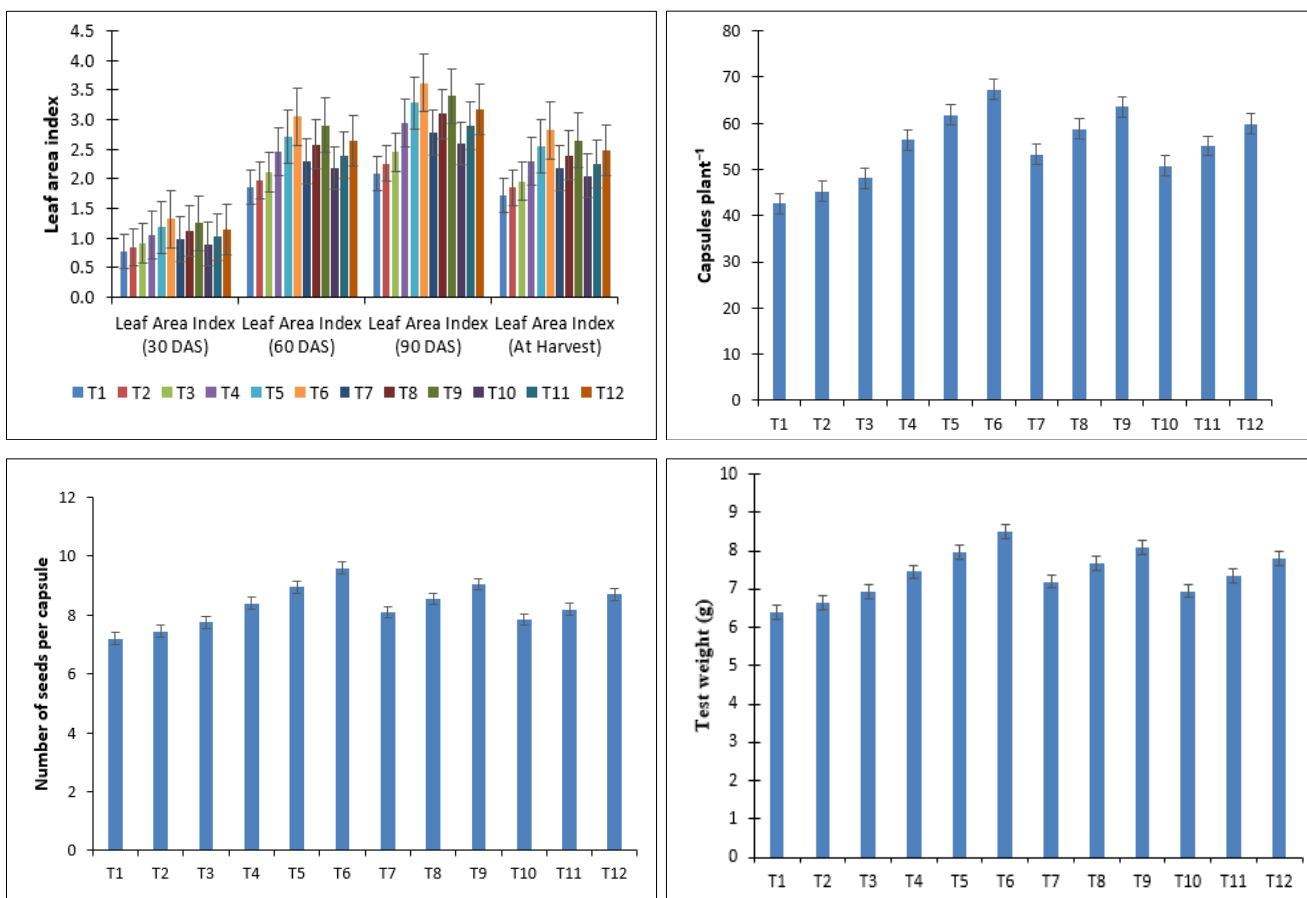


Fig 2: Impact of foliar micronutrient and bio-fertilizer application on yield attributing traits parameters of linseeds

5. Conclusion

The results of the present study clearly demonstrated that foliar application of micronutrients combined with biofertilizer seed inoculation significantly improved the growth and yield attributes of linseed. Among the treatments, ZnSO₄ 0.5% combined with PSB inoculation proved to be the most effective treatment, producing the highest plant height, branches per plant, dry matter accumulation, leaf area index, number of capsules per plant, seeds per capsule and test weight. The improved performance under this treatment may be attributed to enhanced nutrient availability, improved physiological processes and better photosynthetic efficiency. Therefore, the integrated application of foliar zinc along with PSB inoculation can be recommended as an effective nutrient management strategy for improving productivity of linseed under similar agro-climatic conditions.

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