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Improving Rapeseed *(Brassica campestris* L. var. Toria) Performance through Targeted Micronutrient Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A field experiment was conducted during the 2023–24 rabi season at the Agricultural Research Farm of Graphic Era Hill University, Dehradun, Uttarakhand, to evaluate how boron and sulphur applications affect rapeseed (*Brassica campestris* L. var. Toria) growth and yield. The study included ten treatments: one control, three basal applications, and six foliar applications, arranged in a randomised block design with three replications. Both boron and sulphur applications significantly improved crop performance compared to the control. The highest values were recorded following foliar application of 100% recommended fertiliser dose plus 0.5% boron and 1% sulphur during flowering and siliquing stages (T_{10}). This treatment produced maximum plant height (154.43 cm), dry matter accumulation (673.20 g/m²), crop growth rate (12.37 g/m²/day), and chlorophyll content (0.84 mg/g FW). This treatment also produced the highest seed yield (26.95 q/ha) and oil content (43.27%). Compared with the control, this represented a 78.83% increase in seed yield and a 31.80% increase in oil content. Compared with the best-performing basal treatment (T4), foliar application under T10 showed 32.04% higher yield and 11.63% better oil content. These findings indicate that foliar applications of boron and sulphur at flowering and siliquing may improve rapeseed productivity and seed oil content under the conditions examined.

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1. Introduction

Rapeseed (*Brassica campestris* L. var. Toria), commonly known as Brown Sarson and Toria in the Indian subcontinent, is an important source of vegetable oil worldwide. This crop demonstrates remarkable adaptability, thriving across India's diverse agro-climatic regions spanning from the northeastern and northwestern hills to southern territories. Cultivation occurs under heterogeneous conditions including irrigated and rainfed systems, timely and late sowing practices, saline environments, and mixed soil types. Statistical data from 2023–2024 reveal that India's primary rapeseed production is concentrated in Rajasthan (44.97%), followed by Haryana (12.44%), Madhya Pradesh (11.32%), Uttar Pradesh (10.60%), and West Bengal (7.53%) (Wanasundara *et al.*, 2024).

While rapeseed excels in oil production, its utility as a protein source for human or animal nutrition remains limited due to glucosinolate compounds, which may present toxicological concerns (Lietzow, 2021). The presence of these antinutritional factors significantly restricts its application in direct consumption.

Micronutrient limitations constitute a major bottleneck in rapeseed cultivation, substantially affecting plant growth, yield potential, and overall physiological health. The crop exhibits particular sensitivity to deficiencies in essential micronutrients including boron (B), sulphur (S), zinc (Zn), iron (Fe), and molybdenum (Mo). These elements serve crucial functions in fundamental physiological processes such as photosynthetic activity, enzyme activation, nutrient transport, stress adaptation mechanisms, and seed development—all of which collectively determine final yield and oil quality characteristics.

Contemporary research has highlighted sulphur's beneficial effects on grain and protein yields in economically important crops including wheat and oilseed rape. This enhancement occurs through sulphur's involvement in carbohydrate metabolism, oil biosynthesis, protein synthesis, and enzymatic regulation (Francioso *et al.*, 2020). Boron plays an equally critical role in reproductive processes, facilitating cell division, pollen viability, and seed formation. Insufficient boron availability disrupts flower development, impairs anther and pollen tube elongation, and consequently reduces fertility rates (Chhabra, 2022). During seed development, adequate boron supply promotes its accumulation within the seed coat structure (Eggert & von Wirén, 2016). Furthermore, boron participates in cross-linking reactions with structural molecules including pectin, glycosylinositol phosphoryl ceramides, and rhamnogalacturonan, thereby modulating cell wall porosity and mechanical properties (Begum & Fry, 2023). Micronutrient deficiencies generate cascading effects that extend beyond immediate yield reductions and quality deterioration to encompass soil health degradation and threaten agricultural sustainability. Consequently, implementing balanced fertilisation strategies and efficient nutrient management protocols becomes crucial for optimising rapeseed production while maintaining long-term ecological stability.

Recent field investigations in canola and winter oilseed rape have documented variation in seed yield and seed composition under different nitrogen and sulphur fertilisation treatments (Mohammadi & Mosleh Ghahfarokhi, 2023; Spasibionek *et al.*, 2024). In winter rapeseed, field comparisons have also shown that seed yield responses vary with the amount of boron applied (Wang *et al.*, 2025).

The increasing global population coupled with widespread micronutrient malnutrition concerns necessitates enhanced crop productivity per unit area. When soil conditions limit nutrient availability or rapid nutrient delivery becomes necessary, alternative strategies such as foliar fertilisation can be useful. Foliar nutrient application has gained considerable attention due to advances in water-soluble fertiliser formulations and its versatility across diverse climatic conditions. This approach may improve nutrient-use efficiency and maintain leaf nutrient concentrations, thereby enhancing photosynthetic capacity and facilitating nutrient translocation to developing tissues (Solanki *et al.*, 2020; Zain *et al.*, 2015).

Field research in Indian mustard has examined foliar sulphur and boron within a broader nutrient and irrigation management programme and reported differences in crop growth among treatments (Kumar *et al.*, 2025). In another oilseed species, *Camelina sativa*, foliar boron and zinc applications were associated with differences in growth and yield attributes (Haq *et al.*, 2022).

The cited studies do not provide a direct comparison of the basal and foliar boron- and sulphur-based treatments evaluated for Toria rapeseed in Dehradun, particularly with respect to applications at flowering and siliquing. This treatment- and location-specific comparison therefore forms the research gap addressed in the present investigation.

1.1 Objective

The objective of this study was to evaluate the effects of basal and foliar applications of boron and sulphur on growth, photosynthetic pigment content, yield attributes, seed yield and oil content of Toria rapeseed (*Brassica campestris* L. var. Toria) under the field conditions of Dehradun, Uttarakhand.

2. Material and Methods

This field investigation was conducted during the winter (*rabi*) cropping season of 2023-24 at the Research Farm of Graphic Era Hill University, Dehradun, Uttarakhand, India. The experimental site experiences a humid subtropical climate characterised by peak cold conditions during December through February and maximum temperatures occurring from May to July. Soil analysis of the surface layer (0-15 cm) revealed sandy loam texture with neutral pH (6.61), electrical conductivity of 1.5 dS/m, and low organic carbon content (0.39%). Nutrient analysis indicated low available nitrogen (157 kg/ha), while available phosphorus (12.51 kg/ha) and potassium (112.6 kg/ha) levels were classified as medium according to standard soil fertility ratings. The experiment followed a

randomised block design (RBD) incorporating 10 treatments as detailed in Table 1. The Pant Toria 303 variety was selected for cultivation with a seeding rate of 5 kg/ha. Boric acid served as the boron source, while elemental sulphur provided the sulphur component for foliar applications. Treatment solutions were prepared according to specified concentrations and applied using a knapsack sprayer at two critical growth stages: flowering (35 days after sowing) and siliquing (55 days after sowing). The crop was sown on 25 September 2023 and harvested on 5 January 2024. Standard agronomic practices were implemented following established recommendations throughout the growing period. Data collection encompassed growth parameters, yield attributes, and final yield measurements using conventional protocols. Photosynthetic pigment analysis involved chlorophyll a, b, and total chlorophyll quantification using Amon's equations, while carotenoid concentrations were determined following Kirk and Allen (1965) methodology. Fresh leaf samples (0.1 g) from each experimental plot were preserved overnight in dimethyl sulfoxide (5 mL) within sealed vials. Spectrophotometric measurements were obtained at wavelengths of 645 nm, 663 nm, and 480 nm using a UV 2600 spectrophotometer (Techcomp). Oil content determination employed nuclear magnetic resonance (NMR) spectroscopy utilising 10 g seed samples collected from individual plots. Meteorological observations (Fig. 1) were recorded through automated weather stations located at the Research Farm, Graphic Era Hill University, Dehradun, providing comprehensive climatic data throughout the experimental period.

Table 1. Detail of various treatments

Treatments	Details	Treatments	Details
T_1	Control (RDF- 90:60:40)	T_6	100% RDF + S @ 1% FA at Flowering
T_2	100% RDF+ B @ 1kg/ha	T_7	100% RDF+ B @ 0.5% FA at Flowering and Siliquing
T_3	100% RDF+ S @ 40kg/ha	T_8	100% RDF+ S @ 1% FA at Flowering and Siliquing
T_4	100% RDF+ B @1kg/ha+ S @40kg/ha	T_9	100% RDF+ B @ 0.5% + S @ 1% FA at Flowering
T_5	100% RDF + B @ 0.5% FA at Flowering	T_{10}	100% RDF+ B @ 0.5% + S @1% FA at Flowering and Siliquing

FA Foliar Application*

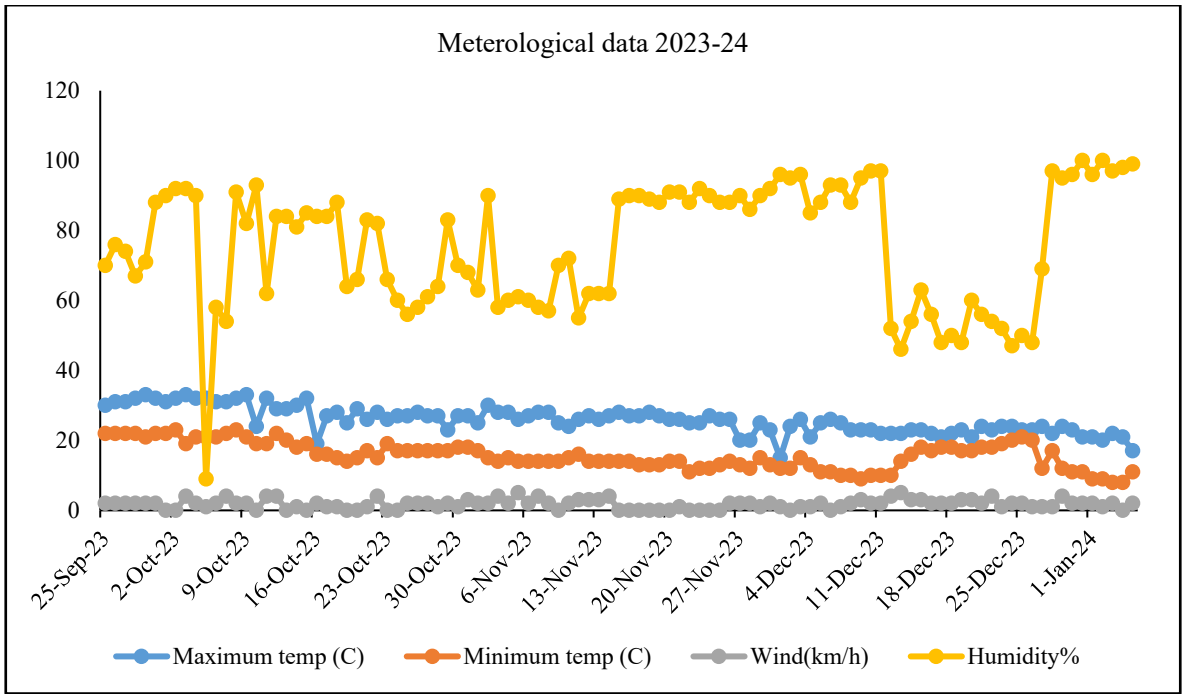


Fig. 1. Meterological data recorded during *rabi* season 2023-24

A post hoc test was conducted for statistical analysis, following analysis of variance (ANOVA), to explore and compare specific pairs of groups. When the ANOVA indicated a significant difference among multiple groups, a post hoc test was used to identify which pairs of groups exhibited significant differences. Tukey's honestly significant difference (HSD) test was used in the present study to compare all possible pairs of group means. The formula for Tukey's HSD is as follows: HSD= q$\times\sqrt{MS\frac{within}{n}}$ where q is the critical value obtained from Tukey's HSD distribution table, MS within is the mean square within groups (residual mean square) from the ANOVA and n is the number of observations in each group. The formula provides a threshold value, and the difference between any two groups indicates that exceeding this threshold is considered statistically significant. Statistical analysis was conducted using the SPSS software.

3. Results

3.1 Plant Height and Biomass Accumulation Dynamics

Plant height and dry matter accumulation exhibited pronounced variation among treatments throughout all developmental stages. At 90 days after sowing, treatment T10 achieved maximum plant height (154.43 cm) accompanied by peak dry matter accumulation (673.2 g/m²), indicating greater recorded biomass accumulation (Table 2). Conversely, T1 displayed minimal values for both parameters, indicating lower vegetative growth in the control. Treatments T8 and T9 demonstrated intermediate performance while maintaining substantial biomass accumulation patterns. Plants receiving micronutrient supplementation consistently exhibited progressive increases in growth metrics across the experimental duration. These observations suggest that foliar nutrient application can improve plant growth and cumulative dry matter production under the experimental conditions.

Table 2. Variation in plant height (cm) and dry matter accumulation (g/m²) of rapeseed under different treatments

Treatments	Plant height (cm)			Dry matter accumulation (g/m²)		
	30 DAS	60 DAS	90 DAS	30DAS	60DAS	90DAS
T_1	$26.33^{b} \pm 0.33$	$116.8^{b} \pm 3.48$	$130.53^{c} \pm 0.33$	$14.42^{d} \pm 0.37$	$176.4^{c} \pm 19.91$	$363.44^{c} \pm 5.47$
T_2	$31.33^{ab} \pm 0.84$	$123.6^{ab} \pm 2.59$	$133.47^{bc} \pm 0.67$	$21.56^{ab} \pm 1.01$	$232.4^{bc} \pm 10.97$	$491.68^{b} \pm 8.32$
T_3	$32.6^{ab} \pm 0.30$	$123.6^{ab} \pm 2.37$	$140.53^{abc} \pm 4.40$	$22.26^{a} \pm 0.64$	$251.7^{ab} \pm 20.99$	$502.18^{b} \pm 6.75$
T_4	$33.8^{a} \pm 3.81$	$124.03^{ab} \pm 3.01$	$140.67^{abc} \pm 3.44$	$22.82^{a} \pm 0.51$	$256.2^{ab} \pm 7.30$	$523.18^{b} \pm 4.57$
T_5	$27.7^{ab} \pm 1.40$	$124.17^{ab} \pm 1.74$	$142.17^{abc} \pm 3.67$	$18.62^{bc} \pm 0.98$	$257.6^{ab} \pm 2.81$	$526.68^{b} \pm 2.23$
T_6	$27.2^{ab} \pm 1.81$	$125.87^{ab} \pm 6.29$	$143^{abc} \pm 3.20$	$17.92^{c} \pm 0.61$	$257.8^{ab} \pm 21.87$	$542.22^{b} \pm 10.63$
T_7	$26.27^{b} \pm 1.44$	$127.47^{ab} \pm 3.13$	$146.53^{abc} \pm 3.48$	$18.48^{bc} \pm 0.49$	$258.89^{ab} \pm 7.94$	$542.5^{b} \pm 18.33$
T_8	$26.87^{ab} \pm 1.56$	$128.93^{ab} \pm 1.17$	$146.8^{abc} \pm 5.78$	$19.32^{bc} \pm 0.49$	$282.03^{ab} \pm 11.15$	$633.12^{a} \pm 46.22$
T_9	$28.33^{ab} \pm 0.33$	$130.87^{ab} \pm 0.48$	$150.67^{ab} \pm 5.10$	$19.18^{bc} \pm 0.85$	$285.27^{ab} \pm 7.38$	$645.167^{a} \pm 15.59$
T_{10}	$28^{ab} \pm 0.58$	$135.57^{a} \pm 2.93$	$154.43^{a} \pm 2.11$	$18.76^{bc} \pm 0.28$	$302.2^{a} \pm 12.03$	$673.2^{a} \pm 16.92$
SEm±	1.5	3.10	3.64	0.66	13.63	15.72
CD at 5%	4.4	9.20	10.82	1.97	40.81	47.07

3.2 Crop Growth Rate and Photosynthetic Pigment Analysis

Treatment effects significantly influenced crop growth rate (CGR) and pigment concentrations throughout the growing season. Treatment T10 achieved the highest CGR at 90 DAS (12.37 g/m²/day) while simultaneously recording maximum concentrations of chlorophyll a (0.31 mg/g FW), chlorophyll b (0.53 mg/g FW), and total chlorophyll (0.84 mg/g FW). Carotenoid accumulation similarly peaked under T10 conditions (30.04 mg/g FW). Treatment T1 consistently demonstrated the lowest pigment concentrations across all measurements (Table 3). The higher pigment concentrations and biomass accumulation observed under these treatments are consistent with improved nutrient availability. These results suggest that balanced foliar nutrition may support photosynthetic pigment accumulation and crop growth.

Table 3. Variation in crop growth rate (g/m²/day) and chlorophyll content (mg/g FW) of rapeseed under different treatments

Treatments	Crop growth rate (g/m²/day)			Chlorophyll content (mg/g FW)			
	30DAS	60DAS	90DAS	Chl a	Chl b	Total Chl	Carotenoid
T_1	$0.48^{c} \pm 0.09$	$5.4^{c} \pm 0.65$	$6.23^{d} \pm 0.56$	$0.08^{c} \pm 0.01$	$0.14^{c} \pm 0.00$	$0.22^{c} \pm 0.01$	$12.86^{i} \pm 0.09$
T_2	$0.72^{a} \pm 0.03$	$7.03^{bc} \pm 0.33$	$8.35^{cd} \pm 0.47$	$0.17^{bc} \pm 0.00$	$0.25^{b} \pm 0.01$	$0.42^{b} \pm 0.01$	$13.81^{h} \pm 0.08$
T_3	$0.74^{a} \pm 0.02$	$7.65^{abc} \pm 0.70$	$8.64^{bcd} \pm 0.26$	$0.17^{bc} \pm 0.00$	$0.26^{b} \pm 0.02$	$0.43^{b} \pm 0.01$	$20.23^{g} \pm 0.11$
T_4	$0.76^{a} \pm 0.06$	$7.78^{ab} \pm 0.25$	$8.9^{abcd} \pm 0.39$	$0.21^{abc} \pm 0.05$	$0.27^{b} \pm 0.02$	$0.48^{b} \pm 0.03$	$21.42^{f} \pm 3.57$
T_5	$0.62^{b} \pm 0.03$	$7.97^{ab} \pm 0.25$	$8.97^{abcd} \pm 0.03$	$0.22^{ab} \pm 0.05$	$0.28^{b} \pm 0.01$	$0.5^{b} \pm 0.04$	$23.28^{e} \pm 0.47$
T_6	$0.60^{b} \pm 0.02$	$8.00^{ab} \pm 0.11$	$9.48^{abcd} \pm 0.85$	$0.26^{ab} \pm 0.05$	$0.3^{b} \pm 0.00$	$0.56^{b} \pm 0.04$	$28.3^{d} \pm 0.22$
T_7	$0.62^{b} \pm 0.02$	$8.01^{ab} \pm 0.73$	$9.45^{abcd} \pm 0.53$	$0.28^{ab} \pm 0.00$	$0.5^{a} \pm 0.01$	$0.78^{a} \pm 0.02$	$28.4^{c} \pm 0.11$
T_8	$0.64^{b} \pm 0.02$	$8.76^{ab} \pm 0.27$	$11.7^{abc} \pm 1.61$	$0.29^{ab} \pm 0.00$	$0.51^{a} \pm 0.00$	$0.8^{a} \pm 0.00$	$28.42^{c} \pm 0.28$
T_9	$0.64^{b} \pm 0.02$	$8.87^{ab} \pm 0.39$	$12^{ab} \pm 0.58$	$0.30^{ab} \pm 0.00$	$0.52^{a} \pm 0.01$	$0.82^{a} \pm 0.01$	$28.82^{b} \pm 0.44$
T_{10}	$0.63^{b} \pm 0.01$	$9.45^{a} \pm 0.39$	$12.37^{a} \pm 0.96$	$0.31^{a} \pm 0.00$	$0.53^{a} \pm 0.02$	$0.84^{a} \pm 0.01$	$30.04^{a} \pm 0.15$
SEm±	0.02	0.45	0.69	0.03	0.01	0.02	1.13
CD at 5%	0.06	1.33	2.06	0.08	0.03	0.06	3.36

3.3 Yield-Contributing Character

Reproductive and yield-contributing traits demonstrated substantial variation across experimental treatments (Table 4). Treatment T10 recorded optimal values for primary branches (5.6), secondary branches (9.47), siliquae per plant (283.1), seeds per siliqua (11.37), siliqua length (6.95 cm), and test weight (4.43 g), collectively indicating superior reproductive efficiency. Treatment T1 consistently exhibited the lowest values across all measured parameters, suggesting constrained yield potential under nutrient-limited conditions. A systematic increase in yield attributes was observed with enhanced nutrient application protocols, particularly involving boron and sulphur supplementation. These nutrients contribute to in flower initiation and seed development processes. The findings indicate that foliar nutrient application can improve the reproductive characteristics associated with rapeseed yield under the conditions examined.

Table 4. Variations in yield contributing character of rapeseed under different treatments

Treatments	Yield attributes					
	Primary branches	Secondary branches	Total siliqua / plant	Seeds/Siliqua (no.)	Siliqua/Length (cm)	Test weight (g)
T_1	$4.47^{b} \pm 0.24$	$7.13^{c} \pm 0.41$	$174.3^{f} \pm 13.39$	$8.0^{c} \pm 0.23$	$5.67^{c} \pm 0.12$	$3.33^{b} \pm 0.18$
T_2	$4.5^{b} \pm 0.21$	$7.8^{bc} \pm 0.35$	$225.3^{e} \pm 2.37$	$9.33^{bc} \pm 0.30$	$5.8^{c} \pm 0.12$	$3.4^{ab} \pm 0.12$
T_3	$5^{ab} \pm 0.23$	$8.2^{abc} \pm 0.46$	$232.9^{de} \pm 13.38$	$9.3^{bc} \pm 0.29$	$5.91^{c} \pm 0.03$	$3.5^{ab} \pm 0.17$
T_4	$5^{ab} \pm 0.20$	$8.3^{abc} \pm 0.27$	$243.2^{cde} \pm 3.29$	$10.07^{ab} \pm 0.41$	$5.95^{c} \pm 0.38$	$3.53^{ab} \pm 0.24$
T_5	$5^{ab} \pm 0.23$	$8.47^{abc} \pm 0.64$	$255.6^{cd} \pm 4.25$	$10.17^{ab} \pm 0.22$	$6.18^{bc} \pm 0.04$	$3.67^{ab} \pm 0.29$
T_6	$5.1^{ab} \pm 0.10$	$8.77^{ab} \pm 0.59$	$257.7^{bc} \pm 9.46$	$10.23^{ab} \pm 0.15$	$6.2^{bc} \pm 0.04$	$3.73^{ab} \pm 0.13$
T_7	$5.17^{ab} \pm 0.19$	$8.8^{ab} \pm 0.12$	$258.5^{bc} \pm 6.06$	$10.47^{ab} \pm 0.24$	$6.27^{bc} \pm 0.07$	$3.73^{ab} \pm 0.18$
T_8	$5.4^{a} \pm 0.12$	$9.27^{a} \pm 0.07$	$280.7^{ab} \pm 5.03$	$11.03^{a} \pm 0.09$	$6.67^{ab} \pm 0.12$	$4.23^{ab} \pm 0.29$
T_9	$5.47^{a} \pm 0.07$	$9.37^{a} \pm 0.03$	$281.7^{ab} \pm 1.58$	$11.17^{a} \pm 038$	$6.81^{ab} \pm 0.11$	$4.3^{ab} \pm 0.25$
T_{10}	$5.6^{a} \pm 0.12$	$9.47^{a} \pm 0.24$	$283.1^{a} \pm 3.38$	$11.37^{a} \pm 0.27$	$6.95^{a} \pm 0.02$	$4.43^{a} \pm 0.26$
SEm ±	0.16	0.28	7.55	0.28	0.15	0.21
CD at 5%	0.49	0.82	22.46	0.82	0.44	0.64

3.4 Yield Performance, Oil Content, and Harvest Index Evaluation

Treatment T10 demonstrated superior performance across all yield parameters, achieving maximum seed yield (26.95 q/ha), stover yield (51.45 q/ha), and biological yield (78.4 q/ha). This treatment also recorded the highest oil yield (11.63 q/ha) concurrent with peak oil content (43.27%). The harvest index was 34.34%; however, differences in harvest index among treatments were not statistically significant (Table 5). In contrast, treatment T1 consistently produced the lowest seed and oil yields across all measured parameters. Treatments T8 and T9 exhibited considerable improvements that corresponded with enhanced nutrient availability patterns observed throughout the experiment (Table 5). These findings emphasise the critical importance of strategic foliar micronutrient management in optimising oilseed rape productivity. The simultaneous increases in biomass accumulation and oil yield indicate benefits for both seed and oil production. These results indicate that the combined foliar treatment improved yield and seed oil content under the experimental conditions.

Table 5. Variation in yield of rapeseed under different treatments

Treatments	Yield					
	Seed yield (q/ha)	Stover yield (q/ha)	Biological Yield (q/ha)	Harvest index (%)	Oil content (%)	Oil yield (q/ha)
T_1	$15.07^{c} \pm 0.56$	$39.53^{b} \pm 0.00$	$54.6^{e} \pm 3.15$	$27.72^{a} \pm 1.41$	$32.83^{b} \pm 3.43$	$4.98^{e} \pm 0.69$
T_2	$18.55^{bc} \pm 0.60$	$43.73^{ab} \pm 3.36$	$62.28^{de} \pm 2.19$	$29.91^{a} \pm 1.89$	$37.09^{ab} \pm 0.38$	$6.88^{de} \pm 0.28$
T_3	$19.23^{bc} \pm 0.54$	$44.16^{ab} \pm 0.93$	$63.39^{cde} \pm 2.61$	$30.02^{a} \pm 2.03$	$36.45^{ab} \pm 0.60$	$7.01^{cde} \pm 0.24$
T_4	$20.41^{bc} \pm 0.62$	$45.17^{ab} \pm 3.89$	$64.57^{cde} \pm 0.84$	$31.6^{a} \pm 0.83$	$38.76^{ab} \pm 0.96$	$7.92^{bcde} \pm 0.40$
T_5	$20.79^{bc} \pm 0.42$	$45.74^{ab} \pm 2.19$	$66.53^{bcd} \pm 1.40$	$31.3^{a} \pm 1.23$	$38.97^{ab} \pm 0.45$	$8.1^{bcd} \pm 0.12$
T_6	$21.00^{bc} \pm 0.79$	$46.23^{ab} \pm 1.64$	$67.23^{bcd} \pm 1.35$	$31.25^{a} \pm 1.15$	$38.91^{ab} \pm 0.40$	$8.17^{bcd} \pm 0.25$
T_7	$21.22^{bc} \pm 0.36$	$46.35^{ab} \pm 3.15$	$67.57^{bcd} \pm 2.27$	$31.5^{a} \pm 1.45$	$41.54^{a} \pm 0.57$	$8.82^{bcd} \pm 0.25$
T_8	$23.27^{ab} \pm 2.35$	$49.57^{a} \pm 1.11$	$72.83^{abc} \pm 2.90$	$31.8^{a} \pm 1.97$	$42.35^{a} \pm 1.05$	$9.89^{abc} \pm 1.22$
T_9	$24.52^{ab} \pm 2.20$	$49.94^{a} \pm 1.01$	$74.47^{ab} \pm 2.22$	$32.83^{a} \pm 2.03$	$42.75^{a} \pm 0.78$	$10.48^{ab} \pm 0.92$
T_{10}	$26.95^{a} \pm 1.46$	$51.45^{a} \pm 0.87$	$78.4^{a} \pm 0.76$	$34.34^{a} \pm 1.55$	$43.27^{a} \pm 1.54$	$11.63^{a} \pm 0.53$
SEm±	1.25	1.89	2.06	1.59	1.40	0.65
CD at 5%	3.72	5.63	6.13	NS	4.18	1.94

4. Discussion

The substantial improvements observed in plant growth characteristics—including plant height, dry matter accumulation, crop growth rate, and chlorophyll content at 60 and 90 DAS—result from enhanced uptake and translocation efficiency of sulphur (S) and boron (B) within plant tissues. Foliar application establishes a more conducive nutrient environment by enabling direct and rapid assimilation of these essential elements into metabolically active meristematic zones, thereby stimulating vertical growth development. Comparable findings have been documented by Singh *et al.* (2022) and Sharma *et al.* (2020) in mustard (*Brassica juncea* L.) cultivation systems. Both sulphur and boron function as crucial components in chlorophyll biosynthesis pathways, contributing to elevated pigment concentrations and intensified green leaf coloration, which may support photosynthetic activity. This enhanced photosynthetic capacity subsequently promotes greater dry matter accumulation and accelerated crop growth rates, as similarly reported by Mounika *et al.* (2021) in *Sinapis alba* studies. The increased chlorophyll content may relate to the essential roles of S and B in protein and peptide synthesis required for chlorophyll a and b complex formation. Moreover, these nutrients serve as activators for critical enzymes including 5-aminolevulinic acid dehydratase and porphobilinogen deaminase, along with antioxidant enzymes such as glutathione reductase and glutathione peroxidase, which maintain chlorophyll stability and enhance stress tolerance mechanisms (Riffat *et al.*, 2020; Yadav *et al.*, 2016; Watsh *et al.*, 2023). Enhanced metabolic functioning, accelerated cell division, and improved assimilate translocation following foliar B and S application at critical phenological stages (flowering and siliquing) were associated with increased primary and secondary branch development. These observations align with findings reported by Sharma *et al.* (2020). The improved nutrient availability during reproductive phases likely optimised the source-sink relationship, facilitating efficient photosynthate movement to siliqua and seed tissues. This enhanced translocation

promoted superior grain filling processes, resulting in increased siliqua per length and higher seed counts per siliqua, corroborating results obtained by Lalrinengi and Taki (2022) and Singh *et al.* (2023).

The synergistic interaction between boron and sulphur throughout vegetative and reproductive developmental phases was associated with optimal siliqua number, size, and length, ultimately contributing to enhanced test weight values. These results demonstrate consistency with findings reported by Saini *et al.* (2024) and Verma and Dawson (2018). The beneficial effects of foliar-applied B and Son reproductive structures translated into improved yield-contributing characteristics and subsequently enhanced seed yield performance, supporting conclusions drawn by Rahangdale *et al.* (2022) and Mounika *et al.* (2021). The increased stover yield (51.45 q/ha) and biological yield (78.40 q/ha) achieved under treatment T10 may be associated with elevated photosynthetic efficiency, stimulated through sulphur and boron-induced improvements in pigment synthesis, nitrogen assimilation, and assimilate utilisation within reproductive sinks. This comprehensive enhancement ultimately resulted in substantial biomass accumulation. Similar observations have been documented by Pant *et al.* (2022), Jaiswal *et al.* (2015), and Sharma *et al.* (2020).

The elevated oil content percentage under combined foliar application of boron and sulphur likely stems from their integral involvement in lipid metabolism and fatty acid biosynthesis pathways. Sulphur, functioning as a structural component of glucosinolates, CoA, and lipoic acid—all critical intermediates in oil synthesis—may have contributed to improvements in oil yield performance. These findings align with reports published by Singh *et al.* (2023), Barthwal *et al.* (2022), and Singh *et al.* (2020).

5. Conclusion

This investigation indicates the effects of boron and sulphur on rapeseed growth dynamics, yield performance, and oil productivity, particularly when delivered through foliar applications during flowering and siliquing developmental stages. Foliar nutrient delivery demonstrated clear advantages over conventional basal application methods, resulting in enhanced plant height, increased dry matter accumulation, elevated chlorophyll concentrations, and improved yield components encompassing both seed and oil production parameters. The superior effectiveness of foliar feeding may be associated with nutrient delivery during physiologically critical growth phases, thereby optimising metabolic efficiency and overall plant performance.

In the context of growing global concerns regarding micronutrient deficiencies and food security challenges, this research highlights the importance of boron and sulphur in sustainable crop nutrition systems. Rapeseed, recognized as a high-value oilseed crop, exhibits responsiveness to these micronutrients, which contribute significantly to reproductive development processes, seed filling mechanisms, and ultimately marketable yield outcomes. The combined foliar application strategy may offer an approach under conditions where soil-based nutrient acquisition becomes constrained due to adverse soil properties or unfavorable environmental factors.

The findings suggest the potential for integrating of boron and sulphur foliar fertilisation protocols into comprehensive nutrient management frameworks designed to enhance crop productivity, product quality, and long-term sustainability within oilseed production systems. The findings provide a basis for further evaluation of foliar nutrient management in rapeseed production. The study provides field evidence relevant to the development of region-specific nutrient management strategies.

6. Future Implications

Future research should prioritise the development of integrated nutrient management approaches that combine basal and foliar micronutrient applications strategically timed with phenologically critical developmental stages. Comprehensive investigations examining rapeseed responses to variable boron and sulphur dosages across diverse climatic zones, soil classifications, and cropping systems remain essential for establishing location-specific fertilisation protocols. Understanding how these micronutrients function under varying environmental conditions may support the development of targeted recommendations that optimise nutrient use efficiency while accounting for regional agricultural constraints. Additionally, examining the capacity of these micronutrients to enhance plant tolerance mechanisms against biotic and abiotic stress factors will provide valuable insights into their potential contributions to crop resilience enhancement. Such investigations may clarify how boron and sulphur supplementation influences stress adaptation pathways and overall plant defense systems under challenging environmental conditions. Long-term experimental studies should systematically evaluate the cumulative impacts of foliar application regimens on soil health parameters, nutrient cycling dynamics, and economic profitability to ensure sustainable implementation within oilseed production systems. These extended investigations may be important for understanding the broader implications of intensive foliar fertilisation practices on agroecosystem stability and economic viability for farmers. Furthermore, research should explore the potential interactions between foliar micronutrient applications and other agronomic practices to develop holistic management strategies that maximize both productivity and environmental sustainability in rapeseed cultivation systems.

7. Limitations

This investigation was conducted with one Toria rapeseed variety at a single experimental site during one rabi season. Consequently, the observed responses reflect the soil, weather and treatment conditions of that trial and may not apply uniformly to other locations, seasons or varieties. The findings are limited to the boron and sulphur rates, application methods and growth stages examined. Further trials under contrasting field conditions are needed to assess the consistency of the observed effects.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and

reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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