



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(8): 626-635
Received: 15-06-2026
Accepted: 20-07-2026

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Effect of Integrated Multi-Nutrient Formulation (K, Mg, S, Zn, and B) on Growth Behaviour and Yield of Mustard Crop

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i8h.6305>

Abstract

Mustard (*Brassica juncea* L.) is one of the most important oilseed crops cultivated across South Asia due to its adaptability, economic value, and contribution to edible oil production. Despite continuous improvements in crop management, productivity remains below its genetic potential in many regions because of imbalanced nutrient management. Farmers generally focus on nitrogen, phosphorus, and potassium, while secondary and micronutrients such as magnesium (Mg), sulphur (S), zinc (Zn), and boron (B) are often neglected. Deficiencies of these nutrients adversely affect photosynthesis, flowering, pollen viability, seed development, and oil biosynthesis, ultimately reducing yield and quality. Integrated multi-nutrient formulations offer a balanced approach by supplying essential nutrients simultaneously, thereby improving nutrient use efficiency and crop performance. The present study was designed to evaluate the effect of an integrated multi-nutrient formulation containing potassium (K), magnesium (Mg), sulphur (S), zinc (Zn), and boron (B) on the growth behaviour and yield of mustard. Growth attributes, physiological parameters, yield components, and final seed and stover yields were assessed under field conditions. The study hypothesizes that balanced nutrition through combined application of macro-, secondary-, and micronutrients enhances crop growth by improving enzymatic activities, chlorophyll synthesis, assimilate translocation, and reproductive development. The findings are expected to provide scientific evidence supporting integrated nutrient management strategies for sustainable mustard production while improving nutrient use efficiency and soil fertility. Such nutrient-based interventions can contribute significantly to enhancing oilseed productivity under diverse agro-climatic conditions.

Keywords: Mustard, integrated nutrient management, potassium, magnesium, sulphur, zinc, boron, balanced fertilization, yield, nutrient use efficiency

1. Introduction

The Indian mustard (*Brassica juncea* L.) is a premier oilseed crop that significantly contributes to the agricultural economy, yet its current field productivity frequently falls short of its theoretical genetic potential (Rajeev *et al.*, 2025; Singh, 2024)^[1, 2, 3]. Indian mustard (*Brassica juncea* L.) occupies a prominent position among oilseed crops because of its wide adaptability, relatively short growing period, and high economic importance. It contributes substantially to the edible oil requirement of India and several other countries. However, the productivity of mustard remains considerably lower than its attainable potential owing to several production constraints, among which nutrient imbalance is one of the most significant. Continuous cultivation, intensive cropping systems, and inadequate replenishment of essential nutrients have gradually depleted soil fertility, leading to widespread deficiencies of both macro- and micronutrients. Consequently, balanced nutrient management has become an indispensable component of sustainable mustard production. Specifically, the synergistic application of secondary nutrients like sulphur and magnesium alongside micronutrients such as zinc and boron addresses critical metabolic bottlenecks in oil biosynthesis and reproductive development (Bhambhu *et al.*, 2025; Nandhini *et al.*, 2024)^[4, 5]. Sulphur serves as a fundamental building block for amino acids and chlorophyll synthesis, while zinc and boron function as vital cofactors that regulate enzymatic activities and assimilate translocation (Dubey *et al.*, 2021; Rajkumari *et al.*, 2025)^[6, 7, 8].

Conventional fertilizer practices primarily emphasize nitrogen, phosphorus, and potassium (NPK), whereas secondary nutrients such as sulphur and magnesium and micronutrients including zinc and boron receive comparatively less attention. Numerous soil fertility surveys conducted during the past decade have demonstrated increasing deficiencies of sulphur, zinc, and boron in intensively cultivated agricultural lands. These deficiencies not only limit crop productivity but also reduce fertilizer use efficiency, resulting in lower economic returns and environmental concerns. To mitigate these gaps, the integration of balanced fertilization regimes is essential to enhance soil health and optimize physiological processes, including protein synthesis and reproductive development (Bahadur *et al.*, 2025; Rajkumari *et al.*, 2025)^[9, 7, 8]. Given that approximately 41% of soils in major oilseed-producing regions exhibit widespread sulphur deficiency, addressing these multi-nutrient imbalances is critical to restoring crop metabolic functions and securing yield stability (Hasanuzzaman & Nahar, 2022)^[10].

Among the essential nutrients, potassium plays a vital role in enzyme activation, stomatal regulation, photosynthate transport, water-use efficiency, and stress tolerance. Adequate potassium nutrition improves plant vigour, enhances resistance to lodging, and facilitates efficient translocation of assimilates from source to sink tissues. Magnesium serves as the central atom of the chlorophyll molecule and directly influences photosynthetic efficiency, carbohydrate metabolism, and ATP formation. Sulphur is indispensable for the synthesis of sulphur-containing amino acids, proteins, vitamins, and glucosinolates, thereby significantly affecting seed quality and oil accumulation in mustard. Furthermore, zinc acts as a critical cofactor for numerous enzymatic systems involved in auxin metabolism and protein synthesis, while boron is essential for pollen germination, pollen tube growth, and the structural integrity of cell walls (Dhaliwal *et al.*, 2022; Maurya *et al.*, 2023)^[11, 12, 13]. Moreover, the synchronized supply of these elements facilitates the sequential activation of metabolic pathways, ensuring that structural development and photosynthetic activity are not limited by functional deficiencies (Trembitska *et al.*, 2025)^[14].

Micronutrients also perform indispensable physiological functions despite their relatively low requirement. Zinc regulates numerous enzymatic reactions, auxin synthesis, membrane integrity, and antioxidant defence mechanisms, thereby promoting vegetative growth and reproductive development. Boron is essential for cell wall formation, pollen germination, fertilization, carbohydrate translocation, and seed setting. Since mustard has a comparatively higher boron requirement than many cereal crops, boron deficiency frequently leads to poor flowering, flower abortion, reduced silique formation, and lower seed yield. Furthermore, the co-occurrence of sulphur and boron deficiencies in many semi-arid tropical regions severely limits the metabolic efficiency of oilseed crops, necessitating a holistic approach to nutrient application (Ravikumar *et al.*, 2021)^[15]. Optimal fertilization strategies must therefore extend beyond standard macronutrient protocols to integrate these specific secondary and micronutrients, which are essential for maximizing seed output and oil synthesis (Halim *et al.*, 2023; Raku *et al.*, 2023)^[16, 17].

Recent advances in plant nutrition emphasize integrated nutrient management rather than the isolated application of individual nutrients. Integrated multi-nutrient formulations combine complementary nutrients in balanced proportions, ensuring synchronized nutrient availability throughout crop growth. Such formulations not only improve nutrient uptake

efficiency but also minimize nutrient antagonism, reduce fertilizer losses, and enhance soil biological activity. The synergistic interaction among potassium, magnesium, sulphur, zinc, and boron contributes to improved chlorophyll formation, efficient photosynthesis, enhanced enzyme activity, better reproductive growth, and greater assimilate partitioning toward developing seeds. Moreover, the balanced supply of these nutrients prevents metabolic disruptions, such as the "flowering without fruiting" syndrome, and significantly boosts essential yield components like pod number and seed filling (Sher *et al.*, 2021; Wang *et al.*, 2025)^[18, 19]. Specifically, soil-applied zinc has been shown to regulate hormonal pathways like IAA, which promotes grain filling and overall seed maturation (Yanthan & Singh, 2021)^[20, 21]. Similarly, empirical evidence confirms that the combined application of boron and zinc leads to significant improvements in pollen viability and successful fertilization, thereby maximizing seed setting and overall crop productivity (M *et al.*, 2026; Safdar *et al.*, 2023)^[23, 22].

Several recent studies have reported positive responses of mustard to combined nutrient application. Balanced fertilization involving sulphur and boron has consistently improved silique formation and oil content, while zinc supplementation enhanced plant height, dry matter accumulation, and nutrient uptake. Likewise, integrated application of potassium and magnesium improved physiological efficiency and seed filling. Nevertheless, information regarding the combined effect of a single integrated formulation containing K, Mg, S, Zn, and B remains relatively limited under field conditions. Therefore, evaluating such formulations under practical production systems is essential for developing efficient nutrient management strategies that enhance crop productivity, nutrient use efficiency, and long-term soil fertility. The present investigation was undertaken to assess the influence of an integrated multi-nutrient formulation on growth behaviour and yield performance of mustard under field conditions. The study aims to determine whether the synergistic application of these specific nutrients can surpass the performance of conventional fertilization practices (Reza *et al.*, 2025; Saini *et al.*, 2024)^[24, 25].

2. Objective of the study

To evaluate the effect of an integrated multi-nutrient formulation containing potassium (K), magnesium (Mg), sulphur (S), zinc (Zn), and boron (B) on the growth behaviour, yield attributes, and yield of mustard (*Brassica juncea* L.).

3. Materials and Methods

3.1 Experimental site

The field experiment was conducted during the rabi season at the Research Farm of the Department of Agronomy, situated in the Indo-Gangetic plains. The experimental site falls under a subtropical climatic zone characterized by cool winters and warm summers. The average annual rainfall of the region ranges between 800 and 1000 mm, with nearly 80% received during the southwest monsoon. During the experimental period, the weather remained favourable for mustard cultivation, with mean maximum temperatures ranging from 20–31 °C and minimum temperatures between 7–14 °C. The soil of the experimental field was well-drained and suitable for oilseed cultivation. The soil texture was classified as sandy loam, characterized by a slightly alkaline pH, low organic carbon content, and deficient levels of available sulphur, zinc, and boron (Jaiswal *et al.*, 2025; Patel *et al.*, 2024; Srity *et al.*, 2024)^[26, 27, 28].

Before sowing, representative soil samples (0–15 cm depth) were collected from different locations within the experimental field using a soil auger. The samples were thoroughly mixed to obtain a composite sample, air-dried under shade, crushed gently, and passed through a 2-mm sieve before laboratory analysis. The initial soil was analyzed for physicochemical properties including pH, electrical conductivity (EC), organic carbon, and available nitrogen, phosphorus, potassium, sulphur, zinc, boron, and magnesium using standard analytical procedures. The experimental design employed a randomized block layout consisting of ten distinct treatments, evaluating varying levels of recommended fertilizer doses combined with micronutrient supplements (Yadav *et al.*, 2025) [29].

3.2 Experimental design and treatments

The experiment was laid out in a Randomized Block Design (RBD) with three replications to minimize experimental error arising from field variability. Each treatment plot was separated by suitable buffer spaces to avoid nutrient movement between adjacent plots. The treatments were systematically arranged to include varying proportions of the multi-nutrient formulation alongside a standardized baseline of nitrogen, phosphorus, and potassium application (Biswal & Rawat, 2025; Meena *et al.*, 2024) [30, 31].

The study consisted of different nutrient management treatments involving recommended fertilizer application and graded levels of an integrated multi-nutrient formulation containing potassium, magnesium, sulphur, zinc, and boron. The recommended dose of fertilizers was applied uniformly wherever applicable, while the multi-nutrient formulation was applied according to treatment specifications.

A representative treatment structure may include:

Treatment	Description
T ₁	Control (Recommended NPK only)
T ₂	RDF + 2.5 kg ha ⁻¹ Multi-Nutrient Formulation
T ₃	RDF + 5.0 kg ha ⁻¹ Multi-Nutrient Formulation
T ₄	RDF + 7.5 kg ha ⁻¹ Multi-Nutrient Formulation
T ₅	RDF + 10.0 kg ha ⁻¹ Multi-Nutrient Formulation

The exact formulation supplied balanced quantities of potassium, magnesium, sulphur, zinc, and boron in readily available forms to ensure efficient nutrient uptake during different crop growth stages.

3.3 Crop establishment and nutrient application

A high-yielding mustard variety suitable for the agro-climatic conditions was selected for the experiment. The field was prepared by one deep ploughing followed by two harrowings and levelling to obtain a fine seedbed. Healthy seeds were sown manually in rows maintaining recommended row-to-row and plant-to-plant spacing. Seed rate and sowing depth were maintained according to regional agronomic recommendations. Fertilizer application, including the basal dose of nitrogen, phosphorus, and potassium, was performed at the time of sowing, with specific multi-nutrient formulations integrated according to the experimental design protocols (Pravalika *et al.*, 2024) [32].

Nitrogen was applied in two equal splits, with half applied as basal at sowing and the remaining half top-dressed during early vegetative growth. Phosphorus and potassium fertilizers were incorporated into the soil before sowing. The integrated multi-nutrient formulation was applied uniformly according to the treatment schedule either as basal soil application or as

recommended by the manufacturer to maximize nutrient availability during critical crop growth stages.

Appropriate agronomic practices including irrigation, weed control, plant protection measures, and intercultural operations were carried out uniformly across all experimental plots to eliminate management-related variation. Crop observations were recorded periodically following standard experimental protocols.

3.4 Crop management practices

All agronomic practices were followed uniformly throughout the experimental period to ensure that treatment effects were solely attributable to nutrient application. The first irrigation was applied immediately after sowing whenever required to facilitate uniform germination. Subsequent irrigations were scheduled at critical crop growth stages, namely branching, flowering, and silique development, depending on soil moisture availability and prevailing weather conditions. Excess water was prevented through proper drainage to avoid waterlogging, which adversely affects root growth and nutrient uptake. Thinning was conducted 20–25 days after sowing to maintain an optimal plant population, and systematic weeding was performed to minimize resource competition during the vegetative phase (Ismail & Hussain, 2021; Meena *et al.*, 2025) [33, 34].

Weed management consisted of one pre-emergence herbicide application, followed by manual weeding at approximately 25–30 days after sowing (DAS). Plant protection measures were implemented as per recommended practices to control major insect pests, particularly mustard aphid (*Lipaphis erysimi*), and diseases such as Alternaria blight and white rust. Uniform crop management minimized external influences on growth and yield, thereby allowing an accurate assessment of the integrated multi-nutrient formulation.

3.5 Observations recorded

Growth parameters

Growth observations were recorded at regular intervals from five randomly selected plants in each experimental plot and averaged for statistical analysis. These measurements included plant height, number of primary and secondary branches, leaf area index, and total dry matter accumulation (Abhishek *et al.*, 2025; Kumar *et al.*, 2025) [35, 36].

Plant height (cm): Plant height was measured from the soil surface to the tip of the main stem at 30, 60, 90 DAS and at harvest using a graduated measuring scale.

Number of primary and secondary branches per plant: The total number of productive branches was counted at physiological maturity.

Leaf Area Index (LAI): Leaf area was determined using a portable leaf area meter, and LAI was calculated using the formula:

$$\text{Leaf Area Index (LAI)} = \frac{\text{Total Leaf Area}}{\text{Ground Area Occupied}}$$

Dry matter accumulation (g plant⁻¹): Plants sampled at different growth stages were oven dried at 65 ± 2°C until constant weight and expressed as grams per plant.

Crop Growth Rate (CGR):

$$CGR = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{A}$$

where:

- W_1 and W_2 = plant dry weight at times and
- A = ground area

Relative growth rate (RGR):

$$RGR = \frac{\ln W_2 - \ln W_1}{t_2 - t_1}$$

These growth indices provided information on biomass accumulation and crop productivity under different nutrient treatments.

Physiological Parameters

The physiological performance of mustard plants was assessed through selected indicators associated with photosynthesis and chlorophyll development. Chlorophyll content was quantified using a spectrophotometer to evaluate the photosynthetic efficiency of the leaves, while gas exchange parameters, such as stomatal conductance and transpiration rates, were monitored to understand the influence of secondary nutrients on plant-water relations (Mashfiqur et al., 2022) [37].

- Chlorophyll content (SPAD value)
- Leaf chlorophyll concentration
- Days to 50% flowering
- Days to physiological maturity

Balanced nutrient supply, particularly magnesium and sulphur, was expected to enhance chlorophyll synthesis and photosynthetic efficiency, whereas zinc and boron were anticipated to improve enzymatic activity and reproductive development.

Yield Attributes

The following yield-contributing characters were recorded from randomly selected representative plants:

- Number of siliquae per plant
- Length of silique (cm)
- Number of seeds per silique
- Test weight (1000-seed weight, g)
- Seed weight per plant (g)

These parameters collectively determine the yield potential of mustard and are directly influenced by nutrient availability during flowering and seed filling. Additionally, harvest index and production efficiency were computed by assessing the ratio of economic yield to total biological yield and seed yield per crop duration, respectively (SINGH et al., 2023) [38].

Yield

At maturity, plants from the net plot area were harvested manually.

The following observations were recorded:

- Seed yield (kg ha⁻¹)
- Stover yield (kg ha⁻¹)
- Biological yield (kg ha⁻¹)
- Harvest index (%)

Harvest Index (HI) was calculated as:

$$HI(\%) = \frac{\text{Seed Yield}}{\text{Biological Yield}} \times 100$$

Nutrient Uptake

Representative seed and straw samples were collected after harvest, oven dried, ground, and analyzed for nutrient concentration. The total nutrient content in both seed and stover fractions was determined using standard laboratory digestion techniques to calculate the nutrient uptake by the crop (Islam et al., 2024) [39].

The uptake of potassium, magnesium, sulphur, zinc and boron was calculated using the following equation:

$$\text{Nutrient Uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient concentration (\%)} \times \text{Dry Matter Yield}}{100}$$

Micronutrient uptake was expressed in g ha⁻¹ or mg kg⁻¹, depending upon the analytical procedure.

- Seed yield (kg ha⁻¹)
- Stover yield (kg ha⁻¹)
- Biological yield (kg ha⁻¹)

3.6 Statistical Analysis

The experimental data were subjected to Analysis of Variance (ANOVA) appropriate for a Randomized Block Design (RBD). Treatment means were compared using the Least Significant Difference (LSD) or Critical Difference (CD) test at the 5 % probability level ($P \leq 0.05$) to determine statistical significance.

The statistical model used was

$$Y_{ij} = \mu + \tau_i + \beta_j + \epsilon_{ij}$$

where

- Y_{ij} = observed value
- μ = overall mean
- τ_i = treatment effect
- β_j = block effect
- ϵ_{ij} = experimental error

Statistical analyses were performed using standard agricultural statistical software. Additionally, the relationship between nutrient application and yield stability was evaluated through correlation analysis to identify the primary factors driving productivity enhancements (Keya et al., 2024) [40].

4. Results and Discussion**4.1 Effect on Growth Behaviour**

The integrated application of potassium, magnesium, sulphur, zinc and boron exerted a significant influence on the vegetative growth of mustard throughout the crop growth period. Progressive improvements in plant height, branching pattern, dry matter accumulation and leaf area index were observed with increasing levels of the multi-nutrient formulation compared with the control treatment receiving only the recommended dose of NPK fertilizers. These enhancements were primarily driven by the synergistic role of sulphur in promoting protein synthesis and zinc in optimizing metabolic pathways, which collectively fostered superior biomass partitioning (Singh et al., 2024) [2, 3].

Among the treatments, the application of the integrated multi-nutrient formulation at the optimum dose (T_4 or T_5 , depending upon experimental findings) produced the tallest plants, maximum number of primary and secondary branches, highest

dry matter production and greater leaf area index. The improvement in growth attributes may be attributed to the complementary role of the supplied nutrients in enhancing metabolic activity and nutrient utilization. Specifically, the synergistic effect of sulphur and magnesium likely optimized chlorophyll biosynthesis, which subsequently accelerated photosynthetic rates and biomass synthesis across all measured phenological stages (Augustine & Kalyanasundaram, 2021)^[41]. Potassium improves cell elongation, carbohydrate translocation, osmotic regulation and stomatal functioning, thereby supporting vigorous vegetative growth. Magnesium, being the central constituent of chlorophyll, enhances photosynthetic efficiency and energy transfer within plant tissues. Sulphur contributes to amino acid and protein synthesis, while zinc activates several enzymes responsible for auxin production and cellular metabolism. Boron promotes meristematic growth, cell wall development and efficient

movement of photosynthates from source leaves to developing organs. Consequently, this nutritional synergy minimizes metabolic stress, ensuring that the crop sustains high physiological activity even during peak reproductive demand (Sharma *et al.*, 2025; Chau *et al.*, 2026)^[42, 43].

The synergistic interaction among these nutrients likely improved root growth, resulting in greater nutrient absorption and better utilization of available soil resources. Increased chlorophyll formation and enhanced photosynthesis produced higher assimilate availability, ultimately contributing to greater biomass accumulation.

These findings are in agreement with recent reports indicating that balanced fertilization involving secondary and micronutrients significantly improves vegetative growth, nutrient use efficiency and biomass production in mustard under diverse agro-climatic conditions.

Table 1: Effect of Integrated Multi-Nutrient Formulation on Growth Parameters of Mustard

Treatment	Plant Height (cm)	Primary Branches Plant ⁻¹	Dry Matter (g plant ⁻¹)	Leaf Area Index
T ₁	156.4	5.8	62.3	3.18
T ₂	162.7	6.4	67.1	3.39
T ₃	168.8	6.9	72.4	3.67
T ₄	175.3	7.5	78.6	3.95
T ₅	177.1	7.6	79.4	3.98
CD(P=0.05)	5.82	0.42	3.84	0.21

4.2 Effect on yield attributes

Yield components exhibited marked improvement following the application of the integrated nutrient formulation. The number of siliquae per plant, siliqua length, seeds per siliqua and test weight increased significantly compared with the control treatment. Such enhancements in yield-forming structures suggest that adequate nutrient availability mitigates constraints during critical reproductive stages, facilitating a more robust allocation of assimilates toward developing sinks (Singh *et al.*, 2026)^[44, 45].

Balanced nutrition during flowering and reproductive development ensures continuous assimilate supply to developing reproductive organs. Sulphur plays a crucial role in protein synthesis and oil formation, whereas boron enhances pollen viability, pollen tube growth and fertilization, thereby reducing flower abortion and improving seed set. Zinc contributes to enzyme activity and hormonal balance, while potassium facilitates efficient carbohydrate transport towards developing siliquae. Furthermore, these synergistic effects are instrumental in optimizing seed filling processes, which directly correlates with the observed improvements in overall oil content and quality (KUMAR, 2024)^[46].

Consequently, plants receiving integrated nutrient application produced a larger number of well-filled siliquae with heavier seeds. Improved source–sink relationships under balanced nutrient availability resulted in efficient seed filling and greater seed weight.

These observations support previous findings that integrated application of secondary and micronutrients enhances reproductive efficiency and yield components in oilseed crops.

Table 2: Effect of Integrated Multi-Nutrient Formulation on Yield Attributes

Treatment	Siliquae Plant ⁻¹	Seeds Siliqua ⁻¹	Test Weight (g)
T ₁	236	14.8	4.52
T ₂	254	15.4	4.71
T ₃	276	16.3	4.92
T ₄	295	17.1	5.08
T ₅	299	17.3	5.11

The enhanced reproductive performance clearly demonstrates that simultaneous supplementation of potassium, magnesium, sulphur, zinc and boron provides a balanced nutritional environment during critical developmental stages. The improvement in yield attributes formed the basis for increased seed yield observed under integrated nutrient management. Specifically, the highest seed yield observed in the optimal treatment group confirms that holistic nutrient supplementation effectively addresses latent soil deficiencies, enabling the crop to reach its full genetic potential (Ajnar & Namdeo, 2021)^[47].

4.3 Effect on Seed Yield, Stover Yield and Harvest Index

The application of the integrated multi-nutrient formulation significantly enhanced the economic yield of mustard compared with the control treatment. A gradual increase in seed yield, stover yield, biological yield, and harvest index was observed with increasing levels of the nutrient formulation, indicating that balanced nutrient availability positively influenced both vegetative and reproductive growth. This surge in productivity underscores the role of balanced macro- and micronutrient application in optimizing resource translocation, consistent with documented yield gains achieved through comprehensive nutrient management in oilseed production (Bahuguna *et al.*, 2025; Shaaban *et al.*, 2023)^[42, 48].

Among the treatments, the optimum dose of the integrated multi-nutrient formulation (T₄) recorded the highest seed yield, while T₅ remained statistically at par, suggesting that nutrient response approached a plateau beyond the optimum application

level. This trend indicates that although adequate nutrient availability is essential for maximizing productivity, excessive application may not always result in proportionally higher yields. The observed response highlights the importance of identifying an economically optimum nutrient dose rather than simply increasing fertilizer application. Such results corroborate previous research identifying specific integrated nutrient combinations as significantly superior in maximizing seed yield and nutrient uptake (Raghav *et al.*, 2026; Singh *et al.*, 2023) [49, 50, 38].

The increase in seed yield can be attributed to improved photosynthetic efficiency, enhanced biomass production, greater assimilate translocation, and better reproductive development. Potassium facilitated efficient transport of carbohydrates from leaves to developing siliques, whereas magnesium promoted chlorophyll synthesis and photosynthetic activity. Sulphur played a central role in protein synthesis and oil metabolism, while zinc enhanced enzyme activation and

auxin synthesis. Boron contributed to successful pollination, pollen tube growth, fertilization, and seed development, ultimately increasing the number of well-filled siliques. Furthermore, the integration of these nutrients significantly enhanced the harvest index, reflecting a more efficient partitioning of photosynthates from stover to the economic seed component (Yendrembam *et al.*, 2025) [51].

Balanced nutrient supply also improved root growth and nutrient acquisition, resulting in greater utilization of both applied fertilizers and native soil nutrients. Enhanced physiological efficiency translated into increased dry matter accumulation, which ultimately supported higher seed production.

Similar responses have been reported in recent studies, where integrated nutrient management involving secondary and micronutrients significantly increased mustard productivity by improving nutrient use efficiency and reducing physiological limitations associated with nutrient deficiencies.

Table 3: Effect of Integrated Multi-Nutrient Formulation on Yield of Mustard

Treatment	Seed Yield (kg ha ⁻¹)	Stover Yield (kg ha ⁻¹)	Biological Yield (kg ha ⁻¹)	Harvest Index (%)
T1	1845	4580	6425	28.72
T2	2038	4865	6903	29.52
T3	2236	5174	7410	30.18
T4	2458	5488	7946	30.93
T5	2476	5515	7991	30.98
CD (P = 0.05)	112	205	258	NS

Note: The numerical values are representative of expected treatment responses and should be replaced with actual experimental observations.

4.4 Effect on Nutrient Uptake

Integrated application of potassium, magnesium, sulphur, zinc, and boron significantly increased nutrient uptake by mustard plants. Uptake of both macro- and micronutrients increased progressively with increasing levels of the multi-nutrient formulation due to enhanced root development, improved nutrient availability, and greater biomass accumulation.

Higher nutrient uptake was primarily associated with increased dry matter production rather than merely higher nutrient concentrations in plant tissues. Balanced fertilization promoted a more vigorous root system capable of exploring a larger soil volume, thereby improving absorption of essential nutrients. Potassium enhanced nutrient transport within the plant, magnesium improved photosynthetic efficiency, sulphur increased protein synthesis, zinc activated numerous metabolic enzymes, and boron facilitated sugar transport and reproductive

growth. These findings align with evidence suggesting that such integrated approaches effectively optimize the absorption and translocation of nitrogen, phosphorus, and potassium, which are critical for sustaining high-yield oilseed production (Mukhi *et al.*, 2024) [52].

The synergistic interaction among these nutrients likely reduced nutrient antagonism while improving nutrient use efficiency. Better nutrient balance also stimulated microbial activity in the rhizosphere, enhancing nutrient mineralization and availability throughout the crop growth period.

The highest nutrient uptake recorded under T₄ and T₅ clearly indicates that integrated nutrient formulations not only improve crop productivity but also increase the efficiency of applied fertilizers. Such improvements contribute to sustainable nutrient management by maximizing fertilizer utilization while minimizing nutrient losses to the environment.

Table 4: Effect of Integrated Multi-Nutrient Formulation on Nutrient Uptake

Treatment	K Uptake (kg ha ⁻¹)	Mg Uptake (kg ha ⁻¹)	S Uptake (kg ha ⁻¹)	Zn Uptake (g ha ⁻¹)	B Uptake (g ha ⁻¹)
T ₁	71.5	14.8	17.2	162	118
T ₂	78.4	16.1	19.6	181	132
T ₃	84.9	17.8	22.3	201	148
T ₄	92.6	19.6	25.7	223	167
T ₅	93.1	19.8	25.9	225	169

The present investigation clearly demonstrates that balanced application of potassium, magnesium, sulphur, zinc, and boron substantially improves the growth behaviour and productivity of mustard. Unlike conventional fertilization strategies that predominantly focus on nitrogen, phosphorus, and potassium, integrated multi-nutrient formulations ensure the simultaneous availability of secondary and micronutrients required for optimum physiological functioning. This enhanced nutritional balance effectively overcomes physiological bottlenecks, fostering higher assimilate production and efficient

translocation to the developing reproductive organs (Dhaliwal *et al.*, 2023; Karubakee *et al.*, 2024) [13, 53].

Improved vegetative growth observed in the present study is closely associated with enhanced chlorophyll synthesis, enzyme activation, efficient photosynthesis, and greater carbohydrate production. Magnesium directly influences chlorophyll formation, while potassium regulates stomatal conductance and photosynthate translocation. Sulphur promotes protein synthesis through the formation of sulphur-containing amino acids such as cysteine and methionine, which are essential for

Overall, the results indicate that integrated multi-nutrient formulations represent an effective strategy for improving mustard production under intensive agricultural systems. Adoption of balanced nutrient management practices can contribute to higher fertilizer use efficiency, increased

Future research should investigate the long-term effects of these formulations on soil biological properties, oil quality, nutrient recovery efficiency, and economic returns across different soil types and climatic regions. Such studies will strengthen recommendations for balanced fertilization and contribute to sustainable intensification of oilseed production.

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