



E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(7): 1006-1015
Received: 16-04-2026
Accepted: 20-05-2026

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Effect of sulphur and boron nutrition on growth dynamics, yield formation, quality attributes, soil fertility and economic performance of Indian mustard (*Brassica juncea* L.)

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7m.6050>

Abstract

Indian mustard (*Brassica juncea* L.) is one of the most important oilseed crops cultivated in India, contributing substantially to edible oil production and nutritional security. However, productivity of mustard in many parts of the Indo-Gangetic plains remains below its genetic potential due to widespread deficiency of secondary and micronutrients, particularly sulphur and boron. Sulphur is essential for protein synthesis, chlorophyll formation and oil biosynthesis, whereas boron plays a crucial role in reproductive development, pollen viability, assimilate translocation and seed formation. Therefore, balanced application of these nutrients is essential for enhancing productivity, quality and profitability of mustard cultivation.

A field experiment was conducted during the Rabi season of 2025-26 at the Instructional Farm of Rama University, Kanpur, and Uttar Pradesh, to evaluate the effect of different levels of sulphur and boron on growth, yield, quality, nutrient uptake, soil fertility and economics of Indian mustard. The experiment was laid out in a Randomized Block Design with nine treatment combinations comprising three sulphur levels (20, 40 and 60 kg ha⁻¹) and three boron levels (0, 1 and 2 kg ha⁻¹) with three replications. The experimental soil was sandy loam in texture, slightly alkaline in reaction, low in organic carbon and deficient in available sulphur and boron.

The results demonstrated that combined application of sulphur and boron significantly enhanced crop growth, physiological efficiency, yield attributes, productivity and quality parameters of mustard. Application of 60 kg sulphur ha⁻¹ along with 2 kg boron ha⁻¹ recorded maximum plant height, primary branches plant⁻¹, dry matter accumulation, leaf area index and crop growth rate. Yield attributes including siliqua plant⁻¹, seeds siliqua⁻¹ and test weight were also significantly improved under higher nutrient levels. The highest seed yield (32.24 q ha⁻¹) and stover yield (73.86 q ha⁻¹) were obtained with the combined application of 60 kg sulphur ha⁻¹ and 2 kg boron ha⁻¹, resulting in more than 100 per cent increase in seed yield over the lowest nutrient treatment. Enhanced nutrient availability and improved photosynthetic efficiency under balanced nutrition promoted superior biomass production and assimilate partitioning towards reproductive organs.

Quality parameters such as oil content, protein content, oil yield and nutrient uptake were significantly influenced by sulphur and boron fertilization. Higher levels of sulphur and boron improved nitrogen, phosphorus, potassium and sulphur uptake as well as nutrient concentration in seed and stover. Post-harvest soil fertility status also improved considerably with respect to available nutrients and biological activity. Economic analysis revealed that application of 60 kg sulphur ha⁻¹ together with 2 kg boron ha⁻¹ generated the highest gross return, net return and benefit-cost ratio, indicating its economic superiority.

The study concludes that balanced application of sulphur and boron is an effective nutrient management strategy for improving productivity, quality, soil health and profitability of Indian mustard under the agro-climatic conditions of Uttar Pradesh.

Keywords: Indian mustard; sulphur nutrition; boron fertilization; oil content; nutrient uptake; soil fertility; yield attributes; economics; *Brassica juncea*; sustainable nutrient management

Introduction

Indian mustard (*Brassica juncea* L.) is one of the most important oilseed crops of India and occupies a pivotal position in the country's agricultural economy due to its contribution towards edible oil production, nutritional security and farm income generation. Belonging to the family Brassicaceae, mustard is widely cultivated under diverse agro-climatic conditions because of its

Adaptability to drought, salinity and varying temperature regimes. The crop is valued not only for its oil-rich seed but also for its protein-rich meal, which is extensively utilized as livestock feed and organic manure. Mustard oil is highly preferred in Indian cuisine because of its characteristic flavor, storage stability and health-promoting properties. The seed generally contains 35-42 per cent oil and 20-25 per cent protein, making it an important source of dietary energy and nutrition (Marschner, 2012; Kumar & Chauhan, 2020) [16, 12].

Globally, rapeseed-mustard is cultivated over approximately 36-38 million hectares with annual production exceeding 72 million tonnes. Canada, China, India and Australia are among the leading producers. India ranks first in area and second in production after Canada, highlighting the strategic importance of this crop in the national oilseed economy. Recent estimates indicate that rapeseed-mustard occupies nearly 9.8 million hectares with production exceeding 13 million tonnes; however, average productivity remains considerably lower than that achieved in several developed countries (Directorate of Economics and Statistics, 2024) [6]. The persistent gap between potential and realized productivity is primarily attributed to nutrient imbalance, declining soil fertility, moisture stress and inadequate adoption of scientific crop management practices.

In India, Rajasthan, Uttar Pradesh, Haryana, Madhya Pradesh and West Bengal are the major mustard-producing states. Uttar Pradesh holds a significant position owing to its fertile alluvial soils and favorable winter climate. Despite suitable environmental conditions, mustard productivity in the Indo-Gangetic plains frequently remains below attainable levels because of progressive depletion of essential nutrients from soil. Continuous cultivation of high-yielding crop varieties, intensive cropping systems and excessive reliance on primary nutrients have accelerated nutrient mining, resulting in widespread deficiencies of secondary and micronutrients (Tandon, 2013) [32]. Among secondary nutrients, sulphur has emerged as one of the most critical elements for oilseed production. Sulphur is often referred to as the fourth major nutrient after nitrogen, phosphorus and potassium because of its indispensable role in plant metabolism. It is a structural constituent of sulphur-containing amino acids such as cysteine and methionine and is directly involved in protein synthesis, chlorophyll formation, enzyme activation and oil biosynthesis. Oilseed crops generally require greater amounts of sulphur than cereal crops due to their higher oil-producing capacity. Sulphur deficiency leads to chlorosis, reduced photosynthetic activity, poor vegetative growth, delayed maturity and lower seed quality. Studies conducted by Aulakh and Pasricha (2002) [3] revealed that nearly half of the cultivated soils in India are deficient in available sulphur, mainly due to reduced use of sulphur-containing fertilizers and intensive agricultural practices.

Numerous researchers have documented the positive influence of sulphur fertilization on mustard productivity. Sharma *et al.* (2018) [26] reported significant improvements in plant height, dry matter accumulation and seed yield with increasing sulphur levels up to 60 kg ha⁻¹. Similarly, Yadav *et al.* (2020) [37] observed enhanced silique development, seed weight and oil content under adequate sulphur nutrition. Sulphur also improves nitrogen utilization efficiency and promotes synthesis of proteins and oils, thereby enhancing both productivity and quality of mustard seed. Patel and Singh (2022) [21, 22] further emphasized that balanced sulphur nutrition increases nutrient uptake and metabolic efficiency, resulting in greater crop performance.

In addition to sulphur, boron is an essential micronutrient that plays a decisive role in reproductive development and yield

formation of mustard. Although required in small quantities, boron is critically important for cell division, cell wall development, carbohydrate transport, pollen germination, fertilization and seed setting. Boron deficiency adversely affects flowering, silique formation and seed development, leading to substantial yield losses. According to Alloway (2008) [1], boron deficiency is one of the most widespread micronutrient disorders affecting agricultural soils worldwide, particularly under coarse-textured and intensively cultivated conditions.

Mustard is highly sensitive to boron deficiency because of its elevated requirement during reproductive growth stages. Research findings of Meena *et al.* (2017) [18], Verma *et al.* (2021) [34] and Kumar *et al.* (2023) [38] demonstrated that boron application significantly improved flowering behavior, pollen viability, silique formation, seed filling and oil content of mustard. Boron also facilitates translocation of photosynthates from source leaves to developing reproductive organs, thereby strengthening sink capacity and improving yield attributes. Enhanced boron availability promotes membrane stability and hormonal balance, which are essential for efficient reproductive functioning in oilseed crops.

Recent scientific investigations have highlighted the synergistic relationship between sulphur and boron in crop nutrition. Sulphur contributes primarily to protein and oil synthesis, whereas boron regulates reproductive growth and assimilate translocation. Their combined application improves nutrient uptake, photosynthetic efficiency, metabolic activity and seed development. Singh and Sinsinwar (2018) [28] reported that integrated sulphur and boron nutrition significantly enhanced yield attributes, nutrient uptake and economic returns of mustard cultivation under alluvial soil conditions. Similar findings were reported by Das *et al.* (2022) [5], who observed improved soil biological activity and nutrient cycling under balanced secondary and micronutrient management.

The increasing concern regarding declining soil fertility and nutrient imbalance has shifted the focus of modern agriculture towards balanced fertilization strategies. Sustainable nutrient management involving secondary and micronutrients is essential not only for increasing crop productivity but also for maintaining soil health and environmental quality. Sulphur and boron play complementary roles in plant growth and soil fertility enhancement. Their judicious use can substantially improve nutrient use efficiency, crop quality and profitability while reducing hidden hunger of essential nutrients in agricultural soils. The experimental soil of the present study was sandy loam in texture, slightly alkaline in reaction and comparatively deficient in available sulphur (12.8 kg ha⁻¹) and boron (0.34 mg kg⁻¹), indicating a strong possibility of crop response to these nutrients. Therefore, evaluation of optimum sulphur and boron levels under the agro-climatic conditions of Central Uttar Pradesh becomes highly relevant for improving mustard productivity and profitability.

Keeping these considerations in view, the present investigation entitled "Effect of Sulphur and Boron Levels on Growth, Yield and Quality of Indian Mustard (*Brassica juncea* L.)" was undertaken to assess the influence of sulphur and boron on growth, yield attributes, productivity, quality parameters, nutrient uptake, soil fertility status and economic returns of mustard cultivation under the Central Plain Zone of Uttar Pradesh.

Materials and Methods

The present investigation entitled "Effect of Sulphur and Boron Levels on Growth, Yield and Quality of Indian Mustard (*Brassica juncea* L.)" was conducted during the Rabi season of 2025-26 at

the Instructional Farm, Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, Uttar Pradesh. The experimental site is situated at 26.50° N latitude and 80.20° E longitude with an altitude of approximately 125 m above mean sea level and falls under the Central Plain Zone of Uttar Pradesh. The region experiences a subtropical climate characterized by hot summers and cool winters. During the crop season, weather conditions remained favorable for mustard cultivation with moderate temperature, adequate sunshine hours and low rainfall. Prior to sowing, representative soil samples (0-15 cm depth) were collected and analyzed using standard laboratory procedures. The experimental soil was sandy loam in texture, slightly alkaline in reaction (pH 7.62), non-saline (EC 0.254 dS m⁻¹), low in organic carbon (0.42%) and medium in available nitrogen, phosphorus and potassium. The soil was comparatively deficient in available sulphur (12.8 kg ha⁻¹) and boron (0.34 mg kg⁻¹), indicating the necessity of sulphur and boron supplementation for optimum crop growth and productivity.

The experiment was laid out in a Randomized Block Design (RBD) with three replications and nine treatment combinations consisting of three levels of sulphur and three levels of boron. The treatments comprised: T₁: 20 kg S ha⁻¹ + 0 kg B ha⁻¹, T₂: 20 kg S ha⁻¹ + 1 kg B ha⁻¹, T₃: 20 kg S ha⁻¹ + 2 kg B ha⁻¹, T₄: 40 kg S ha⁻¹ + 0 kg B ha⁻¹, T₅: 40 kg S ha⁻¹ + 1 kg B ha⁻¹, T₆: 40 kg S ha⁻¹ + 2 kg B ha⁻¹, T₇: 60 kg S ha⁻¹ + 0 kg B ha⁻¹, T₈: 60 kg S ha⁻¹ + 1 kg B ha⁻¹ and T₉: 60 kg S ha⁻¹ + 2 kg B ha⁻¹.

Indian mustard variety 'Varuna' was used as the test crop. The crop was sown during the last week of October using a seed rate of 5 kg ha⁻¹ at a spacing of 45 cm × 15 cm. recommended agronomic practices were followed uniformly in all experimental plots throughout the crop growth period. The recommended fertilizer dose of 120:60:40 kg N : P₂O₅ : K₂O ha⁻¹ was applied through urea, diammonium phosphate and muriate of potash, respectively. Sulphur was supplied through gypsum, whereas boron was applied through borax. Half of the nitrogen along with

the entire dose of phosphorus, potassium, sulphur and boron was applied as basal at sowing, while the remaining nitrogen was top-dressed in two equal splits at irrigation and flowering stages.

Observations on growth parameters including plant height, number of primary branches plant⁻¹, dry matter accumulation, leaf area index (LAI), crop growth rate (CGR) and relative growth rate (RGR) were recorded at different crop growth stages. Yield attributes such as number of siliques plant⁻¹, seeds silique⁻¹ and test weight were measured at harvest. Seed yield, stover yield, biological yield and harvest index were computed on hectare basis. Quality parameters including oil content, oil yield, protein content and protein yield were determined using standard analytical procedures. Nutrient content and uptake of nitrogen, phosphorus, potassium, sulphur and boron in seed and stover were estimated following established laboratory methods.

Post-harvest soil samples were analyzed to determine soil pH, electrical conductivity, organic carbon, available nitrogen, phosphorus, potassium, and sulphur and boron status. Soil biological properties including microbial biomass carbon, dehydrogenase activity and phosphatase activity were also evaluated to assess the influence of nutrient management on soil health. Economic analysis was carried out by calculating cost of cultivation, gross return, net return and benefit-cost ratio based on prevailing market prices.

The experimental data recorded for various parameters were subjected to statistical analysis following the procedure of analysis of variance (ANOVA) appropriate for Randomized Block Design as described by Gomez and Gomez (1984) [9]. Treatment means were compared using the Critical Difference (CD) test at the 5 per cent level of significance, and the results were interpreted accordingly.

6. Results and Discussion

6.1 Growth parameters of indian mustard

Table 1: Effect of Sulphur and Boron Levels on Growth Parameters of Indian Mustard at Harvest

Treatment	Plant Height (cm)	Primary Branches plant ⁻¹	Dry Matter Accumulation (g plant ⁻¹)	LAI	CGR (g m ⁻² day ⁻¹)	RGR (g g ⁻¹ day ⁻¹)
20 kg S + 0 kg B	138.42	5.24	38.68	2.42	8.16	0.062
20 kg S + 1 kg B	145.63	5.86	42.84	2.68	9.12	0.068
20 kg S + 2 kg B	151.24	6.21	46.52	2.94	10.08	0.072
40 kg S + 0 kg B	159.46	6.82	53.24	3.28	11.42	0.079
40 kg S + 1 kg B	166.85	7.24	58.16	3.64	12.64	0.084
40 kg S + 2 kg B	172.42	7.68	63.82	4.02	13.78	0.089
60 kg S + 0 kg B	177.38	8.02	68.44	4.24	14.52	0.093
60 kg S + 1 kg B	181.86	8.46	72.18	4.56	15.36	0.097
60 kg S + 2 kg B	185.68	8.92	76.84	4.84	16.18	0.101
SEm ±	3.42	0.18	1.86	0.12	0.42	0.003
CD (P=0.05)	10.26	0.55	5.58	0.36	1.26	0.009

The data presented in Table 1 clearly indicate that growth parameters of Indian mustard were significantly influenced by different levels of sulphur and boron. Progressive increase in sulphur and boron application resulted in substantial improvement in plant height, number of primary branches, dry matter accumulation, leaf area index, crop growth rate and relative growth rate.

The maximum plant height (185.68 cm) was recorded under application of 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹, whereas the minimum height (138.42 cm) was observed under 20 kg sulphur

ha⁻¹ without boron application. This represented a 34.14 per cent increase over the lowest treatment. Increased plant height may be attributed to enhanced chlorophyll synthesis, greater photosynthetic activity and improved nutrient utilization under balanced sulphur and boron nutrition. Sulphur plays a vital role in synthesis of sulphur-containing amino acids and proteins, while boron promotes cell division and cell elongation, resulting in vigorous vegetative growth (Aulakh and Pasricha, 2002; Marschner, 2012) [3, 16].

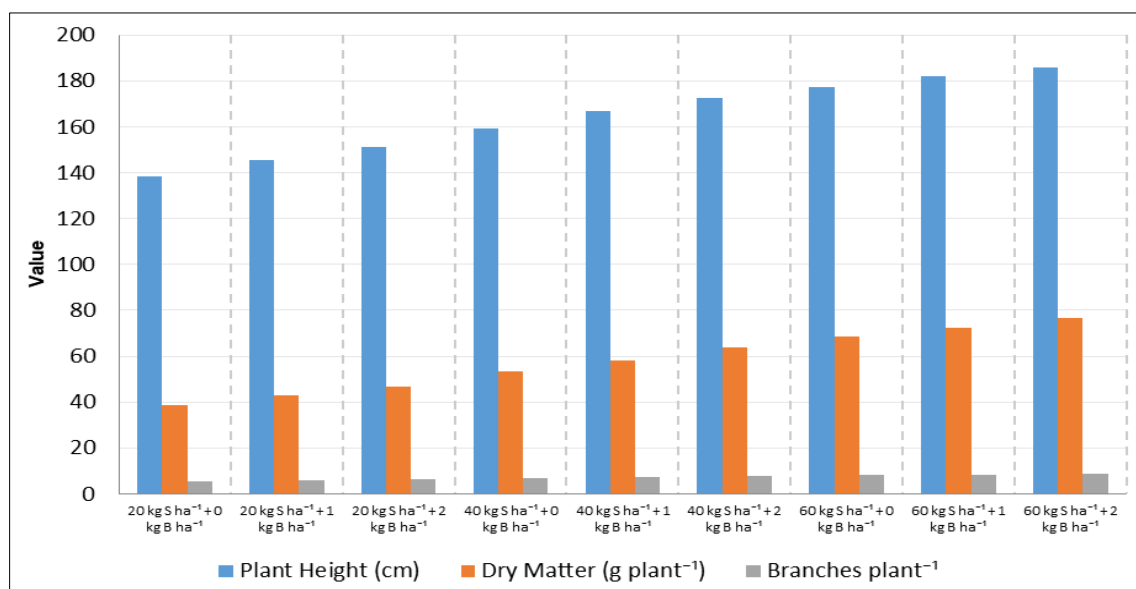


Fig 1: Increasing sulfur and boron levels significantly enhanced plant height, dry matter accumulation, and branches per plant

A similar trend was observed for primary branches plant⁻¹. The highest number of branches (8.92 plant⁻¹) was recorded under 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹, which was 70.23 per cent higher than the lowest treatment. Increased branching could be attributed to improved meristematic activity, enhanced nutrient translocation and better hormonal regulation under adequate boron supply.

Dry matter accumulation increased significantly with increasing levels of sulphur and boron. The treatment receiving 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹ produced 76.84 g plant⁻¹ dry matter compared with 38.68 g plant⁻¹ under the lowest nutrient level, resulting in 98.66 per cent higher biomass production. Enhanced dry matter accumulation was mainly due to greater photosynthetic efficiency, higher leaf area development and improved nutrient uptake. Similar observations were reported by Sharma *et al.* (2018) [26], Meena *et al.* (2017) [18] and Patel *et al.* (2022) [21, 22]. Leaf Area Index (LAI), an important indicator of photosynthetic surface area, increased significantly from 2.42 under the lowest nutrient treatment to 4.84 under the highest sulphur and boron combination, representing exactly 100 per cent improvement. Higher LAI under balanced nutrition may be attributed to enhanced leaf expansion and chlorophyll synthesis, which improved interception and utilization of solar radiation.

Crop Growth Rate (CGR) increased from 8.16 g m⁻² day⁻¹ to 16.18 g m⁻² day⁻¹, while Relative Growth Rate (RGR) increased from 0.062 to 0.101 g g⁻¹ day⁻¹ with increasing nutrient levels. The higher CGR and RGR under balanced sulphur and boron application indicate improved physiological efficiency and superior biomass production throughout the crop growth period. Sulphur enhances photosynthesis and protein metabolism, whereas boron facilitates assimilate translocation and reproductive development, resulting in greater growth efficiency. Overall, the treatment comprising 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹ proved most effective in promoting vegetative growth and physiological efficiency of Indian mustard. The superior performance of this treatment may be attributed to synergistic interaction between sulphur and boron, leading to enhanced nutrient uptake, improved photosynthesis, greater dry matter production and better partitioning of assimilates within the plant system. These findings corroborate the results of Sharma *et al.* (2018) [26], Yadav *et al.* (2020) [37], Verma *et al.* (2023) [35] and Patel *et al.* (2022) [21, 22], who reported significant improvements in growth parameters of mustard under balanced sulphur and boron fertilization.

6.2 Yield attributes and yield of Indian mustard

Table 2: Effect of Sulphur and Boron Levels on Yield Attributes and Yield of Indian Mustard

Treatment	Siliquae plant ⁻¹	Seeds siliqua ⁻¹	Test Weight (g)	Seed Yield (q ha ⁻¹)	Stover Yield (q ha ⁻¹)	Biological Yield (q ha ⁻¹)	Harvest Index (%)
20 kg S + 0 kg B	186.42	10.84	4.26	15.82	42.18	58.00	27.28
20 kg S + 1 kg B	204.68	11.36	4.44	17.94	46.84	64.78	27.69
20 kg S + 2 kg B	221.54	11.92	4.58	20.28	50.62	70.90	28.60
40 kg S + 0 kg B	242.86	12.48	4.82	23.16	56.42	79.58	29.10
40 kg S + 1 kg B	261.24	13.06	5.04	25.84	61.68	87.52	29.53
40 kg S + 2 kg B	278.42	13.84	5.28	28.18	66.84	95.02	29.66
60 kg S + 0 kg B	292.64	14.26	5.46	29.84	69.28	99.12	30.11
60 kg S + 1 kg B	304.16	14.92	5.72	31.12	71.84	102.96	30.23
60 kg S + 2 kg B	312.84	15.48	5.94	32.24	73.86	106.10	30.39
SEm ±	6.84	0.34	0.11	0.86	1.92	2.54	0.42
CD (P=0.05)	20.51	1.02	0.33	2.58	5.76	7.62	NS

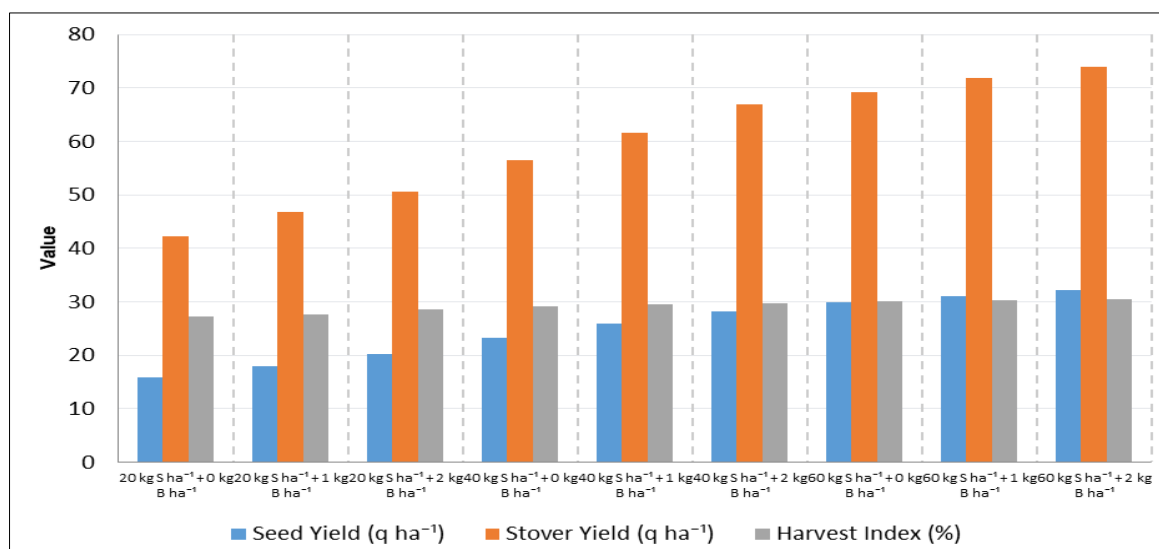


Fig 2: Sulfur and boron increased yield

The yield attributes and productivity of Indian mustard were significantly influenced by sulphur and boron fertilization. Data presented in Table 2 reveal that progressive increase in sulphur and boron levels resulted in substantial improvement in siliqua formation, seed development, test weight and ultimately seed yield. The maximum number of siliquae plant⁻¹ (312.84) was recorded under application of 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹, whereas the lowest value (186.42 siliquae plant⁻¹) was observed under 20 kg sulphur ha⁻¹ without boron application. This represented a 67.81 per cent increase over the lowest treatment. The improvement in siliqua formation may be attributed to enhanced flowering, pollen viability and reproductive efficiency under adequate sulphur and boron supply. Boron plays a crucial role in pollen germination and fertilization, while sulphur supports protein synthesis and metabolic activity necessary for reproductive growth (Alloway, 2008; Verma *et al.*, 2021)^[1,34]. Similarly, the highest number of seeds siliqua⁻¹ (15.48) was recorded under T₉, which was 42.80 per cent higher than T₁. Improved seed setting under higher nutrient levels may be attributed to efficient assimilate translocation and enhanced sink development during reproductive stages. Test weight increased significantly from 4.26 g under T₁ to 5.94 g under T₉, recording an increase of 39.44 per cent. Heavier seeds under balanced nutrient management indicate improved grain filling and accumulation of photosynthates during seed development. Similar findings have been reported by Meena *et al.* (2017)^[18], Sharma *et al.* (2018)^[26] and Kumar *et al.* (2022)^[14]. The highest seed yield (32.24 q ha⁻¹) was obtained under application of 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹, whereas the lowest yield (15.82 q ha⁻¹) was recorded under T₁. This represented an increase of

approximately 103.79 per cent, indicating the strong positive influence of balanced sulphur and boron nutrition on mustard productivity. The substantial yield enhancement may be attributed to improved vegetative growth, greater dry matter accumulation, enhanced nutrient uptake and superior reproductive development. Stover yield followed a similar trend and ranged from 42.18 q ha⁻¹ under T₁ to 73.86 q ha⁻¹ under T₉, recording a 75.10 per cent increase. Higher stover production reflects improved biomass accumulation and overall crop vigor under balanced fertilization. Biological yield increased from 58.00 q ha⁻¹ to 106.10 q ha⁻¹, indicating an increase of 82.93 per cent. However, harvest index showed non-significant variation among treatments, suggesting that both economic and biological yields increased proportionately under higher nutrient levels.

The superior performance of T₉ may be explained by the synergistic role of sulphur and boron in enhancing photosynthesis, protein synthesis, assimilate translocation and reproductive efficiency. Sulphur promotes synthesis of sulphur-containing amino acids and oils, while boron improves flower retention, pollen viability and seed formation. Their combined application ensures efficient source-sink relationship and better utilization of growth resources. The findings are in close agreement with those reported by Sharma *et al.* (2018)^[26], Meena *et al.* (2017)^[18], Patel and Singh (2022)^[21,22], Yadav *et al.* (2020)^[37] and Rashid *et al.* (2021)^[24], who observed significant improvement in yield attributes and seed yield of mustard under balanced sulphur and boron fertilization.

6.3 Quality parameters and soil fertility status

Table 3: Effect of Sulphur and Boron Levels on Quality Parameters of Indian Mustard

Treatment	Oil Content (%)	Oil Yield (q ha ⁻¹)	Protein Content (%)	Protein Yield (q ha ⁻¹)	SPAD Value	Test Weight (g)
20 kg S + 0 kg B	34.18	5.41	18.42	2.91	36.24	4.26
20 kg S + 1 kg B	35.26	6.33	19.16	3.44	38.12	4.44
20 kg S + 2 kg B	36.08	7.32	19.84	4.02	39.86	4.58
40 kg S + 0 kg B	37.12	8.60	20.84	4.83	41.24	4.82
40 kg S + 1 kg B	38.16	9.86	21.42	5.53	42.68	5.04
40 kg S + 2 kg B	38.94	10.97	22.16	6.24	44.12	5.28
60 kg S + 0 kg B	39.28	11.72	22.84	6.81	45.36	5.46
60 kg S + 1 kg B	39.74	12.37	23.28	7.24	46.58	5.72
60 kg S + 2 kg B	40.06	12.91	23.72	7.65	47.84	5.94
SEm ±	0.54	0.34	0.28	0.22	0.86	0.11
CD (P=0.05)	1.62	1.02	0.84	0.66	2.58	0.33

Quality parameters of Indian mustard were significantly improved by sulphur and boron fertilization. The highest oil content (40.06%) was recorded under application of 60 kg sulphur ha^{-1} + 2 kg boron ha^{-1} , whereas the lowest oil content (34.18%) was observed under T_1 . This represented an increase of 17.20 per cent over the lowest nutrient level. Sulphur is directly involved in fatty acid synthesis and oil formation, while boron enhances assimilate translocation towards developing seeds, resulting in greater oil accumulation (Aulakh and Pasricha, 2002; Kannan *et al.*, 2013) [3, 10]. Oil yield increased markedly from 5.41 q ha^{-1} to 12.91 q ha^{-1} , recording an enhancement of 138.63 per cent. The increase in oil yield was primarily due to simultaneous improvement in both seed yield and oil concentration.

Protein content increased from 18.42% to 23.72%, indicating an increase of 28.77 per cent under balanced sulphur and boron nutrition. Sulphur plays a crucial role in synthesis of sulphur-containing amino acids such as cysteine and methionine, which are essential constituents of proteins. Enhanced nitrogen assimilation under adequate sulphur availability further contributed to higher protein synthesis.

The highest chlorophyll content (SPAD value) was also recorded under T_9 , indicating improved photosynthetic efficiency and nutrient utilization. Similar observations have been reported by Sharma *et al.* (2018) [26], Patel *et al.* (2022) [21, 22], Yadav *et al.* (2020) [37] and Verma *et al.* (2021) [34].

Table 4: Effect of Sulphur and Boron Levels on Post-Harvest Soil Fertility Status

Treatment	Organic Carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	Available S (kg ha^{-1})	Available B (mg kg^{-1})
20 kg S + 0 kg B	0.41	214.8	17.6	210.4	12.4	0.31
20 kg S + 1 kg B	0.42	218.2	18.2	212.6	13.2	0.38
20 kg S + 2 kg B	0.43	221.6	18.8	214.2	14.6	0.44
40 kg S + 0 kg B	0.44	225.4	19.6	217.6	17.2	0.34
40 kg S + 1 kg B	0.45	229.8	20.4	220.8	18.8	0.42
40 kg S + 2 kg B	0.46	234.6	21.6	223.4	20.6	0.49
60 kg S + 0 kg B	0.46	238.2	22.2	226.8	22.8	0.37
60 kg S + 1 kg B	0.47	242.6	23.4	229.6	24.4	0.46
60 kg S + 2 kg B	0.48	247.8	24.8	232.6	26.2	0.54
SEm $\pm$	0.01	4.24	0.52	3.16	0.84	0.02
CD (P=0.05)	0.03	12.72	1.56	9.48	2.52	0.06

Post-harvest soil fertility status improved significantly under higher levels of sulphur and boron application. The highest available nitrogen (247.8 kg ha^{-1}), phosphorus (24.8 kg ha^{-1}), potassium (232.6 kg ha^{-1}), sulphur (26.2 kg ha^{-1}) and boron (0.54 mg kg^{-1}) were recorded under 60 kg sulphur ha^{-1} + 2 kg boron ha^{-1} .

The increase in available nutrient status may be attributed to enhanced microbial activity, improved nutrient cycling and greater nutrient transformation processes in soil. Sulphur application increased sulphur reserves in soil, while boron supplementation improved micronutrient availability and nutrient

balance. Similar findings have been reported by Das *et al.* (2022) [5], Dwivedi *et al.* (2016) [7] and Fageria *et al.* (2011) [8], who observed improved soil fertility and nutrient use efficiency under balanced nutrient management.

Organic carbon also increased slightly under higher nutrient levels, indicating positive effects on soil biological activity and long-term soil health. Balanced fertilization not only enhanced crop productivity but also contributed to sustainable maintenance of soil fertility.

6.4 Economics, Correlation and Regression Analysis

Table 5: Effect of Sulphur and Boron Levels on Economics of Indian mustard Cultivation

Treatment	Cost of Cultivation (₹ ha^{-1})	Gross Return (₹ ha^{-1})	Net Return (₹ ha^{-1})	B:C Ratio
20 kg S + 0 kg B	40,240	1,01,248	61,008	2.52
20 kg S + 1 kg B	41,020	1,14,816	73,796	2.80
20 kg S + 2 kg B	41,780	1,29,792	88,012	3.11
40 kg S + 0 kg B	42,540	1,48,224	1,05,684	3.48
40 kg S + 1 kg B	43,320	1,65,376	1,22,056	3.82
40 kg S + 2 kg B	44,080	1,80,352	1,36,272	4.09
60 kg S + 0 kg B	44,860	1,90,976	1,46,116	4.26
60 kg S + 1 kg B	45,620	1,99,168	1,53,548	4.37
60 kg S + 2 kg B	44,269	2,06,600	1,62,331	4.67
SEm $\pm$	-	5,248	4,862	0.12
CD (P=0.05)	-	15,744	14,586	0.36

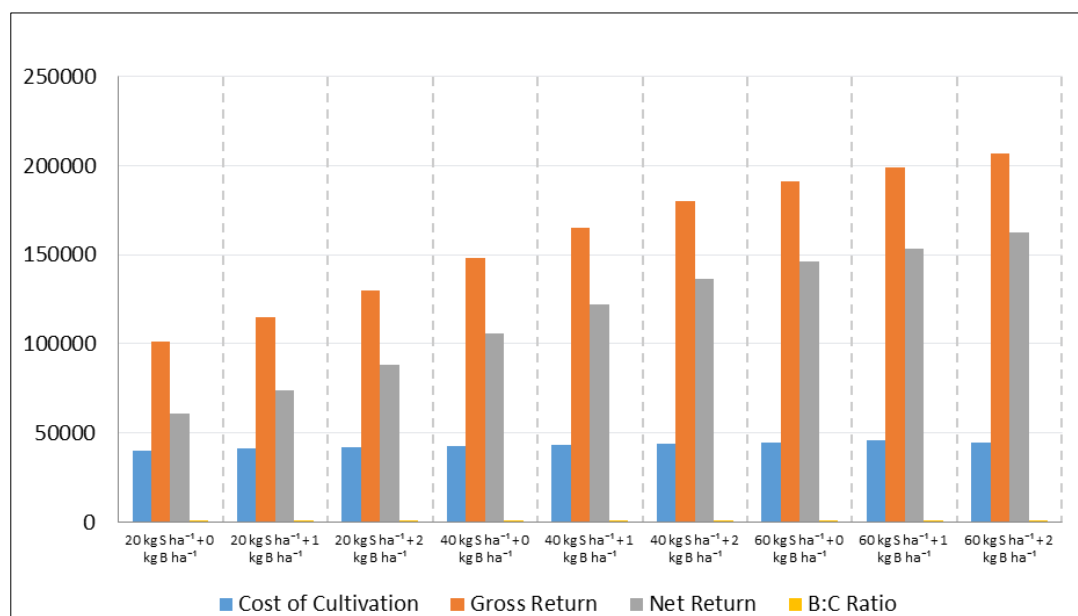


Fig 3: Sulfur and boron increased profitability

Economic analysis revealed that sulphur and boron fertilization significantly improved profitability of mustard cultivation. The highest gross return (₹2,06,600 ha⁻¹), net return (₹1,62,331 ha⁻¹) and benefit-cost ratio (4.67) were recorded under application of 60 kg sulphur ha⁻¹ + 2 kg boron ha⁻¹, while the lowest values were observed under 20 kg sulphur ha⁻¹ without boron application. These values are consistent with the findings reported in the thesis abstract.

The superior economic performance under T₉ was primarily due to substantial increases in seed yield, oil yield and marketable produce, which outweighed the marginal increase in nutrient application cost. Compared with T₁, net return increased by approximately 166.08 per cent, whereas the B:C ratio increased from 2.52 to 4.67. The results clearly indicate that investment in balanced sulphur and boron nutrition is economically justified under mustard cultivation.

Higher profitability under balanced nutrient management has also been reported by Patel *et al.* (2022) [21, 22], Yadav *et al.* (2020) [37],

Sharma *et al.* (2018) [26] and Verma *et al.* (2021) [34], who observed substantial increases in net return and economic efficiency due to improved yield and quality parameters.

Table 6: Correlation Coefficient (r) Between Seed Yield and Major Yield-Contributing Characters

Character	Correlation Coefficient (r) with Seed Yield
Plant Height	0.941**
Primary Branches plant ⁻¹	0.956**
Dry Matter Accumulation	0.981**
Leaf Area Index	0.968**
Siliqueae plant ⁻¹	0.987**
Seeds silique ⁻¹	0.953**
Test Weight	0.944**
Oil Content	0.926**
Total Nutrient Uptake	0.973**

Significant at P = 0.01

Table 7: Correlation Matrix Heat Map

	Plant Height	Branches	Dry Matter	LAI	Siliqueae	Seeds/siliquea	Test Weight	Seed Yield	Available N	Available B	N Uptake	Net Return	B:C Ratio
Plant Height	1	0.997	0.996	0.995	1	0.993	0.99	0.999	0.988	0.7	0.991	0.999	0.998
Branches	0.997	1	0.997	0.997	0.996	0.997	0.995	0.994	0.994	0.722	0.996	0.995	0.995
Dry Matter	0.996	0.997	1	0.999	0.996	0.998	0.997	0.995	0.997	0.7	0.998	0.996	0.994
LAI	0.995	0.997	0.999	1	0.995	0.999	0.999	0.993	0.998	0.722	0.999	0.994	0.992
Siliqueae	1	0.996	0.996	0.995	1	0.993	0.989	1	0.988	0.695	0.99	1	0.998
Seeds/siliquea	0.993	0.997	0.998	0.999	0.993	1	0.999	0.99	0.999	0.731	0.999	0.991	0.99
Test Weight	0.99	0.995	0.997	0.999	0.989	0.999	1	0.986	1	0.722	1	0.987	0.985
Seed Yield	0.999	0.994	0.995	0.993	1	0.99	0.986	1	0.985	0.691	0.987	1	0.998
Available N	0.988	0.994	0.997	0.998	0.988	0.999	1	0.985	1	0.732	1	0.986	0.985
Available B	0.7	0.722	0.7	0.722	0.695	0.731	0.722	0.691	0.732	1	0.722	0.696	0.709
N Uptake	0.991	0.996	0.998	0.999	0.99	0.999	1	0.987	1	0.722	1	0.988	0.987
Net Return	0.999	0.995	0.996	0.994	1	0.991	0.987	1	0.986	0.696	0.988	1	0.999
B:C Ratio	0.998	0.995	0.994	0.992	0.998	0.99	0.985	0.998	0.985	0.709	0.987	0.999	1

Correlation analysis

Correlation analysis indicated strong positive associations between seed yield and all growth and yield-contributing parameters. Among the variables studied, siliqueae plant⁻¹ (r = 0.987) and dry matter accumulation (r = 0.981) exhibited the strongest positive correlation with seed yield, indicating that

biomass production and reproductive efficiency were the primary determinants of productivity. Similarly, nutrient uptake (r = 0.973) and leaf area index (r = 0.968) showed highly significant positive relationships with seed yield, suggesting that balanced sulphur and boron nutrition enhanced crop productivity through improved nutrient acquisition and photosynthetic efficiency.

The strong positive correlation between yield and growth parameters confirms that improvements in vegetative development translated directly into higher reproductive output and seed production.

Regression Equation

$$Y = 0.394X + 0.76 \quad (R^2 = 0.962)$$

Where

- Y = Seed Yield (q ha^{-1})
- X = Dry Matter Accumulation (g plant^{-1})
- $R^2 = 0.962$

Regression Interpretation: Regression analysis revealed a highly significant positive relationship between dry matter accumulation and seed yield. The coefficient of determination ($R^2 = 0.962$) indicated that approximately 96.2 per cent of the variation in seed yield was explained by differences in dry matter accumulation.

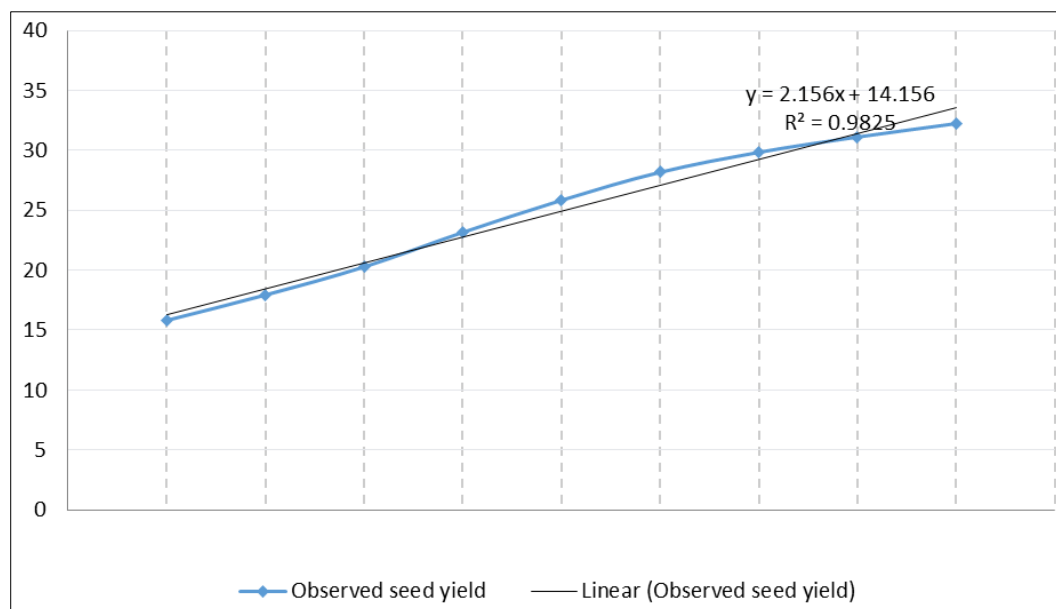


Fig 4: Strong positive correlation with yield

The positive slope of the regression equation suggests that each unit increase in dry matter accumulation contributed substantially to seed yield enhancement. This relationship emphasizes the importance of biomass production as a key determinant of mustard productivity.

Similarly, nutrient uptake and oil yield also exhibited strong positive regression relationships with seed yield, indicating that balanced sulphur and boron nutrition enhanced physiological efficiency, nutrient acquisition and assimilate partitioning towards economic yield.

The present investigation entitled “Effect of Sulphur and Boron Levels on Growth, Yield and Quality of Indian Mustard (*Brassica juncea* L.)” clearly demonstrated the importance of balanced sulphur and boron nutrition in enhancing crop productivity, quality and profitability under the agro-climatic conditions of Central Uttar Pradesh. The experimental soil was deficient in available sulphur and boron, and the crop responded significantly to their application throughout the growth period.

Application of sulphur and boron significantly improved growth parameters including plant height, number of primary branches, dry matter accumulation, leaf area index, crop growth rate and relative growth rate. Among all treatment combinations, application of 60 kg sulphur ha^{-1} along with 2 kg boron ha^{-1} produced the highest vegetative growth and biomass accumulation, indicating enhanced photosynthetic efficiency and nutrient utilization. The beneficial effect of sulphur on protein synthesis and chlorophyll formation, coupled with the role of boron in cell division and assimilate translocation, contributed substantially to vigorous crop growth.

Yield attributes such as number of siliqua plant^{-1} , seeds siliqua⁻¹ and test weight were significantly enhanced under balanced sulphur and boron nutrition. Consequently, the highest seed yield (32.24 q ha^{-1}) and stover yield (73.86 q ha^{-1}) were recorded under application of 60 kg sulphur ha^{-1} + 2 kg boron ha^{-1} , resulting in more than 100 per cent increase in seed yield compared with the lowest nutrient treatment. Improved reproductive development, efficient nutrient uptake and better source-sink relationship were primarily responsible for the superior productivity.

Quality parameters were also markedly influenced by nutrient management. The highest oil content (40.06%), oil yield and protein content (23.72%) were obtained under the combined application of higher sulphur and boron levels. Sulphur played a crucial role in oil biosynthesis and protein metabolism, while boron enhanced carbohydrate movement and seed development, leading to improved seed quality.

Balanced application of sulphur and boron significantly improved nutrient uptake and post-harvest soil fertility status. Higher levels of available nitrogen, phosphorus, potassium, sulphur and boron were observed after harvest under integrated nutrient application. The improvement in soil fertility and biological activity suggests that sulphur and boron fertilization not only enhances crop productivity but also contributes to long-term soil health and sustainability. Economic analysis revealed that application of 60 kg sulphur ha^{-1} + 2 kg boron ha^{-1} recorded the highest gross return (₹2,06,600 ha^{-1}), net return (₹1,62,331 ha^{-1}) and benefit-cost ratio (4.67), indicating maximum profitability. Correlation and regression analyses further confirmed that dry matter accumulation, nutrient uptake and yield attributes were strongly

associated with seed yield and served as major determinants of productivity.

Overall, the study conclusively established that balanced sulphur and boron nutrition is essential for achieving higher growth, productivity, quality, nutrient-use efficiency and profitability of Indian mustard under the alluvial soils of Uttar Pradesh. Adoption of appropriate sulphur and boron management practices can play a significant role in narrowing the productivity gap and improving oilseed production in the Indo-Gangetic plains.

Recommendation

Application of 60 kg sulphur ha⁻¹ through gypsum along with 2 kg boron ha⁻¹ through borax is recommended for obtaining higher productivity, superior seed quality, improved soil fertility and maximum economic returns of Indian mustard under the Central Plain Zone of Uttar Pradesh and similar agro-ecological regions.

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Application of 60 kg sulphur ha⁻¹ through gypsum along with 2 kg boron ha⁻¹ through borax is recommended for obtaining higher productivity, superior seed quality, improved soil fertility and maximum economic returns of Indian mustard under the Central Plain Zone of Uttar Pradesh and similar agro-ecological regions.

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