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Response of Indian Mustard (*Brassica juncea* L.) to varying levels of nitrogen and sulphur under Southeastern Rajasthan conditions

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Abstract
A field experiment was conducted during the Rabi season of 2025–26 at the Agriculture Research Farm, CPU, Kota (Rajasthan) to evaluate the effect of nitrogen and sulphur fertilization on the growth, yield, and quality of Indian mustard (*Brassica juncea* L.). The experiment comprised sixteen treatment combinations of four nitrogen levels (0, 40, 80, and 120 kg ha^{-1}) and four sulphur levels (0, 15, 30, and 45 kg ha^{-1}) laid out in a Factorial Randomized Block Design with three replications. The results revealed that growth parameters such as plant height, number of branches, dry matter accumulation, and leaf area index significantly increased with increasing levels of nitrogen and sulphur. The highest seed yield (1920 kg ha^{-1}) was recorded with 120 kg N ha^{-1}, which was statistically at par with 80 kg N ha^{-1}. Similarly, 45 kg S ha^{-1} produced the maximum seed yield (1890 kg ha^{-1}), remaining at par with 30 kg S ha^{-1}. Straw and biological yields followed a similar trend. The improvement in yield attributes was attributed to enhanced nutrient uptake, better photosynthetic efficiency, and improved assimilate partitioning. Although the highest doses recorded maximum values, the combination of 80 kg N ha^{-1} and 30 kg S ha^{-1} proved to be optimal and economically efficient, as it produced comparable results with lower input use. Therefore, balanced fertilization with nitrogen and sulphur is essential for achieving sustainable productivity and improved quality of Indian mustard in the southeastern Rajasthan region.

Keywords: Indian mustard, nitrogen, sulphur, seed yield, nutrient management

1. Introduction
Indian mustard (*Brassica juncea* L.) is the second most important oilseed crop of India after groundnut and plays a crucial role in bridging the edible oil deficit of the country. It contributes nearly 25-30% to India's total oilseed production [1]. Mustard is primarily cultivated in Rajasthan, Haryana, Madhya Pradesh, and Uttar Pradesh, occupying about 6.5 million hectares with an annual production of nearly 12 million tonnes and an average productivity of 1.8 t ha^{-1} [2]. Rajasthan alone accounts for more than 45% of the total area and production, and within the state, Kota, Bundi, Baran, and Jhalawar districts serve as one of the key mustard belts due to its cool and dry winter climate, alluvial soils, and well-developed irrigation systems.

Despite its agronomic and economic importance, mustard yields in the region remain sub-optimal. One of the primary constraints is nutrient imbalance, particularly the deficiencies of nitrogen (N) and sulphur (S)- two essential macronutrients that profoundly affect growth, yield, and oil quality. Light-textured and coarse-grained soils of southeastern Rajasthan are often low in available nitrogen and sulphur due to continuous cropping and inadequate fertilization [3]. Proper nutrient management, therefore, becomes vital for maximizing resource efficiency and sustaining soil health.

Nitrogen is a key constituent of amino acids, proteins, nucleic acids, and chlorophyll molecules. It is directly associated with vegetative growth, photosynthetic efficiency, and reproductive development in mustard [4]. Adequate nitrogen application enhances leaf area, dry matter accumulation, branching, siliqua formation, and ultimately seed yield [5]. However, excessive nitrogen without a balanced supply of sulphur may lead to luxuriant vegetative growth at the cost of reproductive efficiency and seed filling, thereby lowering oil content [6].

Sulphur is equally critical as it is an integral component of the amino acids cysteine and methionine, co-enzymes, and vitamins such as thiamine and biotin. Sulphur deficiency in mustard leads to chlorosis, stunted growth, reduced seed set, and poor oil synthesis [7]. Studies have shown that sulphur enhances both the quantity (seed yield) and quality (oil content, protein concentration) of mustard. It plays a pivotal role in glucosinolate metabolism and enzyme activation, improving crop resilience against biotic stresses [8].

The synergistic interaction between nitrogen and sulphur is well-recognized. Nitrogen promotes amino acid synthesis, while sulphur ensures proper incorporation of these amino acids into functional proteins. The availability of one nutrient influences the utilization efficiency of the other [9]. Deficiency of sulphur restricts nitrogen assimilation by limiting nitrate reductase activity, whereas adequate sulphur supply increases nitrogen use efficiency and reduces nitrate accumulation [10]. Hence, the balanced application of N and S is indispensable for achieving higher yield, improved oil quality, and sustainable production in mustard-based cropping systems.

Mustard is typically grown on clay loam to loamy soils under irrigated or partially irrigated conditions during the Rabi season. Farmers generally follow a fixed fertilization schedule without considering soil fertility variation or crop demand, leading to either nutrient deficiency or wastage. Empirical research in different parts of Rajasthan and northern India suggests that the optimum combination of nitrogen (80- 120 kg N ha^{-1}) and sulphur (30-45 kg S ha^{-1}) results in superior plant growth, higher seed yield, and enhanced oil recovery [11, 12].

Adoption of a location-specific nutrient management strategy is therefore essential. High cropping intensity and limited organic matter recycling aggravate nutrient depletion. As mustard has a relatively higher sulphur requirement compared to cereals and pulses, the absence of sulphur fertilization leads to severe yield losses ranging from 15 to 40% [13].

Balanced fertilization with nitrogen and sulphur not only improves crop yield but also contributes to nutrient use efficiency, soil fertility maintenance, and economic profitability. Moreover, sulphur enhances oil synthesis enzymes such as acetyl-CoA carboxylase and improves fatty acid composition, particularly oleic and linoleic acid content, which determine oil quality [14].

2. Materials and Methods

The field experiment on the "Effect of nitrogen and sulphur fertilization on growth, yield and quality of Indian mustard (*Brassica juncea* L.)" was conducted at the Agriculture Research Farm, CPU, Kota (Rajasthan) during the Rabi season of 2025-26. The site is located in the Humid South Eastern Plain Zone (Zone V) at 25° 11' N latitude and 75° 54' E longitude. The experimental soil was clay-loam in texture with an alkaline pH of 8.35, low organic carbon (0.42%), low available N (177 kg ha^{-1}), medium available P (14.6 kg ha^{-1}), and high available K (321 kg ha^{-1}). The experiment consisted of 16 treatments involving combinations of four nitrogen levels (0, 40, 80, 120 kg ha^{-1}) and four sulphur levels (0, 15, 30, 45 kg ha^{-1}), laid out in a Factorial Randomized Block Design (FRBD) with 3 replications. The mustard variety DRMRIJ-31 (Giriraj) was sown on October 12, 2025, using a seed rate of 5 kg ha^{-1} with a row-to-row spacing of 35 cm and plant-to-plant spacing of 15 cm. Half the dose of nitrogen and full doses of phosphorus (60 kg P_2O_5 ha^{-1}), potassium (40 kg K_2O ha^{-1}), and sulphur were applied as basal dressing, while the remaining nitrogen was top-dressed after the first irrigation. The crop was harvested at full maturity on February 21, 2026.

2.1 Growth and Development Studies

Five randomly selected plants from each net plot were tagged for recording biometric observations. Initial (15 days after sowing) and final plant counts were recorded and converted to a per-hectare basis. Plant height was measured from the base to the tip of the main axis, and the number of functional leaves per plant was counted. The Leaf Area Index (LAI) was calculated to assess the leaf area produced on a unit ground area. To determine dry matter accumulation, individual plants were chopped, sun-dried, and then oven-dried at 65±2°C until a constant weight was achieved.

2.2 Yield and Quality Studies

Yield attributing characters, including the number of siliquae per plant, length of siliqua, number of seeds per siliqua, and test weight (1000 seeds weight), were recorded from the tagged plants and representative samples. Seed yield for each net plot was recorded and converted to kg ha^{-1}. Biological yield was determined by weighing the total harvestable biomass (seed + straw), and the straw yield was computed by subtracting the seed yield from the biological yield. The harvest index was also calculated. Additionally, quality parameters like oil content (%) were determined using standard extraction/instrumental methods, and nutrient content/uptake (N, P, K) in seeds and straw were chemically estimated.

2.3 Statistical Analysis

The experimental data generated for various parameters were statistically analyzed using the standard "Analysis of Variance" (ANOVA) method as reported by Panse and Sukhatme (1967). The significance of the treatment effects was tested at a 5% probability level. For significant results, the Critical Difference (C.D.) was calculated to compare the differences between treatment means based on the procedure described by Snedecor and Cochran.

3. Results and Discussion

3.1 Growth Attributes

3.1.1 Emergence count and final plant stand

The emergence count and final plant stand were significantly influenced by varying levels of nitrogen, with 120 kg N ha^{-1} (N3) recording the maximum values. However, the effect of sulphur levels and their interaction remained non-significant. This uniformity is expected, as the initial germination and establishment of seedlings are predominantly governed by intrinsic seed traits, physical seedbed conditions, and initial soil moisture rather than external fertilizer applications. Furthermore, the applied doses created no adverse osmotic stress in the rhizosphere [15, 16].

3.1.2 Plant height

Plant height increased progressively at every growth stage up to 90 DAS. The application of 120 kg N ha^{-1} and 45 kg S ha^{-1} produced the tallest plants, though at later stages, they were statistically at par with 80 kg N ha^{-1} and 30 kg S ha^{-1}, respectively. The increase in height with nitrogen is due to its vital role in vegetative growth, enhancing cell division and elongation as a constituent of chlorophyll and proteins [17, 18]. The increase due to sulphur is attributed to its role in synthesizing sulphur-containing amino acids and chlorophyll formation, which promotes vigorous metabolic activity [19, 20].

3.1.3 Number of branches plant^{-1}
The maximum number of branches per plant was recorded with the application of 120 kg N ha^{-1} and 45 kg S ha^{-1}. Nitrogen enhanced axillary bud development and lateral growth through increased cytokinin activity [18, 21]. Similarly, sulphur improved cell division, vigorous root growth, and chlorophyll formation, resulting in higher photosynthesis and consequently more branches [19, 20, 22].

3.1.4 Dry matter plant^{-1}
Dry matter accumulation increased progressively, with the maximum values recorded at 120 kg N ha^{-1} and 45 kg S ha^{-1} (though at par with 80 kg N and 30 kg S ha^{-1} at later stages). This significant increase is a direct result of enhanced plant height, branching, and overall vegetative growth driven by nitrogen [17, 18]. Sulphur contributed to this by aiding in cell division and root elongation, reflecting higher nutrient absorption and photosynthate formation [19, 23].

3.1.5 Leaf area index (LAI)
LAI peaked at 60 DAS and declined towards 90 DAS due to natural leaf senescence. The highest LAI was observed with 120 kg N ha^{-1} and 45 kg S ha^{-1}, which were at par with 80 kg N and 30 kg S ha^{-1}. Nitrogen stimulated meristematic activity, leading to rapid cell division and expansion of leaf blades [24, 25]. Sulphur further enhanced LAI due to its strong synergistic relationship with nitrogen metabolism and its direct participation in photosynthesis via ferredoxin, which delayed leaf senescence [19, 20].

3.3 Yield Studies
3.3.1 Seed yield
The maximum seed yield (1920 kg ha^{-1}) was recorded with the application of 120 kg N ha^{-1}, though it was found to be statistically at par with 80 kg N ha^{-1} (1810 kg ha^{-1}). The significant enhancement under adequate nitrogen supply is primarily attributed to improved vegetative growth attributes, resulting in a greater accumulation of photosynthates [17, 18]. Similarly, the highest seed yield (1890 kg ha^{-1}) was obtained with 45 kg S ha^{-1}, remaining statistically at par with 30 kg S ha^{-1} (1755 kg ha^{-1}). Sulphur plays a pivotal role in siliquae formation and bold seed filling [19, 20].

3.3.2 Straw and Biological yield
The application of 120 kg N ha^{-1} registered the maximum straw yield (4850 kg ha^{-1}) and biological yield (6770 kg ha^{-1}). Nitrogen, being a core structural constituent, promoted vigorous cell division and extended the active vegetative phase, leading to greater dry matter in the stover. Similarly, 45 kg S ha^{-1} recorded the highest straw (4895 kg ha^{-1}) and biological yield (6785 kg ha^{-1}). This increment is associated with sulphur's synergistic role in enhancing nitrogen uptake and its indispensable function in maintaining a robust photosynthetic apparatus [20, 26].

3.3.3 Harvest index
The harvest index was highest with the application of 120 kg N ha^{-1} (28.4%) and 45 kg S ha^{-1} (27.9%). An optimal nitrogen supply maintained a favorable physiological balance, diverting synthesized assimilates towards the economic sink (seeds) rather than excessive structural growth. Similarly, progressive sulphur application created a "stronger sink demand" by directly aiding in the synthesis of oil and proteins in the seeds, thereby efficiently pulling dry matter from vegetative tissues into the developing seeds during the reproductive phase.

Table 1: Effect of different treatments on Plant population/m row length at Emergence count and Final plant stands of mustard

Treatment	Emergence count Arc. Values (%)	Final plant stands Arc. Values (%)
(A) Nitrogen (N)		
N_0- 0 N kg ha^{-1}	70.12 (88.45%)	62.45 (78.60%)
N_1- 40 N kg ha^{-1}	72.85 (91.30%)	66.18 (83.52%)
N_2- 80 N kg ha^{-1}	74.90 (93.25%)	71.40 (89.95%)
N_3- 120 N kg ha^{-1}	76.22 (94.48%)	75.12 (91.10%)
SE±	0.92	0.98
CD at 5%	2.65	2.82
(B) Sulphur (S)		
S_0- Sulphur 0 kg ha^{-1}	71.30 (89.80%)	64.20 (81.15%)
S_1- Sulphur 15 kg ha^{1}	73.55 (92.01%)	68.30 (86.42%)
S_2- Sulphur 30 kg ha^{-1}	74.88 (93.22%)	70.15 (88.05%)
S_3- Sulphur 45 kg ha^{-1}	75.45 (93.75%)	70.50 (88.35%)
SE±	0.85	0.90
CD at 5%	NS	NS

Table 2: Effect of different treatments on Plant height of mustard

Treatment	Plant Height			
	30 DAS	60 DAS	90 DAS	At Harvest
(A) Nitrogen (N)				
N_0- 0 N kg ha^{-1}	3.85	105.15	132.40	132.40
N_1- 40 N kg ha^{-1}	4.92	115.80	142.75	142.75
N_2- 80 N kg ha^{-1}	5.95	134.25	155.10	155.10
N_3- 120 N kg ha^{-1}	6.88	135.90	158.45	158.45
SE±	0.18	3.50	3.65	3.65
CD at 5%	0.55	10.60	11.05	11.05
(B) Sulphur (S)				
S_0- Sulphur 0 kg ha^{-1}	4.60	112.40	138.20	138.20
S_1- Sulphur 15 kg ha^{1}	5.35	122.15	146.10	146.10
S_2- Sulphur 30 kg ha^{-1}	5.82	128.50	148.25	148.25
S_3- Sulphur 45 kg ha^{-1}	6.45	134.60	159.10	159.10
SE±	0.14	3.48	3.15	3.15
CD at 5%	0.52	10.21	10.75	10.75

Table 3: Effect of different treatments on Branch Plant^{-1} of mustard

Treatments	Branches Plant^{-1}			
	30 DAS	60 DAS	90 DAS	At Harvest
(A) Nitrogen (N)				
N_0- 0 N kg ha^{-1}	3.20	7.45	11.55	11.55
N_1- 40 N kg ha^{-1}	4.15	8.82	13.92	13.92
N_2- 80 N kg ha^{-1}	5.12	10.10	15.20	15.20
N_3- 120 N kg ha^{-1}	5.85	10.95	16.45	16.45
SE±	0.21	0.34	0.44	0.44
CD at 5%	0.62	0.99	1.32	1.32
(B) Sulphur (S)				
S_0- Sulphur 0 kg ha^{-1}	3.85	8.15	12.40	12.40
S_1- Sulphur 15 kg ha^{1}	4.62	9.35	14.12	14.12
S_2- Sulphur 30 kg ha^{-1}	5.35	10.05	15.65	15.65
S_3- Sulphur 45 kg ha^{-1}	5.90	10.45	16.15	16.15
SE±	0.19	0.32	0.41	0.41
CD at 5%	0.58	0.97	1.30	1.29

Table 4: Effect of different treatments on dry matter plant^{-1} of mustard

Treatment	Dry Matter Plant^{-1}			
	30 DAS	60 DAS	90 DAS	At Harvest
(A) Nitrogen (N)				
N_0- 0 N kg ha^{-1}	1.45	13.80	51.40	69.20
N_1- 40 N kg ha^{-1}	1.95	16.95	59.80	81.45
N_2- 80 N kg ha^{-1}	2.15	18.85	65.15	89.20
N_3- 120 N kg ha^{-1}	2.40	19.10	65.85	91.10
SE±	0.08	0.52	1.85	2.75
CD at 5%	0.25	1.52	5.55	8.15
(B) Sulphur (S)				
S_0- Sulphur 0 kg ha^{-1}	1.65	15.20	53.90	74.30
S_1- Sulphur 15 kg ha^{1}	1.90	17.40	60.12	83.15
S_2- Sulphur 30 kg ha^{-1}	2.12	18.25	63.85	85.12
S_3- Sulphur 45 kg ha^{-1}	2.35	19.35	66.20	92.45
SE±	0.07	0.50	1.81	2.73
CD at 5%	0.23	1.49	5.51	8.12

Table 5: Effect of different treatments on Leaf area index plant^{-1} of mustard

Treatments	Leaf area index plant^{-1}		
	30 DAS	60 DAS	90 DAS
(A) Nitrogen (N)			
N_0- 0 N kg ha^{-1}	0.52	5.85	0.90
N_1- 40 N kg ha^{-1}	0.68	6.90	1.45
N_2- 80 N kg ha^{-1}	0.75	8.55	3.20
N_3- 120 N kg ha^{-1}	0.85	8.68	3.65
SE±	0.03	0.32	0.12
CD at 5%	0.09	0.95	0.35
(B) Sulphur (S)			
S_0- Sulphur 0 kg ha^{-1}	0.58	6.10	1.15
S_1- Sulphur 15 kg ha^{1}	0.72	7.35	2.40
S_2- Sulphur 30 kg ha^{-1}	0.70	7.95	2.65
S_3- Sulphur 45 kg ha^{-1}	0.88	8.72	3.32
SE±	0.02	0.30	0.10
CD at 5%	0.07	0.92	0.32

Table 6: Effect of different treatments on yield of mustard

Treatments	Seed yield (kg ha^{-1})	Straw Yield (kg ha^{-1})	Biological yield ha^{-1} (kg)	Harvest Index (%)
(A) Nitrogen (N)				
N_0- 0 N kg ha^{-1}	1150	3620	4770	24.1
N_1- 40 N kg ha^{-1}	1525	4410	5935	25.7
N_2- 80 N kg ha^{-1}	1810	4785	6595	27.4
N_3- 120 N kg ha^{-1}	1920	4850	6770	28.4
SE±	58.00	120.00	165.00	-
CD at 5%	175.00	360.00	495.00	-

(B) Sulphur (S)				
S_0- Sulphur 0 kg ha^{-1}	1240	3850	5090	24.4
S_1- Sulphur 15 kg ha^{1}	1545	4390	5935	26.0
S_2- Sulphur 30 kg ha^{-1}	1755	4760	6515	26.9
S_3- Sulphur 45 kg ha^{-1}	1890	4895	6785	27.9
SE±	54.00	117.65	147.26	-
CD at 5%	165.00	347.35	435.17	-

4. Conclusion
Based on the results, it can be concluded that the integrated application of nitrogen and sulphur profoundly improves the growth, biomass accumulation, and yield efficiency of Indian mustard in the Hadoti region. While the maximum application rates of 120 kg N ha^{-1} and 45 kg S ha^{-1} recorded the highest absolute values for growth and yield parameters, the doses of 80 kg N ha^{-1} and 30 kg S ha^{-1} frequently performed statistically at par, indicating an optimum threshold for nutrient efficiency and crop productivity.

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Competing Interests
Authors have declared that no competing interests exist.

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