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Enhancing growth and yield of mustard (*Brassica juncea*) through foliar application of nano-sulphur

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Abstract

A field experiment entitled “Enhancing Growth, Yield, Nutrient Uptake, and Economics of Mustard (*Brassica juncea*) through Foliar Application of Nano-Sulphur” was conducted during the *Rabi* season of 2025–26 at the Agricultural Research Farm, School of Agriculture, Suresh Gyan Vihar University, Jaipur (Rajasthan). The trial was laid out in a randomized block design with three replications evaluating ten treatments, consisting of a control (T_0): Recommended Dose of Fertilizers and different combinations of three nano-Sulphur concentrations (10, 20, and 30 ppm) applied at 30 days after sowing (DAS), 60 DAS, or at both stages (T_1 to T_9). The experimental findings revealed that while the plant population per meter row length showed non-significant differences across treatments, all other biometric and qualitative attributes were significantly enhanced by nano-Sulphur. The maximum plant height (198.74 cm), dry matter accumulation (36.85 g/plant), number of branches per plant ((33.96)), and leaf area index (1.80)) at harvest were recorded under T_9 (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS). This treatment T_9 also produced the highest yield attributes and ultimate outcomes, documenting a peak seed yield of 2402 kg/ha stover yield of 8520 kg/ha, biological yield of 10,922 kg/ha and a harvest index of 21.99%. From an economic perspective, T_9 achieved the maximum net returns of Rs/ha. 105,704. However, the highest benefit-cost (B:C) ratio of 2.98 was obtained with treatment T_7 (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 DAS) due to its reduced cost of cultivation. Consequently, while a dual-stage application of 30 ppm nano-Sulphur maximizes biological productivity, a single early application at 30 DAS delivers the highest capital efficiency for mustard cultivation in the semi-arid region of Jaipur.

Keywords: *Brassica juncea* L., nano sulphur, foliar spray, seed yield, B:C ratio

1. Introduction

Indian mustard (*Brassica juncea* L.) represents one of the most critical winter- cultivated (*Rabi*) oilseed crops globally, playing a pivotal role in meeting vegetable fat requirements. Optimizing the seed yield and oil profiling of cruciferous crops demands targeted and highly balanced macro- and micro-nutrient management programs. Among vital agronomic inputs, Sulphur serves as a fundamental building block for structural sulfur- containing amino acids such as methionine and cysteine, which directly regulate total plant protein translation matrices. Furthermore, adequate sulfur nutrition acts as the primary biochemical driving factor for activating the acetyl-CoA carboxylase enzyme system, directly maximizing seed oil synthesis and glucosinolate composition.

Oilseed species inherently require significantly higher volumes of cellular sulfur per unit of dry matter to reach maximum productivity compared to cereals and pulse species. However, the light-textured, coarse sandy-loam soils characteristic of semi-arid regions like Jaipur, Rajasthan, frequently present widespread baseline secondary nutrient deficiencies due to intensive cropping configurations and high sand leaching rates (Sharma and Meena, 2023) ^[6]. Under these specific dryland environments, conventional soil- applied sulfur formulations (such as gypsum or elemental bentonite sulfur pellets) demonstrate low nutrient-use efficiency (NUE). This agronomic limitation is induced by rapid sub-surface sulfate leaching, extensive chemical soil immobilization, and delayed microbial oxidation pathways in low-moisture zones.

Nanotechnology offers a highly viable strategy to bypass traditional rhizosphere bottlenecks via the deployment of structured nano-fertilizers. Nano-Sulphur particles possess an exceptionally high surface-area-to-volume ratio, facilitating rapid cellular penetration and superior metabolic assimilation when supplied as an atomized foliar spray. These engineered ultra-fine particles cross leaf cuticular membranes and stomatal pathways directly, ensuring localized delivery into active metabolic sinks during key physiological development windows. Field validation trials show that foliar nano-fertilization avoids soil fixation pathways entirely, enhancing chlorophyll biosynthesis and dry matter partitioning while significantly shrinking input wastage footprints.

While the general parameters of macro-sulfur fertilization have been documented, research defining the precision concentration thresholds and application intervals for nano- scale liquid formulations under semi-arid conditions remains sparse. To bridge this gap, a field investigation was conducted during the *Rabi* season of 2025–26 at the Agricultural Research Farm, Department of Agronomy, School of Agriculture, Suresh Gyan Vihar University, Jaipur (Rajasthan). This trial was systematically designed to clarify how varying nano-Sulphur concentrations and precision application intervals regulate the vegetative growth dynamics, yield structural traits, tissue nutrient uptake, and final economic feasibility of *Brassica juncea*.

2. Materials and Methods

2.1 Experimental Site and Agro-Climatic Conditions

The field experiment was carried out during the *Rabi* season of 2025–26 at the Agricultural Research Farm, Department of Agronomy, School of Agriculture, Suresh Gyan Vihar University, Jaipur, Rajasthan, India. The experimental site is situated within the semi- arid agro-climatic zone of Rajasthan, which is characterized by hot, dry summers and cold, dry winters. The average annual rainfall of the region ranges between (500 mm and 650 mm), with the majority received during the southwest monsoon.

2.2 Soil Profile Characterization

Prior to sowing, representative composite soil samples were collected randomly from a depth of (0 to 15 cm) across the experimental block to assess initial physico-chemical properties. The soil of the experimental farm is classified as a typical sandy loam, characterized by its loose structure and high sub-surface drainage capabilities [Sharma and Meena, 2023] ^[6]. Standard chemical laboratory evaluations indicated that the soil profile was alkaline in reaction, low in available soil organic carbon (SOC), low in available nitrogen (N), medium in available phosphorus (P2O5), and low to medium in available sulphur (S).

2.3 Experimental Design and Treatment Structure

The trial was laid out using a randomized block design (RBD) with ten distinct treatments replicated three times. The experimental area was divided into thirty individual plots with uniform dimensions to maintain strict spatial isolation. The baseline treatment structure comprised a standard un-supplemented absolute control alongside nine precision combinations varying in nano-Sulphur application timings and concentrations.

2.4 Crop Management and Liquid Fertilizer Preparation

The experimental field underwent uniform preparatory tillage

consisting of one deep summer ploughing followed by two passes of a tractor-mounted cultivator and planking to establish a firm, fine seedbed. Sowing of the mustard crop was performed at a standard optimal row spacing of 30 and intra-row plant spacing of 10 cm).

The baseline Recommended Dose of Fertilizers (RDF) consisting of nitrogen, phosphorus, and potassium was applied uniformly to all plots (T₀) through (T₉) through traditional inorganic granular sources. Half of the designated nitrogen dose and the full quantities of phosphorus and potassium were incorporated into the soil as a baseline application during final land preparation. The remaining half of the nitrogen dose was top-dressed following the first critical irrigation cycle at vegetative development.

The liquid nano-Sulphur solutions used for the foliar treatments were prepared fresh before each application window. Stable liquid suspensions of nano-Sulphur were diluted with distilled water under continuous magnetic stirring to establish the required experimental thresholds of 10, 20 and 30 ppm. Foliar application was carried out using a calibrated hand- operated knapsack sprayer fitted with a flat-fan nozzle. Liquid applications were completed during the early morning hours to minimize wind drift and optimize cuticular absorption [Das and Malhotra, 2023]. The first spray application was executed at the active vegetative phase (30 DAS), and the second split spray application was performed at the siliquae initiation stage (60 DAS) according to the treatment layout. Standard intercultural crop protection practices, including manual weeding and need-based irrigation, were implemented uniformly across all plots. The collected experimental data were subjected to a rigorous analysis of variance (ANOVA) for a randomized block design using standard statistical procedures [0.1.12; Gomez and Gomez].

3. Results and Discussion

3.1 Growth attributes

Plant height was significantly influenced by nano-sulphur treatments at 30 DAS, 60 DAS and harvest. The maximum plant height was recorded with T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), recording 23.82, 99.62 and 198.74 cm, respectively, whereas the minimum was observed in T₀ (Control) with 16.85, 65.58 and 132.52 cm, respectively. T₉ was statistically at par with T₇, T₈, T₆ and T₄ at the later growth stages. The superior growth under T₉ may be attributed to the improved availability and efficient utilization of sulphur, which plays an important role in chlorophyll formation, enzyme activation, protein synthesis and photosynthetic activity. Foliar application of nano-sulphur may have facilitated rapid nutrient absorption and improved nutrient-use efficiency, thereby promoting vegetative growth and plant height. Similar beneficial effects of sulphur nutrition on plant height and growth have been reported by Singh (2017) ^[11], in different field crops.

Dry matter accumulation was significantly influenced by nano-sulphur treatments at 30 DAS, 60 DAS and harvest. The maximum dry matter accumulation was recorded in T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), with 4.20, 20.35 and 36.85 g/plant, respectively. It was statistically at par with T₇, T₈ and T₆ at 30 DAS, T₇ and T₈ at 60 DAS, and T₇ at harvest. The minimum dry matter accumulation was observed in T₀ (Control), recording 2.58, 9.52 and 16.58 g/plant at 30 DAS, 60 DAS and harvest, respectively. The higher dry matter accumulation under T₉ may be attributed to improved sulphur availability and its efficient utilization, which enhanced

chlorophyll synthesis, photosynthetic activity, protein formation and nutrient metabolism. Foliar application of nano-sulphur may also have improved nutrient absorption and utilization efficiency, resulting in greater biomass production. Similar positive effects of sulphur nutrition on growth, biomass accumulation and productivity have been reported by Singh (2017) ^[11], in different crops.

The number of branches per plant was significantly influenced by nano-sulphur treatments. The maximum number of branches (33.96 plant⁻¹) was recorded in T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), which was statistically at par with T₇ (31.08), whereas the minimum (14.25 plant⁻¹) was observed in T₀ (Control). The increase in branching under T₉ may be attributed to improved sulphur nutrition, which enhanced photosynthetic activity, protein synthesis and vegetative growth, resulting in greater branch development. Similar positive effects of sulphur application on vegetative growth and branching have been reported by Singh (2017) ^[11].

Leaf area index (LAI) differed significantly among nano-sulphur treatments. The maximum LAI (1.80) was recorded in T₉, followed by T₇ (1.72) and T₈ (1.68), while the minimum LAI (1.32) was recorded in T₀ (Control). The higher LAI under T₉ may be due to enhanced sulphur availability and improved photosynthetic efficiency, which promoted leaf expansion and canopy development. Increased leaf area provides greater photosynthetic surface, thereby contributing to higher dry matter accumulation and crop productivity. Similar improvements in growth and canopy development with sulphur nutrition.

3.2 Effect on yield attributes and yield

Length of siliqua was significantly influenced by nano-sulphur treatments. The maximum siliqua length (5.72 cm) was recorded in T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), which was statistically at par with T₇ (5.44 cm) and T₈ (5.30 cm), whereas the minimum (4.42 cm) was observed in T₀ (Control). The improvement may be attributed to better sulphur nutrition, which promotes protein synthesis, reproductive development and assimilate translocation. Similar beneficial effects of sulphur application on yield attributes.

The number of siliquae per plant differed significantly among nano-sulphur treatments. The maximum number of siliquae (285.24 plant⁻¹) was recorded in T₉, while the minimum (158.25 plant⁻¹) was observed in T₀ (Control). Higher siliquae production under T₉ may be associated with enhanced vegetative growth, branching, photosynthetic activity and efficient translocation of assimilates towards reproductive organs. Adequate sulphur nutrition is also important for reproductive growth and seed formation, which may have contributed to the higher number of siliquae.

The number of seeds per siliqua was significantly affected by nano-sulphur treatments. T₉ recorded the maximum number of seeds per siliqua (13.00), whereas the minimum (9.74) was recorded in T₀ (Control). The higher seed number under T₉ could be attributed to improved sulphur availability, enhanced photosynthetic efficiency and better nutrient translocation during reproductive development. Similar improvements in yield attributes with sulphur application.

Test weight did not differ significantly among the nano-sulphur treatments. Although numerical variation was observed among treatments, the differences were statistically non-significant. This indicates that nano-sulphur application had a greater influence on siliqua formation and seed number than on individual seed weight. Sulphur primarily supports protein synthesis and reproductive development, while final seed weight may also be strongly influenced by genotype and assimilate partitioning.

Seed yield was significantly influenced by nano-sulphur treatments. The maximum seed yield (2402 kg ha⁻¹) was recorded in T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), which was statistically at par with T₇ (2345 kg ha⁻¹) and T₆ (2258 kg ha⁻¹), whereas the minimum (1352 kg ha⁻¹) was recorded in T₀ (Control). The higher seed yield under T₉ may be attributed to improved plant growth, greater branching, higher siliquae production and increased seed number, resulting in better assimilate accumulation and partitioning towards seeds. Adequate sulphur also supports protein synthesis and reproductive development, thereby improving seed yield. Similar positive effects of sulphur nutrition on crop yield have been reported by Singh (2017) ^[12].

Stover yield differed significantly among the nano-sulphur treatments. The highest stover yield (8520 kg ha⁻¹) was recorded in T₉, which was statistically at par with T₇ (8375 kg ha⁻¹), T₈ (8236 kg ha⁻¹), T₆ (8145 kg ha⁻¹), T₄ (8025 kg ha⁻¹) and T₅ (7965 kg ha⁻¹). The minimum stover yield (5952 kg ha⁻¹) was observed in T₀ (Control). The increase in stover yield may be due to enhanced vegetative growth, dry matter accumulation, branching and leaf area under adequate sulphur nutrition. Similar improvements in biomass production with sulphur application.

Biological yield was significantly affected by nano-sulphur treatments. The maximum biological yield (10922 kg ha⁻¹) was recorded in T₉, followed by T₇ (10720 kg ha⁻¹), T₈ (10436 kg ha⁻¹), T₆ (10403 kg ha⁻¹), T₄ (10220 kg ha⁻¹) and T₅ (10130 kg ha⁻¹), whereas the minimum (7304 kg ha⁻¹) was recorded in T₀ (Control). The superior biological yield under T₉ was mainly associated with greater plant height, dry matter accumulation, branching, leaf area and reproductive growth, which collectively increased total biomass production. These findings are in agreement with earlier reports showing that adequate sulphur nutrition improves growth, biomass accumulation and yield in field crops (Singh, 2017) ^[12].

3.3 Economics

Application of nano-sulphur significantly improved the economic returns of the crop. The maximum net return (₹105,704 ha⁻¹) was obtained with T₉ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 and 60 DAS), whereas the minimum net return (₹45,252 ha⁻¹) was recorded in T₀ (Control). The highest B:C ratio (2.98) was recorded with T₇ (RDF + foliar spray of nano-Sulphur @ 30 ppm at 30 DAS). The higher profitability under T₉ may be attributed to increased seed and stover yields resulting from improved sulphur nutrition, which more than compensated for the additional cost of nano-sulphur application. Similar economic benefits of sulphur fertilization due to increased crop productivity have been reported by Singh (2017) ^[12].

Table 1: Effect of nano Sulphur on plant population and plant height of mustard

Treatments	Plant population per m row length		Plant height (cm)		
	30 DAS	60 DAS	30 DAS	60 DAS	At harvest
T ₀ -Control	9.10	8.85	16.85	65.58	132.52
T ₁ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 DAS	8.82	7.78	21.45	82.74	169.64
T ₂ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 60 DAS	8.75	8.02	20.66	78.69	165.45
T ₃ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 and 60 DAS	8.92	8.15	21.85	86.45	174.32
T ₄ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 DAS	8.98	8.25	22.35	90.36	183.20
T ₅ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 60 DAS	9.15	8.35	22.00	88.25	178.16
T ₆ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 and 60 DAS	9.05	8.21	22.68	92.45	187.66
T ₇ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 DAS	9.22	8.54	23.25	96.62	193.228
T ₈ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 60 DAS	9.34	8.45	22.89	94.52	190.75
T ₉ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 and 60 DAS	9.45	8.65	23.82	99.62	198.74
S.E.m.±	0.37	0.37	0.81	3.36	6.47
CD	NS	NS	2.40	9.98	19.22
CV%	7.10	7.17	6.42	6.65	6.33

Table 2: Effect of nano Sulphur on dry matter accumulation and number of branches and leaf area index of mustard

Treatments	Dry matter accumulation (g/plant)			Number of branches per plant	Leaf area index
	30 DAS	60 DAS	At harvest		
T ₀ -Control	16.85	65.58	132.52	14.25	1.32
T ₁ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 DAS	21.45	82.74	169.64	20.45	1.46
T ₂ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 60 DAS	20.66	78.69	165.45	18.62	1.42
T ₃ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 and 60 DAS	21.85	86.45	174.32	21.85	1.49
T ₄ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 DAS	22.35	90.36	183.20	25.12	1.58
T ₅ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 60 DAS	22.00	88.25	178.16	23.65	1.52
T ₆ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 and 60 DAS	22.68	92.45	187.66	27.58	1.65
T ₇ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 DAS	23.25	96.62	193.228	31.08	1.72
T ₈ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 60 DAS	22.89	94.52	190.75	29.45	1.68
T ₉ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 and 60 DAS	23.82	99.62	198.74	33.96	1.80
S.E.m.±	0.81	3.36	6.47	1.02	0.06
CD	2.40	9.98	19.22	3.03	0.18
CV%	6.42	6.65	6.33	7.17	6.74

Table 3: Effect of nano Sulphur on yield attributes and yield

Treatments	Length of siliquae	Number of siliquas per plant	Number of seed per siliquae	Test weight (g)
T ₀ -Control	4.42	158.25	9.74	4.02
T ₁ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 DAS	4.72	190.45	10.35	4.32
T ₂ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 60 DAS	4.68	182.62	10.12	4.20
T ₃ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 and 60 DAS	4.83	201.36	10.52	4.42
T ₄ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 DAS	5.00	225.78	11.00	4.78
T ₅ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 60 DAS	4.92	212.52	10.74	4.65
T ₆ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 and 60 DAS	5.15	238.84	11.25	4.95
T ₇ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 DAS	5.44	260.25	12.25	5.08
T ₈ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 60 DAS	5.30	248.44	11.85	5.00
T ₉ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 and 60 DAS	5.72	285.24	13.00	5.14
S.E.m.±	0.17	8.07	0.18	0.46
CD	0.51	23.99	0.54	1.37
CV%	5.97	6.35	6.73	7.14

Table 4: Effect of nano Sulphur on yield and harvest index of mustard

Treatments	Seed yield (kg/ha)	Stover yield (kg/ha)	Biological yield (kg/ha)	Harvest index (%)
T ₀ -Control	1352	5952	7304	18.51
T ₁ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 DAS	1852	7648	9500	19.49
T ₂ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 60 DAS	1745	7585	9330	18.70
T ₃ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 and 60 DAS	2052	7820	9872	20.79
T ₄ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 DAS	2195	8025	10220	21.48
T ₅ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 60 DAS	2165	7965	10130	21.37
T ₆ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 and 60 DAS	2258	8145	10403	21.71
T ₇ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 DAS	2345	8375	10720	21.88
T ₈ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 60 DAS	2200	8236	10436	21.08
T ₉ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 and 60 DAS	2402	8520	10922	21.99
S.E.m.±	80.74	267.29	427.27	0.86
CD	239.88	794.16	1269.47	2.54
CV%	6.80	5.92	7.49	7.16

Table 5: Effect of nano Sulphur on economics

Treatments	Cost of cultivation (Rs/ha)	Gross return (Rs/ha)	Net return (Rs/ha)	B:C ratio
T ₀ -Control	47500	92752	45252	1.95
T ₁ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 DAS	51000	126296	75296	2.48
T ₂ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 60 DAS	51000	119568	68568	2.34
T ₃ -RDF + Foliar spray of nano Sulphur @ 10 ppm at 30 and 60 DAS	52000	138954	86954	2.67
T ₄ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 DAS	52000	148128	96128	2.85
T ₅ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 60 DAS	52000	146178	94178	2.81
T ₆ -RDF + Foliar spray of nano Sulphur @ 20 ppm at 30 and 60 DAS	54000	152214	98214	2.82
T ₇ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 DAS	53000	157953	104953	2.98
T ₈ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 60 DAS	53000	148754	95754	2.81
T ₉ -RDF + Foliar spray of nano Sulphur @ 30 ppm at 30 and 60 DAS	56000	161704	105704	2.89

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