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HARNESSING BIOGENIC NANO-SULPHUR FOR ENHANCED GROWTH, REPRODUCTIVE DEVELOPMENT AND YIELD IN SOYBEAN (*Glycine max* L.)

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ABSTRACT

A field experiment was conducted during the *kharif* season of 2025 at the Research Farm of the All India Coordinated Research Project on Weed Management, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra to evaluate the influence of foliar-applied biogenic nano-sulphur on growth, reproductive development and yield of soybean. The experiment was laid out in a Randomized Block Design with four replications using soybean variety '*PDKV Amba*'. Six treatments comprised absolute control (T_0), General Recommended Dose of Fertilizer (GRDF) (T_1), GRDF + soil application of bentonite sulphur @ 30 kg S ha⁻¹ at sowing (T_2), and GRDF + foliar application of nano-sulphur @ 25, 50 and 75 ppm at 30 and 45 days after sowing (T_3 , T_4 and T_5 , respectively). Foliar application of nano-sulphur significantly influenced plant growth and pod formation. The application of GRDF + nano-sulphur @ 75 ppm at 30 and 45 days after sowing (T_5) recorded the highest plant height at 60 DAS (66.70 cm) and number of branches plant⁻¹ (5.20). The same treatment produced the maximum number of pods plant⁻¹ (39.90), seed yield plot⁻¹ (2.55 kg) and harvest index (46.00%). Stover yield was highest with GRDF + bentonite sulphur @ 30 kg S ha⁻¹ (29.91 q ha⁻¹). The results demonstrated that foliar application of biogenic nano-sulphur @ 75 ppm at 30 and 45 days after sowing in conjunction with GRDF was the most effective treatment for improving soybean growth, reproductive performance and seed yield.

Key words: Biogenic nano-sulphur, foliar application, soybean, plant height, pod, seed yield, stover yield, harvest index.

Introduction

Soybean (*Glycine max* L. Merrill) is an important oilseed and protein crop cultivated worldwide, valued for its high-quality protein and oil and widely used for food, feed and industrial purposes. As a legume, it also contributes to sustainable cropping systems through biological nitrogen fixation. However, soybean productivity is often constrained by nutrient deficiencies particularly

sulphur which plays vital roles in protein synthesis, enzyme activity, photosynthesis, nitrogen metabolism and biological nitrogen fixation. Sulphur is also essential for the synthesis of sulphur-containing amino acids and thereby contributes to seed development and quality. Intensive cropping and inadequate replenishment of sulphur have increased the likelihood of sulphur deficiency in agricultural soils, while the efficiency of conventional sulphur fertilizers depends

on their source, particle size, soil conditions and synchronization with crop demand.

Nanotechnology offers a promising approach for improving nutrient-use efficiency through nano-fertilizers possessing high surface area and enhanced reactivity, potentially facilitating greater nutrient availability and utilization. Nano-sulphur has therefore emerged as a potential alternative sulphur source for crop production. Foliar application can further improve nutrient delivery by supplying sulphur directly to aerial tissues during critical vegetative and reproductive stages. Biogenic nano-sulphur is of particular interest as an emerging nano-enabled nutrient technology because biologically derived nanoparticles offer potential advantages in terms of environmentally compatible production and agricultural application. Previous studies have reported beneficial effects of sulphur and nano-based nutrient application on the growth and productivity of oilseed crops.

Despite these advances, field-based information on the response of soybean to different concentrations of foliar-applied biogenic nano-sulphur remains limited. Therefore, the present investigation was undertaken to evaluate the influence of foliar-applied biogenic nano-sulphur on growth, reproductive development and yield attributes of soybean under field conditions.

Materials and Methods

The field experiment was conducted during the *khari* season of 2025-2026 at the Research Farm of the All India Coordinated Research Project on Weed Management, Dr. PDKV, Akola, Maharashtra, India.

Soybean variety '*PDKV Amba*' was grown in a Randomized Block Design (RBD) with four replications. Seeds were treated with Vitavax @ 2 mL kg⁻¹ seed and sown at a seed rate of 60 kg ha⁻¹ with 45 × 5 cm spacing. The gross plot size was 3.60 × 4.00 m and the net plot size was 2.70 × 3.80 m. Six nutrient-management treatments were evaluated comprising an absolute control (T₀), General Recommended Dose of Fertilizer (GRDF) (T₁), GRDF + soil application of bentonite sulphur @ 30 kg S ha⁻¹ at sowing (T₂) and GRDF + foliar application of nano-sulphur @ 25, 50 and 75 ppm at 30 and 45 days after sowing (DAS) designated as T₃, T₄ and T₅, respectively. GRDF was applied to the respective treatments, bentonite sulphur was applied at sowing and nano-sulphur was applied as foliar spray at 30 and 45 DAS.

Growth, reproductive and yield attributes were recorded following standard field procedures. Plant height and number of branches plant⁻¹ were recorded at 30, 45 and 60 DAS using five representative plants selected from each net plot. Plant height was measured from the

base to the tip of the youngest fully expanded leaf and expressed in centimetres, while primary branches were counted and expressed as number plant⁻¹. At harvest, the number of pods plant⁻¹ and seeds pod⁻¹ were determined from the selected plants. The crop from each net plot was harvested, dried and threshed and seed yield was recorded as kg plot⁻¹. The remaining biomass after threshing was recorded as stover yield and expressed in q ha⁻¹. Harvest index was calculated as the ratio of seed yield to total biological yield and expressed as percentage.

The data obtained for different observations were subjected to analysis of variance appropriate for a Randomized Block Design. Treatment means were compared using the standard error of mean [SE(m)±] and critical difference (CD) at the 5% level of significance.

Results and Discussion

Plant height was significantly influenced by sulphur treatments at 30, 45 and 60 DAS. At 30 DAS, the maximum plant height was recorded with T₂ (30.07 cm) followed by T₅ (29.87 cm), whereas T₀ recorded the minimum (23.95 cm). At 45 DAS, T₅ recorded the highest plant height (61.20 cm) followed by T₄ (59.27 cm), T₃ (58.42 cm), T₂ (56.67 cm) and T₁ (50.67 cm), while T₀ recorded 40.67 cm. At 60 DAS, T₅ remained superior (66.70 cm) followed by T₄ (64.15 cm), T₃ (63.25 cm), T₂ (59.52 cm) and T₁ (52.32 cm) with the minimum value in T₀ (45.67 cm). The enhanced plant height under T₅ may be attributed to improved sulphur availability and utilization during active vegetative growth, supporting protein synthesis, photosynthesis, enzymatic activity and nitrogen metabolism.

The number of branches plant⁻¹ was significantly affected by the treatments at all growth stages. At 30 DAS, T₅ recorded the maximum number of branches (2.51) followed by T₂ (2.41), T₄ (2.40), T₃ (2.34) and T₁ (2.12), whereas T₀ recorded the minimum (1.45). At 45 DAS, T₅ recorded the highest number (4.76) followed by T₄ (4.11), T₃ (3.72), T₂ (3.37) and T₁ (2.85) compared with 2.39 in T₀. At 60 DAS, T₅ maintained its superiority (5.20) followed by T₄ (4.71), T₃ (4.50), T₂ (4.05) and T₁ (3.75), while T₀ recorded 2.67 branches plant⁻¹. The greater branching under T₅ may be associated with improved sulphur nutrition, enhanced shoot development and increased photosynthetic capacity.

The number of pods plant⁻¹ was significantly influenced by the treatments with T₅ recording the maximum number (39.90) followed by T₄ (35.22), T₃ (34.35), T₂ (32.92) and T₁ (27.62), whereas T₀ recorded the minimum (23.65). The enhanced pod formation under T₅ may be attributed to improved sulphur availability during reproductive development, supporting photosynthesis,

Table 1: Performance of Soybean for growth traits influenced by foliar application of biogenic Nano-Sulphur.

Treatment	PH			NBP		
	30 DAS	45 DAS	60 DAS	30 DAS	45 DAS	60 DAS
Absolute control (T_0)	23.95	40.67	45.67	1.45	2.39	2.67
General Recommended Dose of Fertilizer (GRDF) (T_1)	29.22	50.67	52.32	2.12	2.85	3.75
GRDF + Soil application of bentonite sulphur @ 30 kg S ha ⁻¹ at sowing (T_2)	30.07	56.67	59.52	2.41	3.37	4.05
GRDF + Foliar application of nano-sulphur @ 25 ppm at 30 and 45 days after sowing (T_3)	29.02	58.42	63.25	2.34	3.72	4.50
GRDF + Foliar application of nano-sulphur @ 50 ppm at 30 and 45 days after sowing (T_4)	29.40	59.27	64.15	2.40	4.11	4.71
GRDF + Foliar application of nano-sulphur @ 75 ppm at 30 and 45 days after sowing (T_5)	29.87	61.20	66.70	2.51	4.76	5.20
SE(m)±	0.451	0.301	0.390	0.039	0.073	0.078
CD at 5%	1.360	0.907	1.177	0.119	0.221	0.234
F-test	S	S	S	S	S	S
PH: Plant height (cm); NBP: Number of branches plant ⁻¹						

protein synthesis, nitrogen metabolism and assimilate translocation. The number of seeds pod⁻¹ was not significantly affected; the highest numerical value was recorded under T_2 (2.35) followed by T_5 (2.32), T_4 (2.30), T_3 (2.27) and T_1 (2.25), while T_0 recorded the lowest value (1.90). The relatively stable response suggests that seeds pod⁻¹ was less responsive to sulphur nutrition and was probably influenced more by varietal and reproductive characteristics.

Seed yield plot⁻¹ was significantly influenced by the treatments. T_5 recorded the highest seed yield (2.55 kg plot⁻¹) followed by T_2 (2.40 kg), T_4 (2.27 kg), T_3 (1.85 kg) and T_1 (1.77 kg), whereas T_0 recorded the lowest yield (1.55 kg plot⁻¹). The superior performance of T_5 may be attributed to the cumulative improvement in plant height, branching and pod production, together with enhanced sulphur availability during critical growth stages. The greater reproductive sink under T_5 consequently contributed to higher seed production.

Harvest index was significantly influenced by sulphur treatments, with the highest value recorded under T_5 (46.00%) followed by T_4 (45.53%), T_2 (43.90%), T_1

(43.17%), T_3 (41.79%) and T_0 (40.43%). The higher harvest index under T_5 indicates comparatively efficient partitioning of accumulated biomass towards seed production, corresponding with its superior pod formation and seed yield. Stover yield was also significantly influenced, with the maximum value recorded under T_2 (29.91 q ha⁻¹) followed by T_5 (28.28), T_4 (25.65), T_3 (24.23), T_1 (22.41) and T_0 (22.10 q ha⁻¹). The greater Stover production under T_2 suggests that basal bentonite sulphur favoured vegetative biomass accumulation, whereas T_5 showed comparatively greater partitioning towards the economic component.

Biogenic nano-sulphur application emerged as an effective nutrient-management strategy for enhancing soybean productivity under the prevailing field conditions. Its integration with GRDF through foliar application of nano-sulphur @ 75 ppm at 30 and 45 DAS significantly enhanced plant height, number of branches plant⁻¹, pod production, seed yield plot⁻¹ and harvest index. The pronounced response of this treatment suggests that timely foliar sulphur supplementation improved crop growth and reproductive development facilitating greater

Table 2: Performance of Soybean for reproductive and yield contributing traits influenced by foliar application of biogenic Nano-Sulphur.

Treatment	NPP	SYP	HI	SY
Absolute control (T_0)	23.65	1.55	40.43	22.10
General Recommended Dose of Fertilizer (GRDF) (T_1)	27.62	1.77	43.17	22.41
GRDF + Soil application of bentonite sulphur @ 30 kg S ha ⁻¹ at sowing (T_2)	32.92	2.40	43.90	29.91
GRDF + Foliar application of nano-sulphur @ 25 ppm at 30 and 45 days after sowing (T_3)	34.35	1.85	41.79	24.23
GRDF + Foliar application of nano-sulphur @ 50 ppm at 30 and 45 days after sowing (T_4)	35.22	2.27	45.53	25.65
GRDF + Foliar application of nano-sulphur @ 75 ppm at 30 and 45 days after sowing (T_5)	39.90	2.55	46.00	28.28
SE(m)±	0.550	0.042	0.036	0.179
CD at 5%	1.658	0.129	0.108	0.539
F-test	S	S	S	S
NPP: Number of pods plant ⁻¹ ; SYP: Seed yield plot ⁻¹ (kg); HI: Harvest index (%); SY: Stover yield (q ha ⁻¹)				

biomass partitioning towards seed production. These findings are in agreement with the observations of Scherer 2001, Reis *et al.*, 2021, Getinet *et al.*, 2021, and Deak *et al.*, 2025, who demonstrated the importance of sulphur nutrition in improving soybean growth, nodulation, productivity and seed development.

Conclusion

The present investigation demonstrated that foliar application of biogenic nano-sulphur in combination with GRDF significantly improved the major growth, reproductive and yield attributes of soybean. Among the treatments, GRDF + foliar application of nano-sulphur @ 75 ppm at 30 and 45 DAS (T_5) was the most effective recording the highest plant height at 60 DAS (66.70 cm), branches plant⁻¹ (5.20), pods plant⁻¹ (39.90), seed yield plot⁻¹ (2.55 kg) and harvest index (46.00%). In contrast, the highest stover yield was recorded with GRDF + soil application of bentonite sulphur @ 30 kg S ha⁻¹ (T_2). Thus, foliar application of biogenic nano-sulphur @ 75 ppm at 30 and 45 DAS along with GRDF emerged as the most promising treatment for enhancing soybean productivity under the conditions of the present study. Further multi-season and multi-location evaluation is warranted to confirm its consistency and wider agronomic applicability.

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