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Effect of Biogenic Synthesized Nanosulphur for Enhancing Growth and Yield of Soybean

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The present investigation evaluated biogenically synthesised nanosulphur as a foliar nutrient source for improving soybean growth and yield during the Kharif season of 2023–24 at Dr Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra. Sulphur nanoparticles were synthesised under controlled laboratory conditions using sodium thiosulphate as the sulphur precursor and neem (*Azadirachta indica*) leaf extract as a reducing and stabilising agent. Analytical characterisation confirmed high purity, stability, nanoscale size and suitable morphological, structural, elemental and biomolecule-mediated surface characteristics. The field experiment was conducted in a randomised block design with six treatments and four replications. The

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treatments comprised the general recommended dose of fertilisers (GRDF; 30:60:30 kg $N:P_2O_5:K_2O$ ha^{-1}), GRDF supplemented with foliar applications of 25, 50 or 75 ppm biogenically synthesised nanosulphur at 30 and 45 days after sowing, GRDF supplemented with 30 kg S ha^{-1} through bentonite sulphur, and an absolute control. GRDF combined with 75 ppm nanosulphur significantly improved plant height, branches $plant^{-1}$, dry matter accumulation $plant^{-1}$, chlorophyll SPAD value, seed yield and stover yield. This treatment produced 2,551 kg ha^{-1} seed yield and 3,342 kg ha^{-1} stover yield and was statistically comparable with GRDF supplemented with 30 kg S ha^{-1} through bentonite sulphur for most growth and yield attributes. Nodule number was not significantly affected by the sulphur treatments. These findings indicate that foliar application of 75 ppm biogenically synthesised nanosulphur can support soybean growth and yield under the conditions of this experiment.

Keywords: Biogenic nanosulphur; soybean; foliar application; sulphur nutrition; growth attributes; yield.

1. Introduction

Soybean (*Glycine max* (L.) Merrill) is an important *Kharif* oilseed crop belonging to the family Leguminosae and subfamily Papilionoideae. It is considered one of the most valuable legume crops globally because of its high nutritional quality, diverse industrial applications and economic significance. Soybean originated in China (Vavilov, 1951) and is popularly known as the 'Golden Bean' and 'Wonder Crop' owing to its exceptional nutritional composition and multifunctional uses. Soybean seeds contain approximately 41–44% high-quality protein, 16–22% oil and 25–30% carbohydrates. The oil is rich in unsaturated fatty acids (approximately 85%), including about 55% polyunsaturated fatty acids, making soybean an important source of edible oil and plant-based protein.

According to reports from the Soybean Processors Association of India, the United States Department of Agriculture and the Soybean Outlook published by Professor Jayashankar Telangana State Agricultural University (Professor Jayashankar Telangana Agricultural University. (n.d.). Agricultural Market Intelligence,Soybean Processors Association of India, n.d.; United States Department of Agriculture, n.d.), global soybean production in 2024/25 was 427.93 million tonnes, with average productivity of 2,928 kg ha^{-1} and an implied harvested area of approximately 146.2 million hectares. SOPA estimates for Kharif 2025 place India's soybean area at 11.214 million hectares, expected production at 11.027 million tonnes and expected productivity at 983 kg ha^{-1}. Maharashtra accounts for 4.468 million hectares, 5.223 million tonnes and productivity of 1,169 kg ha^{-1}. Within Vidarbha, the combined Amravati and Nagpur divisions account for approximately 1.562 million hectares, 1.764 million tonnes and productivity of approximately 1,130 kg ha^{-1}.

Despite its importance, soybean productivity remains considerably low in many regions because of several biotic and abiotic constraints, including inadequate nutrient availability, declining soil fertility and inefficient nutrient utilisation. Among the essential nutrients, sulphur is particularly important in soybean cultivation because of its critical roles in plant metabolism, protein synthesis and oil accumulation.

Sulphur is an essential secondary macronutrient required for normal plant growth and development. It is a vital constituent of sulphur-containing amino acids, particularly cysteine and methionine, as well as proteins, vitamins, enzymes and coenzyme A. Sulphur plays important roles in fatty-acid metabolism, chlorophyll formation, nitrogen metabolism and various physiological and biochemical processes in plants. In agriculture, sulphur functions not only as a plant nutrient but also as a soil amendment and an important component of several crop-protection products. Adequate sulphur nutrition enhances crop growth, seed yield and oil content in oilseed crops; promotes the availability and uptake of essential nutrients such as phosphorus, potassium and zinc; and may reduce the accumulation of harmful elements such as sodium and chlorine. In soybean, sulphur availability can also influence rhizobial activity, nitrogen fixation and yield formation (Hu et al., 2023).

Sulphur deficiency has emerged as a major nutritional constraint because of intensive crop cultivation, the increased use of high-analysis sulphur-free fertilisers, reduced application of organic manures and decreased atmospheric sulphur deposition. Historically, sulphur deficiency was uncommon because atmospheric inputs and organic-matter mineralisation provided adequate sulphur supplies. However, continuous nutrient mining from soils has resulted in widespread sulphur deficiency, adversely affecting crop productivity and quality.

Sulphur deficiency reduces plant height, delays crop maturity, decreases chlorophyll synthesis, impairs protein formation and lowers crop yield and quality (Kamal et al., 2023).

Soybean, as an oilseed and protein-rich crop, has a high sulphur requirement. Adequate sulphur availability is essential for improving seed yield, oil content, protein synthesis and nutrient-use efficiency. Different sulphur fertilisers, including elemental sulphur, bentonite sulphur, gypsum, phosphogypsum and pyrite, are commonly used to meet the sulphur requirement of soybean, with recommended application rates generally ranging from 30 to 40 kg S ha^{-1}. Plants primarily absorb sulphur as sulphate ions (SO_4^{2-}), although thiosulphate ($S_2O_3^{2-}$) and atmospheric sulphur dioxide (SO_2) may also contribute through foliar absorption (Dileep et al., 2021). However, conventional sulphur fertilisers often have limitations, including low nutrient-use efficiency, slow oxidation, nutrient fixation and reduced plant availability, which necessitate the development of more efficient nutrient-delivery systems.

Nanotechnology has emerged as an innovative approach in modern agriculture and involves the design, synthesis and application of materials with dimensions ranging from 1 to 100 nm. Nanomaterials possess distinctive physicochemical properties, including a high surface area, enhanced reactivity, controlled-release characteristics and improved nutrient-use efficiency compared with their bulk counterparts (Ali et al., 2014; Agrahari & Dube, 2020). Because of these properties, nanotechnology has received considerable attention in electronics, medicine, environmental science, healthcare and agriculture (Ghotekar et al., 2020). Field-based research has also shown that appropriately formulated nano-fertilisers can improve crop productivity and nutrient-use efficiency, although responses depend on the crop, formulation, dose and application method (Singh et al., 2024).

Nanomaterials can be synthesised through top-down and bottom-up approaches. The top-down approach involves reducing bulk materials to nanosized particles, whereas the bottom-up approach involves assembling nanoparticles from atoms, molecules or ions. These approaches have facilitated the development of nano-fertilisers through nutrient encapsulation, adsorption and surface modification, resulting in improved nutrient stability, controlled release and enhanced nutrient availability to plants. Surface modification may further improve nutrient mobility and uptake efficiency within the soil–plant system by increasing the availability of both cationic and anionic nutrients (Elizabath et al., 2019). A recent synthesis of the evidence on nanoscale sulphur highlighted its potential for improving nutrient delivery and crop performance while emphasising the need for field-scale validation and environmental assessment (Sun et al., 2024).

Among the various nanomaterials, sulphur nanoparticles (S-NPs) have attracted considerable interest because of their potential to improve sulphur availability and crop productivity. The biogenic synthesis of nanoparticles using plant extracts has emerged as an environmentally compatible alternative to conventional chemical synthesis methods. Awwad et al. (2015) reported the green synthesis of sulphur nanoparticles from sodium thiosulphate using *Albizia julibrissin* fruit extract as a stabilising agent. The synthesised sulphur nanoparticles exhibited a crystalline elemental-sulphur structure, predominantly spherical morphology and an average particle size of approximately 20 nm, with a size distribution of 10–100 nm. Plant-derived biomolecules acted as capping, stabilising and dispersing agents that prevented nanoparticle aggregation and improved stability.

Biogenically synthesised nanosulphur may improve sulphur availability through its increased surface area, controlled nutrient release and enhanced absorption efficiency. Foliar nano-sulphur has recently improved growth and yield attributes in linseed (Kumar et al., 2025), while nanoscale sulphur has improved soybean biomass and seed yield under nanoparticle-induced stress (Sharma et al., 2023). Its application as a foliar nutrient source may therefore offer an efficient strategy for improving sulphur nutrition, physiological processes, growth and yield in soybean.

Despite increasing interest in nano-enabled nutrient delivery, field evidence on foliar application of biogenically synthesised nanosulphur to soybean under rainfed conditions remains limited, particularly regarding its comparative performance against a conventional sulphur source.

Therefore, the present study aimed to evaluate the effects of foliar applications of 25, 50 and 75 ppm biogenically synthesised nanosulphur at 30 and 45 DAS on soybean growth, physiological traits and yield, and to compare these responses with those obtained from GRDF supplemented with 30 kg S ha^{-1} through bentonite sulphur.

2. Materials and Methods

The field experiment was conducted during the *Kharif* season of 2023–24 at the All India Coordinated Research Project (AICRP) on Weed Management, Dr Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra, India. The experimental site was located at 20°42′ N latitude and 77°02′ E longitude, at an altitude of 307.4 m above mean sea level.

2.1 Weather Conditions during the Cropping Season

The weather conditions prevailing during the 2023–24 cropping season were recorded and analysed. The total rainfall received during the cropping period was 592.8 mm, distributed over 28 rainy days. The mean maximum temperature ranged from 28.5°C to 34.9°C, whereas the mean minimum temperature ranged from 17.8°C to 24.0°C. Mean relative humidity at 7:30 a.m. ranged from 79 to 88%, while that at 2:30 p.m. ranged from 38 to 80%. Mean daily evaporation ranged from 2.7 to 5.5 mm, and bright sunshine duration varied from 0.5 to 9.0 h day^{-1}.

2.2 Soil Characteristics, Crop Details and Field Management

The experimental field consisted of medium-deep black clay soil (Vertisols) with montmorillonitic mineralogy and relatively uniform topography. Soybean variety PDKV Amba was sown on 8 July 2023 and harvested on 10 October 2023. The experimental plot measured 3.6 m × 4.0 m, with a spacing of 45 cm between rows and 5 cm between plants. The seed rate was maintained at 65 kg ha^{-1}, and the crop was sown using the drilling method. The crop was grown under rainfed conditions and received the prevailing rainfall during the growing season.

At physiological maturity, the plants in each plot were uprooted for harvesting. The harvested plants were dried and threshed separately, and observations on yield attributes and yield were recorded. The recommended fertiliser dose of 30:60:30 kg $N:P_2O_5:K_2O$ ha^{-1} was applied basally at sowing through urea, diammonium phosphate (DAP) and muriate of potash (MOP). Bentonite sulphur was applied at 30 kg S ha^{-1} as a basal dose in treatment T_5. Foliar applications of 25, 50 and 75 ppm nanosulphur were applied to treatments T_2, T_3 and T_4, respectively, at 30 and 45 DAS using a hand-operated backpack sprayer with a spray volume of 400 L ha^{-1}.

2.3 Biogenic Synthesis of Sulphur Nanoparticles

Sulphur nanoparticles were synthesised under controlled laboratory conditions using sodium thiosulphate as the sulphur precursor and neem (*Azadirachta indica*) leaf extract as a reducing and stabilising agent. The synthesised sulphur nanoparticles were subjected to comprehensive physicochemical characterisation to determine particle size, morphology, structural properties, stability, surface charge, elemental composition and the functional groups associated with biomolecules involved in nanoparticle stabilisation.

The formation of sulphur nanoparticles was confirmed using ultraviolet–visible (UV–Vis) spectroscopy. Particle-size distribution was analysed to determine the nanoscale dimensions of the synthesised particles, while zeta-potential analysis was conducted to evaluate surface charge and colloidal stability. X-ray diffraction (XRD) analysis was performed to determine crystallinity and phase structure. Fourier-transform infrared (FTIR) spectroscopy was used to identify the functional groups involved in nanoparticle reduction and stabilisation. Elemental composition and purity were analysed using energy-dispersive X-ray spectroscopy (EDS), whereas high-resolution transmission electron microscopy (HR-TEM) was used to examine particle size, shape and lattice structure. These analyses confirmed the successful synthesis of high-purity, stable sulphur nanoparticles with nanoscale dimensions and desirable morphological, structural, elemental and biomolecule-mediated surface properties.

2.4 Experimental Design and Treatments

The field experiment was laid out in a randomised block design (RBD) with six treatments and four replications. The treatment details were as follows:

T_1: General Recommended Dose of Fertilizers (GRDF) 30:60:30 $N:P_2O_5:K_2O$ kg ha^{-1} through urea, diammonium phosphate (DAP) and muriate of potash (MOP).

T_2: T_1 + foliar application of 25 ppm biogenic synthesized nanosulphur at 30 and 45 days after sowing (DAS).
T_3: T_1 + foliar application of 50 ppm biogenic synthesized nanosulphur at 30 and 45 DAS.
T_4: T_1 + foliar application of 75 ppm biogenic synthesized nanosulphur at 30 and 45 DAS.
T_5: T_1 + application of 30 kg S ha^{-1} through bentonite sulphur.
T_6: Absolute control.

2.5 Observations and Statistical Analysis

Observations on growth parameters, physiological traits, yield attributes and yield were recorded at appropriate growth stages using standard experimental procedures. The data were analysed using analysis of variance appropriate for a randomised block design, as described by Gomez and Gomez (1984). The significance of treatment effects was tested using the F-test, and critical difference (CD) values at the 5% probability level (P = 0.05) were calculated for comparisons among treatment means wherever significant differences were observed.

3. Results and Discussion

3.1 Effect of Biogenic Synthesized Nanosulphur on Growth Parameters of Soybean

Most fertilised treatments recorded statistically comparable values for the evaluated growth attributes, including plant height, branches $plant^{-1}$, dry matter accumulation $plant^{-1}$ and chlorophyll SPAD value. All fertilised treatments performed significantly better than the absolute control for these attributes.

Table 1. Effect of biogenic synthesized nanosulphur on plant height (cm)

Treatments	Plant height (cm)		
	30 DAS	45 DAS	60 DAS
T_1: GRDF through Urea, DAP and MOP	28.91	48.53	52.32
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	29.20	54.95	56.66
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	29.58	58.28	61.27
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	29.97	62.22	66.55
T_5: T_1 + 30kg S ha^{-1} (Bentonite sulphur)	30.46	60.62	64.41
T_6: Absolute control	24.06	36.87	42.53
SE (m) ±	**0.13**	**0.67**	**0.76**
CD at 5%	**0.41**	**2.03**	**2.31**

The data presented in Table 1 show that biogenically synthesised nanosulphur significantly influenced plant height at different growth stages of soybean. At 30 DAS, the greatest plant height was recorded in treatment T_5 (T_1 + 30 kg S ha^{-1} through bentonite sulphur; 30.46 cm), followed by T_4 (T_1 + foliar application of 75 ppm nanosulphur at 30 and 45 DAS; 29.97 cm). The lowest plant height was recorded in the absolute control, T_6 (24.06 cm). At 45 and 60 DAS, T_4 recorded the greatest plant heights (62.22 and 66.55 cm, respectively) and was statistically at par with T_5 (60.62 and 64.41 cm, respectively). Treatment T_6 recorded the lowest plant heights at both stages (36.87 and 42.53 cm, respectively). The improvement in plant height under T_4 may be attributed to enhanced sulphur availability and efficient nutrient uptake, which supported metabolic activity, cell division and elongation. The high surface area and dispersion of nanosulphur particles may have improved sulphur absorption and utilisation within plant tissues. Adequate sulphur availability also supports chlorophyll synthesis, protein formation and enzyme activation, thereby contributing to vegetative growth. Similar positive effects of sulphur or nanosulphur on plant growth have been reported by Devi et al. (2022), Yadav et al. (2023) and Kamal et al. (2023).

The data presented in Table 2 show that the sulphur treatments significantly influenced the number of branches $plant^{-1}$ at 30 DAS. Treatment T_5 recorded the highest value (2.37 branches $plant^{-1}$) and was statistically at par with T_4 (2.35 branches $plant^{-1}$). The absolute control, T_6, recorded the lowest value (1.30 branches $plant^{-1}$). At 45 and 60 DAS, T_4 recorded the highest numbers of branches $plant^{-1}$ (4.75 and 5.08, respectively) and was statistically at par with T_5 (4.62 and 4.93, respectively). Treatment T_6 recorded the lowest values at both stages (2.87 and 3.09 branches $plant^{-1}$, respectively). The improvement in branching under sulphur application may be associated with enhanced nutrient availability and physiological activity, which promoted vegetative growth and lateral-branch development.

Table 2. Effect of biogenic synthesized nanosulphur on number of branches plant^{-1}

Treatments	Number of branches plant^{-1}		
	30 DAS	**45 DAS**	**60 DAS**
T_1: GRDF through Urea, DAP and MOP	2.19	3.75	3.99
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	2.30	4.02	4.28
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	2.32	4.25	4.53
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	2.35	4.75	5.08
T_5: GRDF+ 30kg S ha^{-1} (Bentonite sulphur)	2.37	4.62	4.93
T_6: Absolute control	1.30	2.87	3.09
SE (m) ±	**0.03**	**0.07**	**0.07**
CD at 5%	**0.09**	**0.21**	**0.21**

The greater number of branches plant^{-1} under T_4 may be attributed to improved sulphur availability through nanosulphur application, which enhanced nutrient uptake and physiological processes such as protein synthesis, photosynthesis and enzyme activity. Adequate sulphur nutrition also promotes nitrogen assimilation and vegetative growth, resulting in improved branch development. These findings are consistent with the positive responses to sulphur application reported by Dileep et al. (2021), Yadav et al. (2023), Saini et al. (2024) and Giri et al. (2025).

Table 3. Effect of biogenic synthesized nanosulphur on number of nodules plant^{-1}

Treatments	Number of Nodules plant^{-1}	
	45 DAS	**60 DAS**
T_1: GRDF through Urea, DAP and MOP	29.50	24.90
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	33.71	29.23
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	34.61	29.53
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	38.02	34.20
T_5: T_1 + 30kg S ha^{-1} (Bentonite sulphur)	40.25	35.12
T_6: Absolute control	26.66	15.93
SE (m) ±	**3.59**	**4.14**
CD at 5%	**NS**	**NS**

The data presented in Table 3 show that the number of nodules plant^{-1} at 45 and 60 DAS was not significantly influenced by the sulphur treatments. Sulphur is involved in nitrogen metabolism and symbiotic nitrogen fixation through enzymatic processes associated with nodule initiation and development. Positive effects of sulphur application on nodulation have also been reported by Nawange et al. (2011) and Das et al. (2016).

Table 4. Effect of biogenic synthesized nanosulphur on Dry matter accumulation plant^{-1} (g)

Treatments	Dry matter accumulation plant^{-1} (g)	
	45 DAS	**60 DAS**
T_1: GRDF through Urea, DAP and MOP	9.21	15.48
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	12.31	18.23
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	13.30	21.06
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	15.28	23.93
T_5: T_1 + 30kg S ha^{-1} (Bentonite sulphur)	14.69	23.11
T_6: Absolute control	7.06	10.61
SE (m) ±	**0.29**	**0.36**
CD at 5%	**0.90**	**1.09**

The data presented in Table 4 show that biogenically synthesised nanosulphur significantly influenced dry matter accumulation plant^{-1} in soybean. At 45 and 60 DAS, T_4 recorded the greatest dry matter accumulation (15.28 and 23.93 g plant^{-1}, respectively) and was statistically at par with T_5 (14.69 and 23.11 g plant^{-1}, respectively). The absolute control, T_6, recorded the lowest values (7.06 and 10.61 g plant^{-1} at 45 and 60 DAS, respectively).

The greater dry matter accumulation under T_4 may be attributed to enhanced sulphur availability through foliar nanosulphur application, which improved nutrient absorption and utilisation and supported photosynthetic activity and biomass production. Sulphur contributes to chlorophyll synthesis, protein formation, enzyme activation and other physiological processes associated with plant growth. The smaller particle size and higher surface area of nanosulphur may facilitate efficient absorption and utilisation within plant tissues. Similar increases in dry matter production or biomass following sulphur-based nano-formulation application were reported by Kabilan et al. (2025), Kamal et al. (2024), Cao et al. (2021) and Kamal et al. (2023).

Table 5. Effect of biogenic synthesized nanosulphur on chlorophyll SPAD value

Treatments	Chlorophyll SPAD value	
	30 DAS	45 DAS
T_1: GRDF through Urea, DAP and MOP	35.42	37.80
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	38.29	42.47
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	39.41	45.09
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	44.81	49.21
T_5: T_1 + 30kg S ha^{-1} (Bentonite sulphur)	42.42	47.79
T_6: Absolute control	31.44	34.39
SE (m) ±	**0.83**	**0.48**
CD at 5%	**2.51**	**1.45**

The data presented in Table 5 show that the sulphur treatments significantly influenced the SPAD value of soybean at 30 and 45 DAS. Treatment T_4 recorded the highest SPAD values (44.81 and 49.21 at 30 and 45 DAS, respectively) and was statistically at par with T_5 (42.42 and 47.79, respectively). The absolute control, T_6, recorded the lowest SPAD values (31.44 and 34.39 at 30 and 45 DAS, respectively).

The higher SPAD values under T_4 may be attributed to the efficient supply of sulphur through nanosulphur application, which enhanced chlorophyll synthesis and photosynthetic efficiency. The greater reactivity, smaller particle size and penetration ability of nanosulphur may have improved sulphur uptake and prolonged the maintenance of leaf chlorophyll. Because SPAD values provide an indirect indication of leaf chlorophyll and nitrogen status, improved sulphur availability may have contributed to the higher readings. Increased SPAD values following sulphur or nano-sulphur application have also been reported by Kabilan et al. (2025), Cao et al. (2021), Giri et al. (2025) and Yadav et al. (2026).

Table 6. Effect of biogenic synthesized nanosulphur on yield (kg ha^{-1}) of soybean

Treatments	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})
T_1: GRDF through Urea, DAP and MOP	2132	2920
T_2: T_1 + Foliar application of 25 ppm nanosulphur at 30 & 45 DAS	2364	3131
T_3: T_1 + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS	2424	3215
T_4: T_1 + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS	2551	3342
T_5: T_1 + 30kg S ha^{-1} (Bentonite sulphur)	2510	3285
T_6: Absolute control	1544	2142
SE (m) ±	**17.00**	**21.20**
CD at 5%	**51.00**	**63.90**

The data presented in Table 6 and Fig. 1 show that biogenically synthesised nanosulphur significantly influenced the seed and stover yields of soybean. Treatment T_4 recorded the highest seed and stover yields (2,551 and 3,342 kg ha^{-1}, respectively) and was statistically at par with T_5, which recorded 2,510 and 3,285 kg ha^{-1}, respectively. The absolute control, T_6, recorded the lowest seed and stover yields.

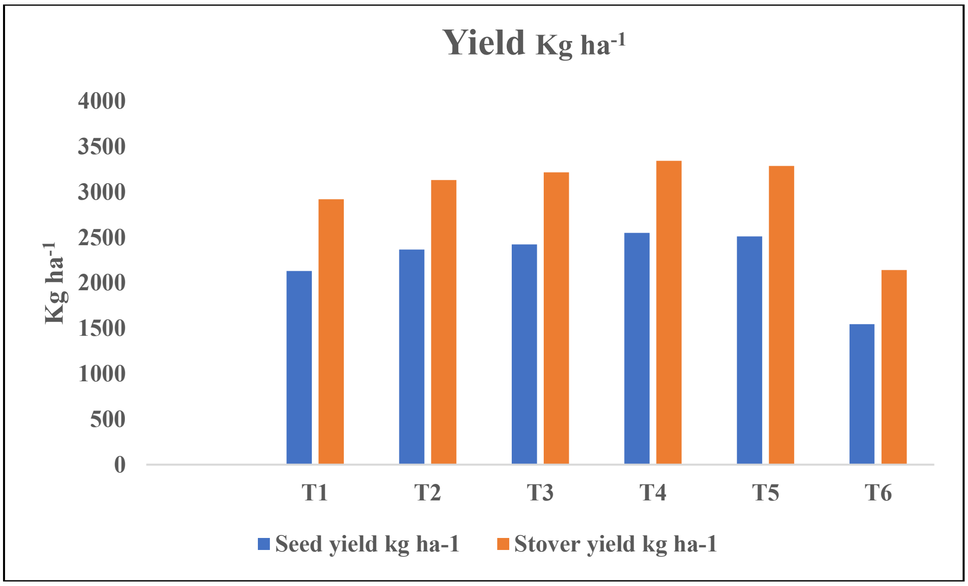

Fig. 1. Soybean Yield Response to Biogenic synthesized nanosulphur

The higher seed and stover yields under T_4 may be attributed to efficient foliar absorption and utilisation of nanosulphur, which ensured timely sulphur availability during critical growth stages. Nano-sized sulphur particles have a high surface area, reactivity and penetration ability, which may enhance nutrient-use efficiency compared with conventional sulphur sources. Foliar application may also reduce losses associated with soil-applied sulphur, including fixation, leaching and microbial immobilisation, thereby increasing plant availability (Subramanian et al., 2022). Adequate sulphur nutrition supports chlorophyll synthesis, photosynthetic activity, protein formation and enzyme activation, which may improve vegetative growth, dry matter accumulation, pod formation and seed development.

The improved yield performance under T_4 may also be associated with interactions between sulphur and nitrogen metabolism, because sulphur is required for the synthesis of sulphur-containing amino acids and proteins that influence seed development. The greater stover yield indicates increased biomass production associated with improved physiological activity and nutrient assimilation. Kabilan et al. (2025) similarly reported that foliar nanosulphur applied with recommended NPK enhanced dry matter production, pod development and yield attributes. Improvements in crop yield following sulphur application have also been reported by Choudhary et al. (2024), Balagangathar et al. (2024), Giri et al. (2025) and Yadav et al. (2026).

4. Conclusion

The study demonstrated that the general recommended dose of fertilisers combined with foliar application of 75 ppm biogenically synthesised nanosulphur at 30 and 45 days after sowing produced the strongest overall growth and yield response in soybean. This treatment recorded a seed yield of 2,551 kg ha^{-1} and a stover yield of 3,342 kg ha^{-1}. Its performance was statistically comparable with that of the treatment receiving the recommended fertiliser dose plus 30 kg S ha^{-1} through bentonite sulphur, which produced 2,510 kg ha^{-1} seed yield and 3,285 kg ha^{-1} stover yield. The 75 ppm nanosulphur treatment also supported greater plant height, branches plant^{-1}, dry matter accumulation plant^{-1} and chlorophyll SPAD values during the later growth stages. However, nodule number did not differ significantly among sulphur treatments. Under the soil, weather and management conditions of this field experiment, foliar application of 75 ppm biogenically synthesised nanosulphur therefore provided a response comparable with conventional bentonite sulphur while using a foliar nano-formulation. Further validation across seasons and locations is required before broader recommendations are made.

5. Limitations

The experiment was conducted during one Kharif season at a single rainfed location using one soybean variety. Consequently, the observed treatment responses may be specific to the prevailing soil, weather and crop-management conditions. The study compared three nanosulphur concentrations with one conventional sulphur treatment but did not evaluate multi-season consistency. Validation across additional locations, seasons, soil types and soybean varieties is therefore required before the findings are generalised.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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