

<https://doi.org/10.48047/AFJBS.7.4.2025.236-249>



African Journal of Biological Sciences

Journal homepage: <http://www.afjbs.com>



Research Paper

Open Access

Impact of zinc fertilization and solubilizing microorganism on growth and productivity of soybean in Nagaland

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Volume 7, Issue 4, Apr 2025

Received: 15 Feb 2025

Accepted: 05 Mar 2025

Published: 05 Apr 2025

[doi:10.48047/AFJBS.7.4.2025.236-249](https://doi.org/10.48047/AFJBS.7.4.2025.236-249)

Abstract

An experiment on soybean was conducted during the Kharif seasons of 2021 and 2022 at the experimental field of the School of Agricultural Sciences, Nagaland University, Medziphema. The field trial was laid out in a Randomized Block Design (RBD) with fourteen treatment combinations and three zinc (Zn) sources. ZnSO₄·7H₂O, ZnO, and EDTA-Zn @ 5, 7.5 kg ha⁻¹, along with and without a zinc-solubilizing microorganism (ZSM), *Bacillus subtilis* @ 7.5 kg ha⁻¹, and replicated thrice. The result revealed that Zn fertilized with ZSM @ 7.5 kg ha⁻¹ made plant height progressively increased with crop growth stages, ranging from 10.6 to 14.9 cm at 25 days after sowing (DAS) and exhibiting a similar trend at 50 and 75 DAS, also demonstrated a 21.09% increase over the control at harvest. Further, the number of nodules, fresh and dry weight of nodules at the time of flowering were also found highest at T₆ and least in control. Also, the 7.5 kg ha⁻¹ Zn application as ZnSO₄ 7H₂O + ZSM (T₆) had 6.4 to 33.4% greater number of pods plant⁻¹ and number of filled pods plant⁻¹, but no significant difference was observed for test weight. In both the years, the seed and stover yield was recorded highest under T₆ (1661 kg ha⁻¹) followed by T₅ (1640 kg ha⁻¹), T₄ (1591 kg ha⁻¹) and least under T₁ (1013.50 kg ha⁻¹).

Keywords: *Bacillus subtilis*, soybean growth, nodulation, yield, zinc fertilizer, zinc solubilizing microorganism

Introduction

Soybean (*Glycine max*) is a potential multifaceted legume and oilseed crop, widely grown in the tropical, subtropical, and temperate climates. It is a rich source of protein, oil, vitamins, minerals, and other macronutrients, of which it contains ~40-45% protein and 20% oil (Ibrahim and Kandil, 2007). It is used in many ways, as a staple in human and animal diets,

paper, textiles and pharmaceutical industries, and as a medicinal crop, thus often referred to as a “Wonder crop”. India ranks fifth in the world in soybean production, accounting for 3 % of total production (USDA), and cultivation is mainly concentrated in Madhya Pradesh, Maharashtra, Rajasthan and Telangana (Srivastava and Mishra, 2014). The country has a total area under cultivation and production of 11.4 million hectares (Mha) and 10.9 million tonnes (MT), with an annual productivity of 2300 kg ha⁻¹ (Anon., 2020). In the northeastern region, particularly in Nagaland, soybean is mainly grown in jhumlands, which cover an area of 25 ha, with an average annual productivity of 1250 kg ha⁻¹ (Statistical Handbook of Nagaland, 2018). However, the productivity of soybean in this region is still low compared to the other major soybean producing states due to inappropriate nutrient management practices (Raghuwanshi, 2017). This limitation could be addressed through appropriate nutrient management strategies that can improve the yield potential of soybean. Among the nutrients, Zn is an important micronutrient directly involved in physiological and metabolic processes (Cakmak, 2008), making soil Zn availability a critical determinant of crop productivity and human nutrition. However, globally, soil Zn deficiency is reported approximately 30% of the cultivated land, widespread in regions including South Asia, sub-Saharan Africa and parts of Latin America (Alloway, 2008). According to Singh et al., 2022, in Indian soils, nearly 50% of arable lands are deficient in Zn, primarily due to intensive cropping, imbalanced fertilizer uses etc. Zn performs many catalytic and regulatory functions in various biochemical pathways including transformation of carbohydrates, chlorophyll and protein synthesis, auxin (growth regulator) metabolism, pollen formation, maintenance of the integrity of biological membranes nucleic acid and lipid metabolisms (Kelaestaghi *et al.* 2007). Therefore, the deficiency of Zn delays photosynthesis and N metabolism, reduces flowering, and prolongs growth periods.

The deficiency could be managed by adopting appropriate strategies that involve selecting the correct rate, source, timing and method of application (Roberts, 2007). Many organic and inorganic forms of Zn fertilizers viz., ZnSO₄, ZnO, Zn₃(PO₄)₂, chelated Zn etc. are commonly used to enhance Zn nutrition in crops. However, its effectiveness varies depending on the form of Zn fertilizer that exhibit differences in their solubility and plant availability (Ramesh et al., 2014). Notably, only 1-5% of applied Zn fertilizer is utilized by crop and ~95% is converted to less soluble forms such as zinc hydroxide, zinc carbonate, zinc phosphate, zinc sulphide, etc, thereby reducing its bioavailability. Hence, incorporation of beneficial bioinoculants, ZSM along with zinc fertilizers is an effective strategy that necessitates the release of ionic zinc for better plant uptake (Shafigh *et al.* 2019) through biochemical actions of the inoculated microorganisms (Singh and Prasanna 2020) and Zn availability and promote

low input and sustainable agricultural practices (Kushwaha *et al.* 2021). In this context, the present study hypothesized that integrating different Zn fertilizer sources with ZSM through soil application would improve the growth, nodulation and yield of soybean under the agro-climatic conditions of Nagaland.

Materials and method

Experimental site

The fixed-plot experiment on soybean was conducted at the experimental farm of School of Agriculture Sciences (SAS), Medziphema, 25° 45' 43" N and 95° 53' 4" E, at 310 m above mean sea level (MSL) for the two consecutive years i.e., 2021 and 2022. The experimental site falls under sub-tropical zone having hot summer and cold winter. Throughout the experimentation from June to September, an average annual rainfall of ~1069.8 mm was received. The monthly mean maximum and minimum temperatures ranged between 33.4 to 33.6°C and 11.7 to 16°C, respectively. The soil of the experimental site was sandy clay loam in texture and strongly acidic soil pH of 5.01. Further, the initial physico-chemical properties of the soil and the procedure followed for the analysis are presented in Table 1.

Table 1 Initial physico-chemical and biological properties of the soil

Soil properties	Content
B _D (g cm ⁻³)	1.43
Soil pH	5.01
Soc (g kg ⁻¹)	6.60
N (kg ha ⁻¹) (KMnO ₄ -oxidizable N)	218.3
P (kg ha ⁻¹) (0.03 N NH ₄ F + 0.025 N HCl extractable P)	15.0
K (kg ha ⁻¹) (1N NH ₄ OAc exchangeable K)	126.6
S (kg ha ⁻¹)	14.3
Zn (mg kg ⁻¹) (0.005 M DTPA extractable Zn)	0.43

Treatment details

The field experiment was set up in a randomized block design (RBD) with three (03) replications with an individual plot dimension of 2.25 m x 2.0 m. The soybean variety JS 97-52 was sown in line at a spacing of 45 cm x 10 cm. Plant protection measures was taken at necessary intervals against weeds, pests and diseases. The experiment consisted of 14 treatments in combination with Zinc fertilizer from three different sources viz. Zn 21% (ZnSO₄

7 H₂O); Zn-EDTA 12%; and ZnO 80% at two different doses i.e. 5 kg ha⁻¹ and 7.5 kg ha⁻¹ with and without ZSM i.e. *Bacillus subtilis*, which was obtained from Department of Soil Microbiology, Assam Agricultural University (AAU), Jorhat. The treatment details are T₁: Control, T₂: ZSM, T₃: 5 kg ha⁻¹ Zn (ZnSO₄).7H₂O, T₄: 5 kg ha⁻¹ Zn (ZnSO₄).7H₂O + ZSM, T₅: 7.5 kg ha⁻¹ Zn (ZnSO₄).7H₂O, T₆: 7.5 kg ha⁻¹ Zn (ZnSO₄).7H₂O + ZSM, T₇: 5 kg ha⁻¹ Zn (ZnO), T₈: 5 kg ha⁻¹ Zn (ZnO) + ZSM, T₉: 7.5 kg ha⁻¹ Zn (ZnO), T₁₀: 7.5 kg ha⁻¹ Zn (ZnO) + ZSM, T₁₁: 5 kg ha⁻¹ Zn (EDTA-Zn), T₁₂: 5 kg ha⁻¹ Zn (EDTA-Zn) + ZSM, T₁₃: 7.5 kg ha⁻¹ Zn (EDTA-Zn) and T₁₄: 7.5 kg ha⁻¹ Zn (EDTA-Zn) +ZSM. Before sowing of soybean crop, ZSM was applied to selective plots according to the treatment combinations @ 7.5 kg ha⁻¹. The recommended dose of fertilizers @ 20: 80: 40: 30: (N, P₂O₅, K₂O, S) kg ha⁻¹, was applied in each of the experimental plots.

Growth, nodulation, and yield attributes

Plant height

Every year, the height of five randomly selected and tagged plants from the middle rows was recorded at various growth stages: 25, 50, 75, and 100 DAS and at harvest.

Number of nodules plant⁻¹

At the flowering stage, five randomly selected plants per plot were uprooted, and roots were immersed in water to separate nodules, followed by gentle washing. The number and fresh weight (FW) of nodules were recorded, and dry weight (DW) was determined after oven drying.

Number of pods plant⁻¹,

The total number of pods per plant was counted from tagged plants, and the average was computed.

Number of seeds pod⁻¹, and

The number of seeds per pod was recorded from tagged plants, and the average was calculated.

Test weight

A random sample of 1000 filled seeds from each plot was counted and weighed using an electric balance and expressed in grams (g).

Yield

Seed and stover yield (kg ha⁻¹)

The seed yield was determined from the net sampling area ($1 \text{ m} \times 1 \text{ m}^2$) situated in the middle of each plot leaving the border rows and was sun dried, and their biological yield (seed + stover) was recorded. The seed yield for each plot was then converted to yield ha^{-1} . Stover yield was calculated by subtracting seed yield from the total biomass.

Statistical analysis

The results were subjected to normality and homogeneity tests followed by an analysis of variance (ANOVA) using f-test under the randomized block design (Gomez and Gomez, 1984).

Result and discussion

Plant height

The different Zn fertilizers with and without ZSM had a significant ($p < 0.05$) impact on plant height in both the years (Table 2). The plant height of soybean increases with increasing crop growth stages during the experimentation. At 25 DAS, the plant height ranged from 10.6 to 14.9 cm and 10.5 to 15 cm in the respective years. The pooled data revealed that, the T₆ had produced tallest plant (15.03 cm), followed by T₄ (14.06 cm) and T₅ (13.89 cm) while, the least values were registered in T₁ and T₇. Similarly, the plant height at 50 and 75 DAS showed the similar trend as in 25 DAS. Overall, at 50 and 75 DAS T₆ had 2.5 to 25.9% greater plant height than the control. Again, at harvest, T₆ produced the tallest plants closely followed by T₄ and T₅ and it produced 21.09% greater height than the control (T₁). Among the Zn fertilizers, ZnSO₄ 7 H₂O + ZSM (*Bacillus subtilis*) significantly ($p < 0.05$) enhances the height of soybean than the EDTA-Zn and zinc oxide (ZnO), which might be primarily ascribed to its superior bio-availability, and solubility in soil (Torres *et al.*, 2021). Zn as an essential micro-nutrient plays an important role in cell elongation, differentiation and metabolism leading to enhance plant growth (Raghuwanshi *et al.*, 2017). Furthermore, Zn is responsible for increasing the rate of photosynthesis and chlorophyll formation, thereby accelerating plant meristem activity, which leads to an increase in internode length (Maurya *et al.*, 2010). Besides this, it enhances auxin metabolism, leading to increased cell division, elongation, and root and shoot development ultimately increased plant height of soybean (Krishna, 2007; Maurya *et al.*, 2010). Our results of increasing plant height were also in line with the findings of Shivay *et al.* (2010); Tayyeba *et al.* (2017) and Deotale *et al.*, (1998), who observed that zn fertilization aid in various physiological processes. Additionally, Habbasha *et al.* (2013) revealed that, the foliar

application of ZnSO₄ increases plant growth in chickpea, emphasising the role of ZnSO₄ in enhancing plant height due to its superior soil absorption and nutrient delivery system.

Table 2 Effect of zinc and zinc-solubilizing microorganism on plant height of soybean during two years of experimentation

Treatments	Plant height (cm)											
	25 DAS			50 DAS			75 DAS			Harvest		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T ₁	10.6	10.5	10.62	30.5	30.5	30.54	43.3	43.0	43.15	40.2	40.4	40.32
T ₂	11.4	11.8	11.67	33.8	33.7	33.78	46.6	46.8	46.74	43.2	43.4	43.36
T ₃	13.7	13.6	13.72	35.8	36.0	35.94	52.6	52.7	52.71	46.7	47.5	47.15
T ₄	14.1	14.0	14.06	38.3	38.2	38.27	56.5	55.6	56.09	51.3	50.8	51.10
T ₅	13.7	14.0	13.89	37.1	37.3	37.23	55.1	55.1	55.13	49.4	49.0	49.26
T ₆	14.9	15.0	15.03	41.4	40.9	41.23	57.2	57.8	57.53	50.7	51.2	50.99
T ₇	10.8	10.9	10.89	32.7	33.0	32.90	45.1	44.6	44.92	41.3	41.5	41.40
T ₈	11.4	11.5	11.54	34.1	33.8	34.00	47.0	46.8	46.97	39.6	38.6	39.17
T ₉	11.3	11.6	11.48	33.1	32.9	33.04	46.5	46.3	46.43	40.6	39.4	40.05
T ₁₀	11.7	11.6	11.71	34.2	34.5	34.38	48.6	49.0	48.83	39.8	42.0	40.96
T ₁₁	11.6	11.7	11.69	33.8	33.7	33.82	48.3	48.5	48.45	41.6	42.4	42.03
T ₁₂	12.2	12.6	12.46	34.5	34.6	34.63	49.1	50.1	49.60	41.6	41.8	41.72
T ₁₃	12.5	12.5	12.56	34.8	34.1	34.46	48.9	49.2	49.10	43.2	43.0	43.13
T ₁₄	13.0	13.2	13.12	35.6	35.2	35.47	50.1	50.0	50.11	45.8	44.8	45.36
Sem±	0.58	0.53	0.39	1.03	1.49	0.91	1.46	2.10	1.28	1.95	1.61	1.26
CD at 5%	1.69	1.55	1.12	3.00	4.34	2.58	4.23	6.11	3.63	5.67	4.67	3.59

Note: DAS = Days after sowing

Nodulation

The data on the number of nodules plant⁻¹, fresh, and dry weight of the nodules is presented in Table 4. The results indicate a significant ($p < 0.05$) impact of Zn combined with ZSM on nodulation. The highest number of nodules plant⁻¹ was documented in T₂, and least in un-inoculated plots. On average T₂ had 3.68-33.57% greater number of nodules plant⁻¹ than the other treatments. The inoculated treatments with graded levels of Zn as ZnSO₄. 7H₂O also showed an increase in the number of nodules plant⁻¹ with each incremental dose of zinc up to 7.5 kg Zn ha⁻¹. Similarly, regarding fresh weight of the nodules, T₂ produced the maximum weight, which was in tune of 12.22 to 51.14% higher than the remaining treatments. While, the dry weight of the nodules was registered maximum in T₆, which was 10.53 to 63.16% in first and 20 to 53.33% in second year greater than the remaining treatments. The higher number of nodules, fresh and dry weight of nodules plant⁻¹ with ZnSO₄. 7H₂O+ZSM could be attributed to the improved availability of zinc during the critical nodulation period of soybean (El-Azouni, 2008). Similarly, the application of *Bradyrhizobium japonicum* with *Bacillus megaterium* and *methylobacterium oryzae* exhibited an increase in nodule number and nodules activity as reported by Subramanian *et al.* (2015). Further, the Zn plays a significant role in improving leghaemoglobin synthesis, and leghaemoglobin content, besides enhancing rooting system; and thus improves nodulation in legume crops (Das *et al.*, 2012, Edulamudi *et al.*, 2019). Srivastava

et al. (2006) also reported a higher number of nodules with the application of *Rhizobium* inoculation with 30 kg S and 5 kg Zn ha⁻¹ due to the favourable edaphic environment for nitrogen-fixing bacteria. In chickpea, the application of 10, and 25 kg ZnSO₄ ha⁻¹ increased the nodule dry weight by 2.75 to 16.87% and 4.27 to 32.82%, respectively as compared to control plot suggesting that Zn enhances the rooting traits like root length, and volume etc. thereby promoting nodulation Das *et al.* (2012). Similar, results were also observed by Tiwari *et al.* (2018). Debnath (2018) and Ahlawat *et al.* (2007) also noted a significant increase in nodule dry weight at 60 DAS with the combined application of RDF + Zn @7.5 kg ha⁻¹ over the RDF alone. Further, Upadhyay *et al.* (2016) also revealed a higher fresh weight of nodules with the use of 5.0 kg Zn ha⁻¹ in cluster bean and 15 kg Zn ha⁻¹ in cowpea compared to the control plots. Similarly, Gour *et al.* (2014) also reported higher nodulation and fresh weight with the application of 100% RDF+ ZnSO₄ at 25 kg ha⁻¹ + MgSO₄ at 25 kg ha⁻¹.

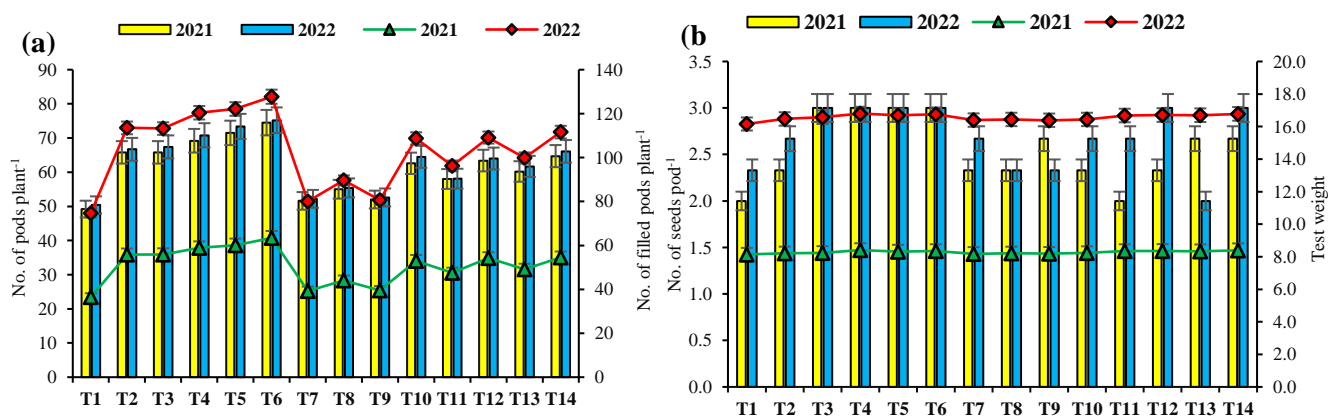
Table 3 Effect of zinc, and zinc solubilizing micro-organism on nodule number, fresh (FW) and dry weight (DW) during two years of experimentation.

Treatments	No. of nodules plant ⁻¹			FW (g)			DW (g)		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T ₁	18.6	19.8	19.20	0.43	0.45	0.44	0.07	0.07	0.07
T ₂	28.0	27.2	27.60	0.88	0.90	0.89	0.14	0.12	0.13
T ₃	22.1	24.1	23.12	0.62	0.64	0.63	0.17	0.10	0.14
T ₄	23.8	25.5	24.65	0.65	0.70	0.68	0.12	0.14	0.13
T ₅	25.0	25.7	25.39	0.69	0.68	0.69	0.17	0.12	0.15
T ₆	25.5	26.2	25.89	0.77	0.79	0.78	0.19	0.15	0.17
T ₇	18.9	19.0	18.99	0.48	0.45	0.47	0.10	0.09	0.09
T ₈	20.0	21.0	20.50	0.55	0.56	0.55	0.13	0.09	0.11
T ₉	19.8	21.9	20.85	0.54	0.61	0.57	0.08	0.09	0.09
T ₁₀	20.5	21.9	21.20	0.56	0.58	0.57	0.11	0.11	0.11
T ₁₁	20.5	21.3	20.94	0.56	0.59	0.58	0.12	0.12	0.12
T ₁₂	20.5	21.4	20.95	0.58	0.61	0.59	0.11	0.14	0.13
T ₁₃	21.8	22.2	22.04	0.59	0.60	0.60	0.11	0.16	0.13
T ₁₄	23.1	23.6	23.39	0.63	0.65	0.64	0.10	0.16	0.13
Sem±	1.21	1.30	0.89	0.03	0.03	0.02	0.01	0.01	0.0043
CD at 5%	3.53	3.77	2.52	0.10	0.10	0.07	0.02	0.02	0.01

Yield attributes

Among the treatments, the number of pods plant⁻¹ varied from 49.82 to 74.87 and T₆ had the maximum number of pods plant⁻¹ i.e. 74.5 in first year and 75.2 in second year, which

was 50.3% greater than the T₁ irrespective of the years (Fig 1). With regards to number of filled pods plant⁻¹ similar trend was observed in which T₆ registered the maximum values of 63.4 and 64.3, which was in tune of 71.0% greater than the T₁ in both years. The critical analysis of data revealed a non-significant ($p < 0.05$) variation in seeds pod⁻¹ and 1000 seed weight across the years, although the highest number of seed pod⁻¹ was observed in T₃₋₆ and lowest with control. Similarly, the regarding 1000 seed weight T₆ gave the highest value and the lowest in T₁ during the experimentation. It has been reasoned out that, the improvement in yield-attributes viz. no. of pods plant⁻¹, no. of filled pods plant⁻¹, no. of seeds pod⁻¹, and 1000 seed weight (g) could be associated to critical role of Zn in the biosynthesis of indole-3-acetic acid (IAA), which regulates auxin and initiates primordia for reproductive growth (Michail *et al.*, 2004). In addition, the Zn augment enzyme activity and thus promoting an efficient translocation of metabolites from source to sink and results in greater yield attributes (Raghuwanshi *et al.*, 2017). Similarly, Meena *et al.* (2017) suggested that, the higher number of pods plant⁻¹ might be attributed to a greater number of branches, and dry matter accumulation plant⁻¹. Further, Singh *et al.* (2012), also reported that, the combined application of ZnSO₄ with FYM in chickpea substantially increased the number of pods plant⁻¹ by 17% than the no Zn application. Similarly in common bean, the soil application of ZnSO₄ at 20 kg Zn ha⁻¹ led to the highest number of pods plant⁻¹ (Nadergoli *et al.*, 2011). As per Ram *et al.* (2011) the application of Zn stimulated both vegetative and reproductive growth, thereby improving yield-related traits in mung bean. Additionally, Masih *et al.* (2020) noted a significant rise in the number of pods plant⁻¹ under similar Zn treatments.



during two years of experimentation.

Yield

Seed and stover yield

The different treatments had a significant ($p < 0.05$) impact on the seed yield of soybean (Table 4). The soybean seed yield varies from 1007 to 1669 kg ha⁻¹ across the treatments. However, T₆ produced the maximum seed yield 1654 and 1669 kg ha⁻¹, in the respective years, but it remained statistically at par with T₅ (1634, 1647 kg ha⁻¹), followed by T₄ (1586, 1595 kg ha⁻¹), T₃ (1503, 1515 kg ha⁻¹) and T₂ (1519, 1489 kg ha⁻¹). The increment in seed yield in T₆ and T₅ was in tune of 4.11-39.12% greater than the remaining treatments. Further, the Zn fertilization combined with a ZSM significantly ($p < 0.05$) influenced the stover yield of soybean (Table 4.4). Across the years, the stover yield ranged from 1250 to 2063 kg ha⁻¹ and following the trend T₆ (2045, 2063 kg ha⁻¹) > T₅ (1998, 2013 kg ha⁻¹) > T₄ (1967, 1982 kg ha⁻¹) > T₃ (1889, 1903 kg ha⁻¹) > T₂ (1864, 1872 kg ha⁻¹). In T₆, the overall increment in stover yield was 3.81 to 38.92% greater than the others in both the years. The possible reason for the increment in seed and stover yield might be ascribed to abundant supply of zinc, which enhanced the protoplasmic content which in turn facilitated cell division and elongation, improved photosynthesis, respiration and other bio-chemical and physiological processes (Maurya *et al.*, 2010). Further, Zn application increases yield attributes, grain and stover yield through translocation of photosynthates to reproductive parts (Shivay *et al.*, 2008; Ozkutlu *et al.*, 2006). Since, T₆ had a higher crop growth, and yield attributing characters that might help in improving grain and stover yield of soybean. Besides this, being a legume crop it also fixes atmospheric nitrogen and helps in enhancing the soil physico-chemical and biological properties which might have help in obtaining greater seed and stover yield (Pooniya *et al.*, 2012). Furthermore, the ZnSO₄·7H₂O proved to be more effective than ZnO in pollen germination, seed formation and increased fertility percentage; which in turn increased seed formation and thus enhances seed yield (Kanase *et al.*, 2008; Shivay *et al.*, 2008). Similarly, Nayyar *et al.* (2001) reported that ZnO was less effective than zinc sulfate heptahydrate in increasing seed yield in rice, due to the superior solubility of ZnSO₄·7H₂O. Further, the inoculation of *Bradyrhizobium japonicum* strains SB-12 and various isolates of *Pseudomonas*, both individually or in combination improved soybean yield due to a reduction in soil pathogen infection and improved seedling emergence (Zaidi and Singh 2001). Goudar *et al.* (2008) also found greater grain yield of soybean by seed inoculation with *Bradyrhizobium japonicum* strains and the application of micro-nutrients.

Table 4 Effect of zinc, and zinc solubilizing microorganism on seed and stover yield of soybean during two years of experimentation

Treatments	Seed yield (kg ha ⁻¹)			Stover yield (kg ha ⁻¹)		
	2021	2022	Pooled	2021	2022	Pooled

T ₁	1007	1019	1013.50	1250	1260	1255.67
T ₂	1519	1489	1504.17	1864	1872	1868.20
T ₃	1503	1515	1509.67	1889	1903	1896.72
T ₄	1586	1595	1591.17	1967	1982	1974.88
T ₅	1634	1647	1640.83	1998	2013	2006.33
T ₆	1654	1669	1661.67	2045	2063	2054.53
T ₇	1178	1186	1182.33	1460	1471	1466.23
T ₈	1253	1257	1255.33	1537	1543	1540.55
T ₉	1250	1256	1253.17	1471	1479	1475.65
T ₁₀	1323	1295	1309.67	1615	1622	1618.97
T ₁₁	1309	1292	1301.00	1589	1600	1594.60
T ₁₂	1330	1340	1335.50	1632	1644	1638.53
T ₁₃	1279	1284	1281.83	1599	1607	1603.20
T ₁₄	1394	1401	1397.83	1790	1799	1794.98
Sem±	69.0	55.8	44.40	70.9	70.4	49.97
CD at 5%	200.6	162.4	125.99	206.1	204.7	141.82

Conclusion

The study highlights the significant role of Zn fertilization, particularly ZnSO₄·7H₂O combined with ZSM, in enhancing soybean growth, nodulation, and yield. Among the treatments, 7.5 kg ha⁻¹ ZnSO₄·7H₂O + ZSM (T₆) consistently exhibited superior performance in terms of plant height, number of pods per plant, seed yield, and stover yield, demonstrating increases of up to 39.12% and 38.92%, respectively, over the control. The improved nodulation in inoculated treatments, particularly T₂, underscores the synergistic effect of Zn and microbial inoculation in enhancing biological nitrogen fixation. Furthermore, Zn application played a crucial role in physiological and biochemical processes, including auxin metabolism, photosynthesis, and enzyme activation, contributing to better translocation of assimilates and improved reproductive efficiency. The results confirm that ZnSO₄·7H₂O, in combination with ZSM, offers a promising strategy for optimizing soybean productivity by improving nutrient bioavailability and soil microbial activity. Future studies should explore the long-term impact of Zn fertilization on soil health and nutrient cycling to refine sustainable agronomic practices.

Declaration of competing interest: The authors report no declarations of interest.

Acknowledgements: We acknowledged the Dean, School of Agricultural Sciences, Nagaland University for the financial support and for providing necessary field and laboratory facilities.

Author's contribution: All authors contributed equally.

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