



Evaluation of Agronomic Biofortification on Yield, Quality and Nutrient Acquisition of Soybean [*Glycine max* (L.) Merrill] in the Mid-hills of Nagaland

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ABSTRACT

Background: Sulfur (S) and zinc (Zn) are vital nutrients for oilseed crops like soybean, significantly influencing their growth, yield and quality. Sulfur is essential for protein synthesis, enzyme function and chlorophyll formation, which are crucial for the overall health and productivity of the plant. Zinc, on the other hand, plays a critical role in enzyme activation, hormone regulation and protein synthesis. It enhances disease resistance and stress tolerance in soybeans.

Methods: During the *kharif* seasons of 2017 and 2018, a field experiment was carried out at Nagaland University to evaluate the influence of different sulfur and zinc levels on soybean. The treatments consisted of three sulfur levels (0, 20 and 40 kg ha⁻¹) and five zinc levels (0, 5, 10, 15 and 20 kg ha⁻¹) arranged in a factorial randomized block design.

Result: The findings showed that the use of 20 kg S ha⁻¹ along with 20 kg Zn ha⁻¹ greatly enhanced parameters for growth, yield attributes, seed quality and nutrient uptake. These findings suggest that balanced application of sulfur and zinc is an effective strategy for enhancing soybean productivity under rainfed conditions.

Key words: Agronomic biofortification, Nutrient uptake, Soybean, Sulfur, Yield, Zinc.

INTRODUCTION

One important oilseed crop in the world is soybeans [*Glycine max* (L.) Merrill], valued for its high nutritional and economic significance. It contains approximately 40% protein and 18-22% oil, along with a well-balanced amino acid composition and several extractable bioactive compounds (FAO, 1982). Owing to these characteristics, soybean is widely utilized in human diets, livestock feed and various industrial applications. In India, it is primarily cultivated during the *kharif* season and contributes nearly 35-65% of the total oilseed production (Sharma *et al.*, 2022; Gathiye *et al.*, 2022). The productivity and quality of soybean are strongly influenced by the availability of essential nutrients in the soil. Among these, secondary nutrients and micronutrients play a vital role in regulating physiological and biochemical processes within the plant system. Proteins, enzymes and amino acids all require sulphur and it is also involved in chlorophyll formation and oil synthesis (Marshner, 2005). Zinc, on the other hand, is required for several enzymatic activities and plays a crucial role in auxin synthesis, protein metabolism and maintenance of membrane integrity, thereby contributing to overall plant growth and development.

In recent years, deficiencies of sulfur and zinc have become increasingly common in agricultural soils, particularly under intensive cropping systems. Sulfur deficit has been extensively documented in Indian soils, particularly in soils with light textures with little organic matter and high drainage capacity (Jamal *et al.*, 2005; Waddoups, 2011). Similarly, zinc deficiency is a major constraint affecting crop productivity, with nearly half of the

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cultivated soils in India reported to be deficient in zinc (Sharma, 2008). The situation is even more severe in the northeastern region of India, where acidic soils, high rainfall and leaching losses significantly reduce nutrient availability (Bandyopadhyay *et al.*, 2018). The underlying causes of these deficiencies include continuous nutrient mining, imbalanced fertilizer application, low organic matter content and unfavorable soil conditions such as high concentrations of iron and aluminum oxides, which restrict nutrient availability. These constraints not only limit crop productivity but also affect the nutritional quality of produce. To overcome these challenges, agronomic biofortification has emerged as an effective strategy to enhance the concentration of essential nutrients in crops. Biofortification involves increasing the bioavailability of nutrients in the edible parts of plants through genetic or agronomic approaches (White and Broadley, 2005). Among these, zinc

biofortification has gained considerable attention due to its potential to alleviate zinc deficiency in human populations. Studies have shown that increasing zinc content in crops such as soybean can significantly improve grain nutritional quality and help address micronutrient malnutrition (Bouis and Saltzman, 2017). Despite the well-recognized importance of sulfur and zinc in plant nutrition, there is limited information available on their combined effects under the specific agro-climatic conditions of northeastern India. Variability in soil characteristics, rainfall patterns and nutrient dynamics necessitates location-specific research to optimize nutrient management practices. Therefore, a detailed understanding of how sulfur and zinc influence growth, yield, quality and nutrient uptake of soybean under these conditions is essential. In light of the aforementioned factors, the current study was conducted to assess the impact of varying sulfur and zinc concentrations on the growth performance, yield characteristics, quality metrics and nutrient uptake of soybeans cultivated under rainfed circumstances in Nagaland's mid-hills.

MATERIALS AND METHODS

During the *kharif* seasons of 2017 and 2018, the field experiment was conducted at the Agronomy Research Farm of the Department of Agronomy, School of Agricultural Sciences, Nagaland University, Medziphema, Nagaland, India. The experimental site is geographically situated at 25°45'43" N latitude and 95°53'04" E longitude at a height of roughly 360 meters above mean sea level. The experimental field's soil had a sandy loam texture with an acidic reaction (pH 4.9) and contained 1.46% organic carbon. The initial available nutrient status of the soil was 340.86 kg ha⁻¹ N, 18.25 kg ha⁻¹ P₂O₅, 226.82 kg ha⁻¹ K₂O, 15.3 kg ha⁻¹ S and 0.48 mg kg⁻¹ Zn. A factorial randomised block design (FRBD) with three replications was used to set up the experiment. Three sulphur levels (0, 20 and 40 kg ha⁻¹) and five zinc levels (0, 5, 10, 15 and 20 kg ha⁻¹) were used as treatments (Cochran and Cox, 1957).

JS 97-52 soybeans were planted on 8 July 2017 and 11 July 2018. Prior to sowing, seeds were treated with Bavistin fungicide at the rate of 2 g kg⁻¹ seed and inoculated with *Rhizobium japonicum* at 2 g kg⁻¹ seed. The treated seeds were shade-dried for approximately one hour before sowing. Seeds were planted at a depth of 1.5-2.0 cm, keeping plant spacing at 10 cm and row spacing at 40 cm. All plots received a homogeneous application of the prescribed baseline dose of 20-60-40 kg N-P₂O₅-K₂O ha⁻¹ using DAP and MOP. Sulfur was applied in the form of elemental sulfur (90% S), while zinc was supplied as zinc oxide (70% Zn) according to treatment levels.

To promote healthy germination and crop establishment, irrigation was provided right away after seeding. Depending on the amount of rainfall, additional irrigations were given as needed. From each plot, five plants were chosen at random to record growth and yield

observations. When the crop reached physiological maturity, as indicated by yellowing leaves and hardened seeds, it was manually harvested. The harvested produce was sun-dried and pods were separated, dried, threshed and cleaned manually. Plant height and dry matter accumulation were recorded at harvest. Grain and stover yields were calculated on a net plot basis and expressed in tonnes per hectare (t ha⁻¹).

Nitrogen concentration was multiplied by a conversion factor of 6.25 to determine the crude protein content (%) following standard procedures (A.O.A.C. 1955). Oil content was determined using the Soxhlet extraction method (A.O.A.C. 1960). Nitrogen content in plant samples was analyzed using the Micro-Kjeldahl method (Jackson, 1973). Using a spectrophotometer and the vanadomolybdo-phosphoric acid yellow colour technique, phosphorus was measured (Jackson, 1973). Potassium content was measured using a flame photometer, while zinc concentration was estimated using an atomic absorption spectrophotometer (Lindsay and Norvell, 1978). The turbidimetric method (Chesnin and Yien, 1950) was used to determine the sulphur concentration. The following relationship was used to calculate the nutrient intake by seed:

Nutrient uptake (kg ha⁻¹) =

$$\frac{\text{Nutrient concentration (\%)} \times \text{Seed yield (kg ha}^{-1}\text{)}}{100}$$

Analysis of variance (ANOVA) was used to statistically analyse the data and the F-test was used to examine treatment differences at the proper significant levels (Cochran and Cox, 1957).

RESULTS AND DISCUSSION

Growth attributes

Plant height

Soybean plant height increased steadily from the seedling stage onward, leveling off at harvest. Significantly higher plants (45.84 cm) were produced by applying 20 kg S ha⁻¹ (Table 1). Both the 20 kg S ha⁻¹ and 40 kg S ha⁻¹ treatments produced comparable plant heights that were noticeably greater than the control. Sulfur's positive effects on nitrogen metabolism, which in turn promotes soybean plants' vegetative growth, may be the cause of this height gain (Akter *et al.*, 2013). Protein structure, vitamins and other elements that enhance plant growth and yield depend on sulphur (Marshner, 2005).

Increasing zinc levels also had a significant impact on plant height. Plants with varying zinc concentrations (5, 10, 15 and 20 kg Zn ha⁻¹) were all taller than the control. At harvest, the plants with 20 kg Zn ha⁻¹ were the tallest (45.80 cm), whereas the control group had the shortest (38.85 cm). Similar results were found by Maurya *et al.* (2010), who noted that zinc addition enhances photosynthesis and chlorophyll formation, increasing meristem activity and

internode length, ultimately boosting plant height. Singh *et al.* (2017) reported comparable findings.

Dry matter accumulation

When photosynthesis exceeds respiration, dry matter accumulates, leading to plant growth. Table 1 shows that 20 kg S ha⁻¹ produced the highest accumulation of dry matter (25.81 g plant⁻¹), while the control had the lowest (17.61 g plant⁻¹). This higher dry matter production is likely due to improved crop growth and development from better sulfur absorption, which enhances growth attributes. Similar observations were reported by Sahebagoada *et al.* (2019).

The control group had the lowest dry weight (19.57 g plant⁻¹), whereas the application of 20 kg Zn ha⁻¹ produced the maximum dry matter accumulation (25.33 g plant⁻¹), then succeeded by 15 kg Zn ha⁻¹ (24.26 g plant⁻¹). These results align with those of Thenua *et al.* (2014), who observed increased dry matter with higher zinc doses up to 20 kg ha⁻¹ at all crop stages.

Yield parameters

Seed yield

Due to similar patterns in plant growth attributes, it was observed that applying 20 kg S ha⁻¹ greatly enhanced seed production, resulting in the maximum seed yield (1.07 t ha⁻¹), which was followed by 40 kg S ha⁻¹ (1.01 t ha⁻¹) and the least amount of yield was obtained by the control (0.74 t ha⁻¹). The increase in soybean seed yield with sulfur treatment can be attributed to sulfur's role in chloroplast protein synthesis, which enhances photosynthetic activity and thereby increases crop yield. These findings are consistent with Sharma *et al.* (2014).

Similarly, increasing zinc levels led to an increase in soybean seed yield up to 20 kg Zn ha⁻¹. Maximum seed yield was recorded with 20 kg Zn ha⁻¹ (1.10 t ha⁻¹), while the control plot had the lowest yield (0.78 t ha⁻¹). Zinc is essential

for the biosynthesis of the plant growth regulator IAA and nitrogen metabolism, contributing to the increase in crop yield (Suresh *et al.*, 2013). These results are some what consistent with those of Thenua *et al.* (2014), who reported a greater seed yield of 30 kg Zn ha⁻¹ that was similar to 20 kg Zn ha⁻¹.

Stover yield

Pooled data showed the highest stover yield with 20 kg S ha⁻¹ (1.97 t ha⁻¹), significantly greater than the control (1.51 t ha⁻¹) and comparable to 40 kg S ha⁻¹ (1.79 t ha⁻¹). Similar conclusions were drawn by Mamatha *et al.* (2018), who reported that graded sulfur levels significantly increased soybean haulm yield.

The use of 20 kg Zn ha⁻¹ caused a notable rise in stover yield, recording the highest value (2.02 t ha⁻¹), whereas the control, with no additional zinc, had the lowest stover yield (1.46 t ha⁻¹). This result is supported by Raghuwanshi *et al.* (2017), who also found that application of zinc significantly increased plant growth and yield parameters.

Quality parameters

Protein content

The greatest protein content was displayed in Table 1 which was obtained by applying 20 kg S ha⁻¹ (36.55%), similar to 40 kg S ha⁻¹ (36.28%) and superior to the control (34.08%). Minerals like phosphorus, potassium, nitrogen and sulphur have a significant impact on soybean protein synthesis (Mahmoodi *et al.*, 2013). These findings are consistent with Mamatha *et al.* (2018), who reported enhanced soybean seed's protein levels at 30 kg S ha⁻¹ in contrast to the control.

Similarly, when zinc was applied, the maximum protein content was found at 20 kg Zn ha⁻¹ (36.99%), while the control had the lowest protein content (34.41%) (Table 1). Zinc application increases the concentration of zinc in

Table 1: Effect of sulphur and zinc fertilization on growth, yield and quality of soybean.

Treatments	Plant height (cm)	DMA (g plant ⁻¹)	Seed yield (t ha ⁻¹)	Stover yield (t ha ⁻¹)	Protein content (%)	Oil content (%)
Sulphur levels						
S ₀	37.06	17.61	0.74	1.51	34.08	14.77
S ₂₀	45.84	25.81	1.07	1.97	36.55	17.48
S ₄₀	44.55	24.58	1.01	1.79	36.28	16.95
SEm ±	0.36	0.22	0.02	0.05	0.31	0.10
CD (P=0.05)	1.06	0.64	0.06	0.16	0.89	0.29
Zinc levels						
Zn ₀	38.85	19.57	0.78	1.46	34.41	15.29
Zn ₅	41.13	21.20	0.88	1.73	35.29	15.97
Zn ₁₀	42.21	22.99	0.91	1.76	35.48	16.53
Zn ₁₅	44.44	24.26	1.02	1.81	36.02	16.84
Zn ₂₀	45.80	25.33	1.10	2.02	36.99	17.36
SEm ±	0.47	0.29	0.03	0.07	0.39	0.13
CD (P=0.05)	1.36	0.83	0.08	0.2	1.41	0.37

soybeans, supporting the development of ribosomes and RNA, which may speed up the synthesis of proteins (Pable and Patil, 2011). Awlad *et al.* (2003) reported similar findings.

Oil content

Regarding oil content (Table 1), the application of 20 kg S ha⁻¹ resulted in the highest value (17.48%), while the lowest oil content was recorded with no sulfur application (14.77%). Sulfur is involved in lipid synthesis, fatty acid synthesis and acetyl-CoA enzyme activity (Ahmed and Abidin, 2000), which could explain the increased oil content. Oilseeds have the highest sulfur requirement among crops, which is crucial for oil biosynthesis (Ahmad *et al.*, 2007). These results align with previous studies by Hosmath *et al.* (2014) and Farhad *et al.* (2010), who also noted significant spikes in soybean oil content with 20 kg S ha⁻¹ in comparison to other sulfur levels.

Increased zinc levels were associated with an increase in soybean oil content. Data showed that 20 kg Zn ha⁻¹ resulted in higher oil content (17.36%), while the control had the lowest (15.29%). These results are broadly consistent with Pable *et al.* (2010), who found that zinc application increased oil content.

Nutrient acquisition

Nutrient uptake increased progressively when applying sulfur at a rate of up to 20 kg ha⁻¹ (Table 2). Higher nitrogen content and seed uptake were the outcomes of applying 20 kg S ha⁻¹ (5.85% and 61.13 kg ha⁻¹), comparable to 40 kg S ha⁻¹ (5.81% and 59.54 kg ha⁻¹) and significantly higher than the control (5.45% and 41.47 kg ha⁻¹). Sulfur plays a critical role in enzymatic activity for nitrate reduction in plants; thus, its application is essential for enhancing nitrogen uptake. The observed increase in root activity and soil nutrient availability to the crop may also be attributed to the higher nutrient content and uptake with sulfur application

(Wani *et al.*, 2000). Biswas (2006) similarly reported a significant influence on nitrogen content with sulfur fertilizer. An increase in nitrogen content and uptake was additionally noted with rising levels of zinc. Pooled data indicated that the highest nitrogen content and uptake in seed occurred with 20 kg Zn ha⁻¹ (5.92% and 63.41 kg ha⁻¹), whereas the control group had the lowest levels (5.51% and 43.70 kg ha⁻¹). Rathod *et al.* (2017) also found that applying lime, zinc and boron by soil and foliar spray in addition to RDF increased nitrogen content and uptake. This treatment greatly enhanced the uptake of N, P, K, Ca, Mg and S by soybeans.

Regarding phosphorus content, different levels of sulfur did not show a significant effect on phosphorus content in seed (Table 2). However, the 20 kg S ha⁻¹ treatment increased phosphorus uptake in the seed (2.69 kg ha⁻¹), comparable to 40 kg S ha⁻¹ (2.65 kg ha⁻¹), while the control had the lowest uptake (1.99 kg ha⁻¹). Dhage *et al.* (2014) similarly reported the highest phosphorus uptake at the 40 kg S ha⁻¹ level. Different levels of zinc did not show a significant difference in phosphorus content, but an increase in phosphorus uptake was observed with increasing levels of zinc. Pooled data recorded the highest phosphorus uptake with 20 kg Zn ha⁻¹ (2.71 kg ha⁻¹) in seed, while the control recorded the minimum uptake. The addition of zinc has been reported to increase phosphorus translocation to the leaves (Shittu and Ogunwale, 2012). Recena *et al.* (2021) also noted that notwithstanding the impact of soil phosphorus an antagonistic interaction between phosphorus and zinc may be anticipated with elevated phosphorus content based on zinc adsorption and availability.

Significant differences in potassium content and uptake in seed were observed with different sulfur levels (Table 2). The 20 kg S ha⁻¹ treatment showed significant variation in potassium content and uptake by seeds (1.31% and 13.71 kg ha⁻¹), while the control recorded the lowest values. The synergistic effect of sulfur on potassium uptake

Table 2: Effect of sulphur and zinc fertilization on NPK content and uptake by soybean.

Treatments	N content in seed (%)	N uptake by seed (kg ha ⁻¹)	P content in seed (%)	P uptake by seed (kg ha ⁻¹)	K content in seed (%)	K uptake by seed (kg ha ⁻¹)
Sulphur levels						
S ₀	5.45	41.47	0.27	1.99	1.17	8.95
S ₂₀	5.85	61.13	0.26	2.69	1.31	13.71
S ₄₀	5.81	59.54	0.26	2.65	1.27	12.97
SEm ±	0.05	1.98	0.002	0.09	0.02	0.47
CD (P=0.05)	0.14	5.74	NS	0.26	0.07	1.36
Zinc levels						
Zn ₀	5.51	43.70	0.27	2.07	1.20	9.61
Zn ₅	5.65	50.80	0.27	2.36	1.23	11.08
Zn ₁₀	5.68	52.53	0.26	2.41	1.25	11.57
Zn ₁₅	5.77	59.80	0.26	2.68	1.27	13.16
Zn ₂₀	5.92	63.41	0.26	2.71	1.31	13.97
SEm ±	0.06	2.56	0.003	0.12	0.03	0.61
CD (P=0.05)	0.18	7.41	NS	0.34	NS	1.75

in the crop likely contributed to the higher potassium content in seed and stover (Sahebagouda *et al.*, 2019). Zinc levels had no discernible impact on the levels of potassium of seeds; however, the highest potassium uptake occurred with the highest zinc application (20 kg Zn ha⁻¹) in seed (13.97 kg ha⁻¹), while the control recorded the lowest uptake. Rathod *et al.* (2017) similarly reported increased potassium uptake because lime, zinc and boron were sprayed on the soil and foliage in addition to RDF.

From the Table 3, a significant increase in sulfur content and uptake was captured using the application of sulfur at 20 kg S ha⁻¹ in seed, with the highest content and uptake (0.309% and 3.23 kg ha⁻¹) observed, which was superior to the control (0.289% and 2.19 kg ha⁻¹). These findings align with Dhanashree *et al.* (2011), who reported the highest sulfur uptake with the application of 30 kg ha⁻¹ sulfur. Sulfur content and uptake in seed increased with different levels of zinc application, with the highest values observed at 20 kg Zn ha⁻¹ (0.308% and 3.30 kg ha⁻¹), while the control recorded the lowest values. Rathod *et al.* (2017) also reported increased sulfur content and uptake with the application of lime, zinc and boron through soil and foliar spray along with RDF.

The application of 20 kg S ha⁻¹ was observed to increase zinc content and uptake in seeds (31.77 mg kg⁻¹ and 33.14 g ha⁻¹), comparable to 40 kg S ha⁻¹ (30.66 mg kg⁻¹ and 31.46 g ha⁻¹) and higher than the control (28.58 mg kg⁻¹ and 21.80 g ha⁻¹) (Table 3). Choudhary *et al.* (2014) similarly reported an increase in zinc content with increasing levels of sulfur up to 30 kg S ha⁻¹. Zinc content and uptake in seed increased with higher levels of zinc application. Pooled data showed the highest zinc content and uptake with 20 kg Zn ha⁻¹ in seed (31.61 mg kg⁻¹ and 33.91 g ha⁻¹). These findings are consistent with Mall *et al.* (2017), who reported higher zinc uptake with zinc application. The synergistic interaction between zinc and sulphur may be the cause of the increase in zinc absorption, as reported by Sahebagouda *et al.* (2019).

Soil parameters

The soil parameters after the harvest of the soybean crop were statistically analyzed and are presented in Table 4. According to the results, there was no discernible difference in the soil's pH or organic carbon percentage between the various sulphur and zinc application levels.

Among the sulfur treatments, the highest available nitrogen was recorded at 20 kg S ha⁻¹ (353.21 kg ha⁻¹), while the control treatment recorded the lowest (336.11 kg ha⁻¹). These findings partially align with those of Wasmattkar *et al.* (2002), who observed a substantial impact on N, P, K, S and Zn uptake at harvest with the addition of 15 kg ha⁻¹ sulfur.

Among zinc treatments, available soil nitrogen was greatly impacted by the various zinc levels. The highest amount of nitrogen in the soil was found at 20 kg Zn ha⁻¹ (355.16 kg ha⁻¹), while the control treatment recorded the lowest (338.08 kg ha⁻¹).

The results showed that applying 20 kg S ha⁻¹ reduced the soil's available phosphorus content (17.62 kg ha⁻¹), whereas the control recorded a higher phosphorus content (21.13 kg ha⁻¹). These results are consistent with Gajghane *et al.* (2015), who reported lower soil phosphorus content with sulfur application due to the antagonistic effect between sulfur and phosphorus. The available soil phosphorus was not significantly impacted by the various zinc levels.

The soil had the most potassium available with the 20 kg S ha⁻¹ treatment (256.35 kg ha⁻¹) and lowest in the control (229.03 kg ha⁻¹). These findings partially conform to Gajghane *et al.* (2015), who observed an increase in soil potassium content with the application of 30 kg S ha⁻¹ in mustard. The different levels of zinc did not significantly alter the available soil potassium.

The different levels of sulfur significantly influenced the available sulfur in the soil. The sulfur content in the soil increased, with the highest available sulfur content recorded at 20 kg S ha⁻¹ (20.33 kg ha⁻¹), comparable to 40 kg S ha⁻¹

Table 3: Effect of sulphur and zinc fertilization on sulphur and zinc content and uptake by soybean.

Treatments	S content in seed (%)	S uptake by seed (kg ha ⁻¹)	Zn content in seed (%)	Zn uptake by seed (g ha ⁻¹)
Sulphur levels				
S ₀	0.289	2.19	28.58	21.80
S ₂₀	0.309	3.23	31.77	33.14
S ₄₀	0.303	3.11	30.66	31.46
SEm ±	0.002	0.10	0.23	1.01
CD (P=0.05)	0.027	0.30	0.66	2.92
Zinc levels				
Zn ₀	0.29	2.29	28.77	22.92
Zn ₅	0.299	2.70	29.90	26.98
Zn ₁₀	0.302	2.79	30.43	28.13
Zn ₁₅	0.303	3.15	30.99	32.05
Zn ₂₀	0.308	3.30	31.61	33.91
SEm ±	0.003	0.13	0.29	1.30
CD (P=0.05)	0.009	0.38	0.85	3.77

Table 4: Effect of sulphur and zinc fertilization on soil nutrient status at harvest of soybean.

Treatments	Soil pH	SOC (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available S (kg ha ⁻¹)	Available Zn (mg kg ⁻¹)
Sulphur levels							
S ₀	4.54	1.49	336.11	21.13	229.03	18.02	0.53
S ₂₀	4.59	1.53	353.21	17.62	256.35	20.33	0.69
S ₄₀	4.57	1.58	351.41	19.94	236.91	20.16	0.67
SEm±	0.02	0.03	2.03	0.45	5.25	0.44	0.01
CD (P=0.05)	NS	NS	5.89	1.30	15.21	1.28	0.04
Zinc levels							
Zn ₀	4.54	1.48	338.08	20.84	230.8	18.44	0.55
Zn ₅	4.68	1.56	344.05	20.10	234.00	19.11	0.61
Zn ₁₀	4.57	1.55	346.39	19.54	242.87	19.41	0.63
Zn ₁₅	4.59	1.49	350.87	18.85	247.14	19.80	0.67
Zn ₂₀	4.60	1.57	355.16	18.48	249.00	20.77	0.70
SEm±	0.04	0.03	2.62	0.58	6.78	0.57	0.02
CD (P=0.05)	NS	NS	7.60	NS	NS	NS	0.05

(20.16 kg ha⁻¹) and superior to the control (18.02 kg ha⁻¹). An increase in sulfur levels influences the sulfur status in the soil, as sulfur fertilizer application is known to enhance the available sulfur status of soils (Dhage *et al.*, 2014). The soil available sulfur was not significantly affected by the different levels of zinc.

Sulfur levels also had a significant influence on the available zinc content in the soil following crop harvest. The application of 20 kg S ha⁻¹ recorded the highest soil zinc content (0.69 mg ha⁻¹), while the control noted the lowest (0.53 mg ha⁻¹). Zinc content in the soil increased with higher zinc levels in contrast to the control. The application of 20 kg Zn ha⁻¹ recorded a higher zinc content (0.70 mg ha⁻¹), comparable to 15 kg Zn ha⁻¹ (0.67 mg ha⁻¹), while the control recorded the lowest zinc content (0.55 mg kg⁻¹). These results are in line with those of Rohini *et al.* (2020), who found that raising zinc levels considerably increased the soil's overall zinc concentration in comparison to the control.

CONCLUSION

One of the most significant oilseed crops grown in India's various agricultural settings is soybeans. Based on the findings, the application of sulfur and zinc significantly improved soybean growth, yield and quality with 20 kg S ha⁻¹ and 20 kg Zn ha⁻¹ emerging as optimal levels, beyond which no substantial additional benefits were observed. The enhanced performance can be attributed to improved metabolic activity, nutrient uptake and nodulation, which translated into higher seed and stover yields. Sulfur and zinc also improved oil and protein content, highlighting their role in enhancing seed quality and supporting biofortification. Increased nutrient uptake and residual soil fertility further indicate better nutrient use efficiency without adversely affecting soil properties. Overall, these findings suggest that moderate and balanced application of sulfur and zinc is an effective and sustainable strategy for

improving soybean productivity particularly in acidic, nutrient-deficient agro-ecological regions such as Northeast India. However, nutrient requirements vary from region to region, so it is recommended to conduct additional studies to determine the most appropriate fertilizer dosages for specific areas.

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Conflict of interest

Each of the research manuscript's authors affirms that they have no conflicts of interest with regard to this submission.

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