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# Effect of Integrated Nutrient Management on Soybean Productivity and Soil Health

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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 into the effect of integrated nutrient management on soybean productivity and soil health was conducted during *kharif* 2024 at the experimental farm of Krishi Vigyan Kendra, Kangra, under Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The experiment comprised nine treatments, namely NPK 100% recommended dose of fertilizers (RDF) (20:60:40 kg ha$^{-1}$) ($T_1$), NPK 100% RDF + FYM 10 t ha$^{-1}$ ($T_2$), NPK 75% RDF + FYM 10 t ha$^{-1}$ + *Rhizobium* + PSB ($T_3$), NPK 100% RDF + FYM 10 t ha$^{-1}$ + *Rhizobium* + PSB ($T_4$), NPK 100% RDF + S 25 kg ha$^{-1}$ ($T_5$), NPK 75% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ ($T_6$), NPK 100% RDF + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB ($T_7$), NPK 75% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB ($T_8$) and NPK 100% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB ($T_9$), arranged in a randomized block design with three replications. The soil had a silty clay loam texture and was slightly acidic (pH 5.8). Soil samples were taken from a depth of 0 – 0.15 m after the harvest of soybean and analyzed for chemical parameters of the soil using standard analytical

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methods. Grain and straw samples were also analyzed for nutrient concentrations, and nutrient uptake was determined. The results showed that the application of NPK 100% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB ($T_9$) significantly increased grain yield (19.00 q ha$^{-1}$) and straw yield (28.50 q ha$^{-1}$) compared with the sole application of NPK at 100% RDF ($T_1$), which recorded the lowest values. Similarly, N, P and K concentrations and uptake in soybean grain and straw were highest in $T_9$ and lowest in $T_1$. Treatment $T_8$ (NPK 75% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB) was statistically at par with $T_9$ for growth and yield attributes, indicating a 25% reduction in the mineral fertilizer dose. Moreover, available soil nitrogen, phosphorus and potassium were also highest in the same treatment $T_9$ i.e., NPK 100% RDF + FYM 10 t ha$^{-1}$ + S 25 kg ha$^{-1}$ + *Rhizobium* + PSB; the lowest reported post-harvest available N was under $T_6$, whereas the lowest available P and K were under $T_1$.

*Keywords: INM; urea; sulphur bentonite; FYM; yield; uptake.*

## 1. Introduction

Soybean (*Glycine max* L.) is an annual herbaceous plant of the family Fabaceae that has been grown for its edible seeds in southeastern Asia for more than 3,000 years. It is usually an erect bush with woody stems and alternately arranged leaves. It is one of the major oilseed crops produced and consumed in the world. It is also known as the 'miracle bean' or 'golden bean' because it is a relatively inexpensive source of protein. Its high protein (40%) and oil (20%) contents make it an attractive crop (Tukamuhabwa and Maphosa, 2010). Soybean contains all essential amino acids, is rich in lysine and can be used to supplement a cereal-based diet. Soybean cake, a by-product of oil production, is a rich source of protein used as cattle feed. It is also used to prepare milk, curd, cheese and other food products. It is also a suitable rotational crop and helps improve soil fertility by fixing up to 40 kg ha$^{-1}$ for the subsequent crop (Pushpendra *et al.*, 1992). A field-based assessment of compost, mineral nutrient management and phosphate-solubilizing bacterial inoculation reported improvements in selected soybean yield and seed-quality measures under the evaluated treatments (Amanullah *et al.*, 2025).

Soybean is cultivated extensively under rainfed conditions in India. In India, it occupies 12.09 million hectares, with a production of 11.22 million tones and a productivity of 928 kg ha$^{-1}$ (United States Department of Agriculture). In the country, Madhya Pradesh is the leading state, accounting for 55.69 per cent of production, followed by Maharashtra at 43.84 per cent (Soybean Processors Association of India). In Himachal Pradesh, it is grown during the *kharif* season on about 0.6 thousand hectares with a production of 0.9 thousand tonnes and productivity of approximately 1715 kg ha$^{-1}$ (Directorate of Economics and Statistics, 2022).

India ranks fifth in the world in soybean production. However, productivity is still low because of unpredictable rainfall patterns, the erratic onset of the southwest monsoon and poor germination associated with low soil organic matter, soil flooding and acidic conditions. Integrated nutrient management combines chemical fertilisers with organic resources, including organic manures, green manures, biofertilizers and other decomposable crop materials. The integrated plant nutrition system (IPNS) is an environmentally compatible approach that can help cultivators improve productivity while maintaining soil fertility. Integrated nutrient management promotes the use of on-farm organic resources and may reduce the costs associated with crop nutrient supply. It involves an appropriate combination of mineral fertilizers, organic manures, crop residues, nitrogen-fixing crops, including rice bean and black gram, other pulses, oilseeds such as soybean, and biofertilizers suited to local land use and ecological, social and economic conditions (Gupta *et al.*, 2024).

In a separate soybean field experiment, the combined application of farmyard manure, phosphorus-related biofertilizers and mineral fertilisers improved selected soil indicators, while a reduced-fertiliser treatment produced seed yield statistically comparable to the full recommended fertilizer dose (Mansare *et al.*, 2026). Plant growth-promoting microorganisms have also been reviewed as potential contributors to nutrient acquisition and crop performance, supporting their inclusion among the biological components of integrated nutrient management (Kumar *et al.*, 2025).

In a field evaluation of fertilizer-bioformulation combinations, Virk *et al.* (2026) reported that soybean seed yield under selected treatments receiving 75% RDF with bioformulations was comparable to that under 100 per cent RDF. This provides a relevant comparison for examining reduced mineral fertilizer inputs alongside biological amendments, while recognizing that treatment formulations and growing conditions differ between studies.

Nitrogen, phosphorus and potassium are major macronutrients involved in numerous plant metabolic and physiological processes. Nitrogen is an important component of plant metabolism and contributes to chlorophyll synthesis, which enables the capture of solar energy (Wang *et al.*, 2024). Phosphorus is a structural component of cellular membranes, chloroplasts and mitochondria and, as a constituent of adenosine triphosphate and ribulose bisphosphate, is involved in energy transfer and numerous metabolic reactions. Potassium application increases plant resistance to abiotic stresses, such as drought, heat, frost and lodging, and to biotic stresses associated with fungi and nematodes.

Under the conditions of a soybean field experiment, combining biochar with *Bradyrhizobium japonicum* inoculation was associated with improved soil nutrient status and higher soybean yield relative to the untreated control (Aziz *et al.*, 2025).

A two-year soybean study likewise reported differences in crop production and soil biochemical responses among mineral-fertiliser, farmyard-manure and combined treatments, indicating the value of assessing crop and soil outcomes together (Ramazanoglu *et al.*, 2026). A two-season soybean trial also evaluated seed biopriming with liquid biofertilizers and reported treatment-dependent differences in crop productivity and soil-related indicators (Talavar *et al.*, 2026). Such studies suggest that responses to microbial inputs should be interpreted in relation to the particular fertilizer combination, location and observation period.

The response to the particular combinations of recommended NPK fertilizers, farmyard manure, sulphur and microbial inoculants examined in this study therefore warrants evaluation under the slightly acidic soil conditions at the experimental site in Kangra.

The objective of the present study was to compare nine nutrient-management treatments involving NPK fertilizers, farmyard manure, sulphur, *Rhizobium* and phosphate-solubilizing bacteria, including 75% and 100% recommended fertilizer doses, with respect to soybean grain and straw yields, nutrient uptake, and post-harvest soil availability of nitrogen, phosphorus and potassium.

## 2. Materials and Methods

The present study was conducted during the *kharif* season of 2024 at the experimental farm of Krishi Vigyan Kendra, Kangra, under the administrative control of Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The experiment followed a randomized block design with nine treatments and three replications. The experimental farm is located at 32.1047º N latitude and 76.2692º E longitude, at an elevation of approximately 714 metres above mean sea level. The site is in Kangra district, Himachal Pradesh, within the Mid Hills Sub-Humid Agro-climatic Zone.

The recommended NPK fertilizer dose (100% RDF) was 20:60:40 kg ha$^{-1}$. The 75% RDF treatments represented three-quarters of each stated dose (15:45:30 kg ha$^{-1}$ on the same NPK basis). Farmyard manure (FYM), sulphur (S), *Rhizobium* and phosphate-solubilizing bacteria (PSB) were included in the treatment combinations specified below.

The nine treatments were T1, 100% RDF alone; T2, 100% RDF + FYM (10 t ha$^{-1}$); T3, 75% RDF + FYM (10 t ha$^{-1}$) + *Rhizobium* + PSB; T4, 100% RDF + FYM (10 t ha$^{-1}$) + *Rhizobium* + PSB; T5, 100% RDF + S (25 kg ha$^{-1}$); T6, 75% RDF + FYM (10 t ha$^{-1}$) + S (25 kg ha$^{-1}$); T7, 100% RDF + S (25 kg ha$^{-1}$) + *Rhizobium* + PSB; T8, 75% RDF + FYM (10 t ha$^{-1}$) + S (25 kg ha$^{-1}$) + *Rhizobium* + PSB; and T9, 100% RDF + FYM (10 t ha$^{-1}$) + S (25 kg ha$^{-1}$) + *Rhizobium* + PSB.

The experimental soil was described as silty clay loam with an initial pH of 5.8. Following soybean harvest, soil samples were collected from a depth of 0-0.15 m to assess available N, P and K. Grain and straw samples were analyzed for nutrient concentrations, and nutrient uptake values were reported for the harvested components. The tables provide treatment means and critical-difference (CD) values at $P \leq 0.05$ for evaluating differences among treatments.

## 3. Results and Discussion

### 3.1 Grain Yield

Grain yield differed among nutrient-management treatments (Table 1; $P \leq 0.05$), ranging from 14.11 q ha$^{-1}$ under T1 to 19.00 q ha$^{-1}$ under T9. The highest grain yield (19.00 q ha$^{-1}$) was recorded for $T_9$(100% NPK + FYM @ 10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB), followed by $T_8$ 75% NPK + FYM @10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB) (18.40 q ha$^{-1}$) and $T_4$(100% NPK + FYM @10 t ha − 1 + *Rhizobium* + PSB), (17.87 q ha$^{-1}$). The lowest grain yield (14.11 q ha$^{-1}$) occurred under $T_1$ (100% RDF).

The treatment comprising 100% NPK + FYM @ 10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB produced a grain yield statistically comparable to that of the treatment comprising 75% NPK + FYM @10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB (Table 1).

The treatment receiving only the recommended NPK dose (20:60:40 kg ha$^{-1}$) produced the lowest grain and straw yields. Grain yield (19.00 q ha$^{-1}$) and straw yield (28.50 q ha$^{-1}$) were highest under $T_9$. These values exceeded those under $T_1$ (100% NPK), which produced 14.11 q ha$^{-1}$ of grain and 21.17 q ha$^{-1}$ of straw (Table 1).

Treatment $T_8$ (75% NPK + FYM @10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB) and treatment $T_9$ produced statistically comparable grain and straw yields according to the critical-difference values in Table 1. Thus, the 75 per cent RDF treatment-maintained yields comparable to the 100% RDF treatment when accompanied by the same additional inputs.

The comparable grain yields of $T_8$ and $T_9$ are consistent with the findings of Virk *et al.* (2026), who observed comparable soybean productivity under selected 75 per cent RDF plus bioformulation treatments and 100 per cent RDF. Mansare *et al.* (2026) also reported favorable crop responses to integrating biofertilizers, mineral fertilizers and FYM. These comparisons concern different treatment combinations and environments and therefore support a similar direction of response rather than identical treatment effects.

### 3.2 Straw Yield

The straw yield data in Table 1 indicate significant differences among treatments involving various combinations of organic and inorganic nutrient sources.

Straw yield ranged from 21.17 q ha$^{-1}$ under $T_1$ to 28.50 q ha$^{-1}$ under $T_9$. The highest straw yield was obtained under $T_9$(100% NPK + FYM @ 10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB) (28.50 q ha$^{-1}$), followed by $T_8$(75% NPK + FYM @10 t ha$^{-1}$ + S @ 25 kg ha$^{-1}$ + *Rhizobium* + PSB), (27.60 q ha$^{-1}$) and treatment $T_4$ ((100% NPK + FYM @10 t ha − 1 + *Rhizobium* + PSB); 26.80 q ha$^{-1}$). The yield under T9 was greater than that under T1(100% NPK) (Table 1).

**Table 1. Effect of integrated nutrient management on grain and straw yield $(\mathbf{q\ ha^{-1}})$ of soybean**

| Treatment | Grain Yield | Straw Yield |
|---|---|---|
| $T_1$: 100% NPK $(20:60:40\ \text{kg ha}^{-1})$ | 14.11 | 21.17 |
| $T_2$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ | 14.82 | 22.23 |
| $T_3$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 16.86 | 25.29 |
| $T_4$: 100% NPK + FYM@ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 17.87 | 26.80 |
| $T_5$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ | 14.14 | 21.21 |
| $T_6$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ | 15.48 | 23.22 |
| $T_7$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 17.12 | 25.68 |
| $T_8$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 18.40 | 27.60 |
| $T_9$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 19.00 | 28.50 |
| CD $(P \leq 0.05)$ | 0.65 | 0.97 |

## 3.3 Nutrient Uptake

### a. Nitrogen Uptake

Table 2 summarizes reported nitrogen uptake in soybean seed and straw. Treatment $T_9$(100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) recorded the greatest seed and straw nitrogen uptake (110.66 and 57.86 kg $\text{ha}^{-1}$, respectively), followed by $T_8$(75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) (103.05 and 52.99 kg $\text{ha}^{-1}$, respectively). The lowest values for both components were reported under $T_1$.

In the uptake tables, the highest reported values were generally associated with treatment $T_9$ (100% NPK + 10 t FYM $\text{ha}^{-1}$ + 25 kg S $\text{ha}^{-1}$ + *Rhizobium* + PSB), followed by treatment $T_8$ (75% NPK + 10 t FYM $\text{ha}^{-1}$ + 25 kg S $\text{ha}^{-1}$ + *Rhizobium* + PSB). Phosphorus and potassium uptake are presented separately in Tables 3 and 4.

Because total nutrient uptake depends on nutrient concentration and dry matter production (Uptake = Concentration × Yield), improvements in grain and straw yield and nutrient concentration contributed to higher overall uptake. FYM mineralization releases nutrients gradually, which can reduce leaching and volatilization losses. Inoculation with *Rhizobium* contributes to nitrogen availability, while orthophosphates solubilized by PSB support early root elongation and cellular energy transfer (ATP/ADP systems). Furthermore, sulphur application supports nitrogen utilization by maintaining suitable N:S ratios in soybean tissue. These observations align with those reported by Chaudhari *et al.* (2019).

Recent field research provides further context for the observed nutrient-uptake patterns. In a two-season study, Talavar *et al.* (2026) found treatment-dependent crop and soil responses to microbial biopriming, while Aziz *et al.* (2025) described changes in soybean performance and soil properties when biochar and bacterial inoculation were combined. The present study did not directly measure microbial processes, so the current nutrient-uptake results are interpreted as crop responses to the tested treatment packages.

**Table 2. Effect of integrated nutrient management on nitrogen uptake $(\mathbf{kg\ ha^{-1}})$**

| Treatment | Seed Uptake | Straw Uptake | Total Uptake |
|---|---|---|---|
| $T_1$: 100% NPK $(20:60:40\ \text{kg ha}^{-1})$ | 72.49 | 29.56 | 99.40 |
| $T_2$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ | 77.34 | 33.28 | 108.46 |
| $T_3$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 92.63 | 46.60 | 138.87 |
| $T_4$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 94.83 | 50.40 | 148.64 |
| $T_5$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ | 74.14 | 30.83 | 105.97 |
| $T_6$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ | 83.98 | 37.19 | 121.17 |
| $T_7$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 101.32 | 46.13 | 144.67 |
| $T_8$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 103.05 | 52.99 | 159.70 |
| $T_9$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 110.66 | 57.86 | 168.05 |
| CD $(P \leq 0.05)$ | 3.68 | 2.28 | 8.26 |

## 3.4 Phosphorus Uptake

Table 3 presents phosphorus uptake by soybean seed and straw, as well as total phosphorus uptake, under the different integrated nutrient management treatments.

The greatest reported phosphorus uptake in soybean seed and straw occurred under $T_9$ (100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB ), with seed and straw values of 13.62 and 7.22 kg $\text{ha}^{-1}$, respectively. Treatment $T_8$(75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) followed with 11.53 and 5.52 kg $\text{ha}^{-1}$, respectively. The lowest seed and straw phosphorus uptake values occurred under $T_1$ (Table 3).

**Table 3. Effect of integrated nutrient management on phosphorus uptake $(\text{kg ha}^{-1})$**

| Treatment | Seed Uptake | Straw Uptake | Total Uptake |
|---|---|---|---|
| $T_1$: 100% NPK $(20:60:40\ \text{kg ha}^{-1})$ | 4.23 | 2.48 | 6.58 |
| $T_2$: 100% NPK + FYM 10 t $\text{ha}^{-1}$ | 6.77 | 3.04 | 9.85 |
| $T_3$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 8.83 | 4.21 | 12.61 |
| $T_4$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 9.83 | 5.00 | 13.92 |
| $T_5$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ | 6.65 | 2.76 | 9.27 |
| $T_6$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ | 7.75 | 3.20 | 11.17 |
| $T_7$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 9.19 | 3.93 | 13.13 |
| $T_8$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 11.53 | 5.52 | 16.13 |
| $T_9$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 13.62 | 7.22 | 18.46 |
| CD ($P \leq 0.05$) | 1.00 | 0.62 | 0.98 |

### 3.5 Potassium Uptake

Table 4 presents potassium uptake by soybean under the different organic and inorganic nutrient treatments, which significantly influenced uptake.

Seed and straw potassium uptake were greatest under $T_9$ (100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB), at 29.83 and 74.87 kg $\text{ha}^{-1}$, respectively. Treatment $T_8$(75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) recorded 27.24 and 69.27 kg $\text{ha}^{-1}$, respectively. The lowest values occurred under $T_1$ (Table 4).

**Table 4. Effect of integrated nutrient management on potassium uptake $(\text{kg ha}^{-1})$**

| Treatment | Seed Uptake | Straw Uptake | Total Uptake |
|---|---|---|---|
| $T_1$: 100% NPK $(20:60:40\ \text{kg ha}^{-1})$ | 16.23 | 46.49 | 61.10 |
| $T_2$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ | 19.28 | 52.11 | 70.21 |
| $T_3$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 24.44 | 59.84 | 84.26 |
| $T_4$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 26.33 | 67.81 | 93.43 |
| $T_5$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ | 17.49 | 47.37 | 65.34 |
| $T_6$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ | 22.16 | 54.98 | 77.14 |
| $T_7$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 25.00 | 62.05 | 87.00 |
| $T_8$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 27.24 | 69.27 | 97.61 |
| $T_9$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 29.83 | 74.87 | 102.89 |
| CD ($P \leq 0.05$) | 1.08 | 2.34 | 4.97 |

### 3.6 Available Nitrogen

Table 5 presents the soil nitrogen content after the application of the different organic and inorganic nutrient treatments at the end of the experiment.

After harvest, available soil nitrogen was highest under $T_9$ (100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) at 273.26 kg $\text{ha}^{-1}$, followed by $T_8$ (75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) at 262.55 kg $\text{ha}^{-1}$. The lowest value was 248.72 kg $\text{ha}^{-1}$ under $T_6$ (Table 5).

### 3.7 Available Phosphorus

Post-harvest soil-available phosphorus differed among the nutrient-management treatments (Table 5).

Post-harvest soil-available phosphorus ranged from 16.74 kg $\text{ha}^{-1}$ under T1 to 19.59 kg $\text{ha}^{-1}$ under T9 (Table 5). Treatment T9 (100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) had the highest numerical value, followed by T8 (75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB) at 18.90 kg $\text{ha}^{-1}$. The difference between T9 and T8 was smaller than the reported 5% critical difference (0.82 kg $\text{ha}^{-1}$).

### 3.8 Available Potassium

Table 5 shows the effects of the different treatments on soil available potassium after soybean harvest.

Post-harvest available soil potassium was highest under T9 ((100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB)) at 167.35 kg $\text{ha}^{-1}$, followed by T8 ($T_8$(75% NPK + FYM @10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB)) at 163.75 kg $\text{ha}^{-1}$. The lowest value was 152.76 kg $\text{ha}^{-1}$ under T1 (Table 5).

Post-harvest available soil N, P and K varied among the nine treatments, with relatively high values under $T_9$, $T_8$ and $T_7$. These measurements describe soil nutrient availability after one season rather than changes in microbial biomass or soil enzyme activity.

The residual build-up of available nitrogen may be associated with atmospheric nitrogen fixation by *Rhizobium* and gradual N mineralization from FYM. The increase in available phosphorus may be associated with organic acids produced during FYM decomposition, which chelate iron and aluminium ions ($Fe^{3+}$, $Al^{3+}$), potentially reducing $P$-fixation and promoting $P$-solubilisation via PSB. Soil potassium availability may also benefit from organic matter additions that increase exchange-site retention and minimise potassium leaching. These findings are consistent with those of Kalaiyarasi *et al.* (2019) and Yadav *et al.* (2024).

The post-harvest available N, P and K patterns can be compared with the soybean study of Ramazanoglu *et al.* (2026), which evaluated mineral and FYM inputs over two growing seasons and measured soil biochemical indicators in addition to crop responses. Unlike that investigation, the present experiment measured soil nutrient availability after a single season; therefore, no conclusion about changes in soil enzyme activity or microbial biomass is drawn from these data.

**Table 5. Effect of integrated nutrient management on available N, P, and K $\left(\text{kg ha}^{-1}\right)$ in post-harvest soil**

| Treatment | Available N | Available P | Available K |
|---|---|---|---|
| $T_1$: 100% NPK $\left(20:60:40\ \text{kg ha}^{-1}\right)$ | 248.90 | 16.74 | 152.76 |
| $T_2$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ | 251.24 | 17.05 | 155.39 |
| $T_3$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 254.92 | 17.26 | 158.35 |
| $T_4$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + *Rhizobium* + PSB | 260.42 | 18.52 | 161.78 |
| $T_5$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ | 249.85 | 16.88 | 155.24 |
| $T_6$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ | 248.72 | 17.02 | 153.24 |
| $T_7$: 100% NPK + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 262.41 | 17.98 | 161.85 |
| $T_8$: 75% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 262.55 | 18.90 | 163.75 |
| $T_9$: 100% NPK + FYM @ 10 t $\text{ha}^{-1}$ + S @ 25 kg $\text{ha}^{-1}$ + *Rhizobium* + PSB | 273.26 | 19.59 | 167.35 |
| CD ($P \leq 0.05$) | 8.11 | 0.82 | 2.36 |

## 4. Conclusion

The 2024 field investigation at Kangra found that integrating mineral fertilizer with FYM, sulphur and microbial inoculants improved soybean grain and straw yields relative to the sole use of the recommended NPK dose. Treatment $T_9$, comprising 100 per cent RDF, FYM at 10 t $\text{ha}^{-1}$, sulphur at 25 kg $\text{ha}^{-1}$ and *Rhizobium* plus PSB inoculation, recorded the greatest grain and straw yields (19.00 and 28.50 q $\text{ha}^{-1}$, respectively). Treatment $T_8$ combined the same FYM, sulphur and inoculants with 75 per cent RDF and yielded 18.40 q $\text{ha}^{-1}$ of grain and 27.60 q $\text{ha}^{-1}$ of straw. Its yields were statistically comparable with those of $T_9$, suggesting that a lower mineral fertilizer dose can maintain yield under the conditions examined. Post-harvest soil analyses also identified the highest available nitrogen, phosphorus and potassium under $T_9$. Collectively, the results support integrated nutrient management as an approach to improving soybean productivity and post-harvest nutrient availability in the slightly acidic soil of the experimental site. The findings apply to the single-season, site-specific conditions investigated and do not establish longer-term changes in soil biological functioning.

## 5. Limitations of the Study

The field experiment was conducted at one site during a single kharif season. Treatment responses should therefore be interpreted as site- and season-specific. Soil assessment comprised post-harvest available N, P and K and did not include direct measurements of microbial biomass, enzyme activities or changes over successive crop cycles. Multi-season studies across different soils would be needed to evaluate the persistence of the observed responses and any longer-term soil-health effects.

## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. 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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