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A study the effect of various treatments on nutrient (N, P, K, S) uptake in soybean (*Glycine max* L.)

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Abstract
Soybean is a vital legume crop known for its high protein content and significant contribution to global agriculture. This study investigates the effect of micronutrients, biofertilizers, and organic amendments on the nutrient uptake, symbiotic traits, and overall quality of soybean. The experiment was conducted using different treatment combinations of recommended doses of fertilizers (RDF) along with Rhizobium and Phosphate Solubilizing Bacteria (PSB) inoculation, micronutrients such as $ZnSO_4$, $FeSO_4$, $MnSO_4$, Borax, and Ammonium Molybdate, and organic amendments like Farmyard Manure (FYM). The results revealed that integrating RDF with Ammonium Molybdate + Rhizobium + PSB inoculation (T4) led to the highest improvement in nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) content in both seeds and straw, along with increased protein content. The application of FYM (T8) also significantly enhanced nutrient uptake, indicating the beneficial role of organic amendments in improving soil fertility. The statistical analysis showed a significant increase ($p < 0.05$) in nutrient content across treatments, demonstrating the positive impact of integrated nutrient management on soybean productivity. The findings suggest that a balanced combination of chemical fertilizers, biofertilizers, and organic amendments can enhance nutrient availability and soybean quality while promoting sustainable agricultural practices. Future research should explore the long-term impact of these treatments on soil health and yield stability.

Keywords: Soybean, biofertilizers, micronutrients, nutrient uptake

Introduction
Soybean (*Glycine max* L.) is a vital leguminous crop, widely cultivated for its high protein and oil content, serving as a key ingredient in food, animal feed, and industrial applications. It plays a significant role in soil fertility improvement through biological nitrogen fixation, making it an essential component of sustainable agriculture. However, its productivity is often constrained by nutrient deficiencies, necessitating effective nutrient management practices to enhance crop yield and quality. Among essential nutrients, nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) are crucial for soybean growth and development [1]. Nitrogen is a fundamental component of amino acids and proteins, phosphorus is essential for energy transfer and root development, potassium regulates enzyme activation and water balance, while sulfur contributes to protein synthesis and enzyme function [2-4]. Deficiencies in these nutrients can lead to poor nodulation, reduced biomass production, and lower seed quality. To optimize soybean production, integrated nutrient management (INM) combining chemical fertilizers, biofertilizers, and organic amendments is increasingly being adopted. Biofertilizers like Rhizobium and Phosphate Solubilizing Bacteria (PSB) enhance nitrogen fixation and phosphorus availability, while micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), boron (B), and molybdenum (Mo) support enzymatic and metabolic functions. Additionally, farmyard manure (FYM) improves soil structure, microbial activity, and nutrient retention. This study evaluates the impact of micronutrients, biofertilizers, and organic amendments on symbiotic traits, nutrient uptake, yield attributes, and quality of soybean. By integrating biological and chemical inputs, this research aims to develop sustainable nutrient management strategies that enhance productivity while preserving soil health." The findings will contribute to eco-friendly agricultural practices, reducing dependency on synthetic fertilizers and promoting long-term soil fertility and crop sustainability [5-7]. "

Literature review

Billore *et al*. (1999) investigated the effect of integrated micronutrient management on soybean production and emphasized the importance of combining chemical fertilizers with bio-inoculants for sustained yield improvement. Their findings highlighted that the inclusion of micronutrients, particularly molybdenum and zinc, significantly enhanced nitrogen fixation and phosphorus availability, leading to increased soybean productivity [8].

Bist and Chandel (1996) studied the impact of integrated nutrient management on yield attributes, yield, and quality of soybean. Their research indicated that a balanced application of organic and inorganic fertilizers improved not only the yield but also the overall quality of soybean grains. They reported that the use of Rhizobium and phosphate-solubilizing bacteria (PSB) in combination with recommended doses of fertilizers enhanced nodulation and nitrogen assimilation, ultimately improving plant growth and yield [9].

Chapman and Pratt (1982) provided standardized methods for analyzing soils, plants, and water, which are essential for evaluating nutrient availability and soil fertility. Their work forms a critical foundation for studies focusing on soil nutrient dynamics and fertilizer efficiency in soybean cultivation [10].

Chesnin and Yien (1951) developed a turbidimetric method for determining available sulfates in soil, which remains a widely used technique for assessing sulfur availability. Their methodology has been instrumental in evaluating the role of sulfur in legume production, including soybean, where sulfur is a key nutrient for protein synthesis and overall crop development [11].

Chandra *et al*. (1995) examined the effect of phosphate-solubilizing bacteria (PSB) on rhizobial symbiosis in soybean under rainfed conditions. They found that PSB significantly improved phosphorus solubility in the soil, leading to better root development and nodulation. This, in turn, enhanced nitrogen fixation and plant vigor, particularly in nutrient-deficient soils. Their study reinforced the potential of microbial inoculants in reducing dependency on chemical fertilizers while maintaining high yields [12]."

Chaturvedi and Chandel (2005) assessed the influence of organic and inorganic fertilization on soil fertility and soybean productivity. Their findings suggested that integrating farmyard manure (FYM) with recommended doses of chemical fertilizers resulted in higher yields and improved soil health. They emphasized that continuous reliance on inorganic fertilizers alone could lead to soil degradation, whereas combining them with organic inputs enhanced soil microbial activity and nutrient retention [13].

Chaturvedi *et al*. (2010) further expanded on the productivity, profitability, and quality aspects of soybean cultivation under an integrated nutrient management system. Their study demonstrated that a well-balanced nutrient supply, including micronutrients and biofertilizers, not only improved yield but also contributed to higher economic returns for farmers. Additionally, they observed a positive impact on residual soil fertility, ensuring sustained productivity in subsequent cropping seasons [14].

Research methodology

Experimental Site and Design

The experiment was conducted in field No.51 of R.A.K. College of Agriculture Farm, Sehore, (M.P) during Kharif season, 2013 under "All India Co-Ordinated Research Project on Soybean" Experimental site having fairly uniform topography, normal fertility status except available nitrogen and soil homogeneity. The experiment was conducted to evaluate the effect of micronutrients, organics, and biofertilizers on the nutrient content of soybean (*Glycine max* L.) seeds and straw. A randomized block design (RBD) with eight treatments and three replications was used. The treatments included various combinations of recommended fertilizers, biofertilizers, and micronutrients.

Treatments and Fertilizer Application

The experiment involved different fertilizer treatments, including:

1. Control (No Fertilizer Application)
2. Recommended Dose of Fertilizer (RDF)
3. Organic Manure-Based Treatments (e.g., FYM, Vermicompost, Poultry Manure)
4. Integrated Nutrient Management (INM) (Combination of organic and inorganic fertilizers)
5. Micronutrient Enriched Fertilization

The fertilizers were applied at specific rates based on soil test values and recommended agronomic practices.

Treatment Details

The following eight treatments were applied to assess their effects on nitrogen, phosphorus, and potassium content in soybean:

1. **T1** – RDF (20:60:20:20, $N:P_2O_5:K_2O:S$ kg ha^{-1}) (Control)
2. **T2** – RDF + Rhizobium + PSB inoculation
3. **T3** – RDF + $ZnSO_4$ (50 kg/ha) + Rhizobium + PSB inoculation
4. **T4** – RDF + Ammonium Molybdate (1 g/kg seed) + Rhizobium + PSB inoculation
5. **T5** – RDF + Borax (5 kg/ha) + Rhizobium + PSB inoculation
6. **T6** – RDF + $FeSO_4$ (10 kg/ha) + Rhizobium + PSB inoculation
7. **T7** – RDF + $MnSO_4$ (25 kg/ha) + Rhizobium + PSB inoculation
8. **T8** – RDF + FYM (5 t/ha) + Rhizobium + PSB inoculation

Soil and Plant Sampling

- **Soil Sampling**: Collected before sowing and after harvest to analyse nutrient availability.
- **Plant Sampling**: Samples were collected at stages to assess nutrient uptake.

Laboratory Analysis

- **Nitrogen (N)**: Estimated using Kjeldahl's Method
- **Phosphorus (P)**: Determined by Spectrophotometry (Olsen's Method)
- **Potassium (K)**: Measured by Flame Photometer
- **Sulfur (S)**: Analyzed using Turbidimetric Method

Results and Discussion

The present study was conducted to evaluate the impact of micronutrients, organics, and biofertilizers on the nutrient content of soybean (*Glycine max* L.) seeds and straw. The results provide valuable insights into the role of various treatments in enhancing nitrogen (N), phosphorus (P), and potassium (K) uptake in soybean. The application of biofertilizers and micronutrients, along with the recommended dose of fertilizers (RDF), significantly influenced the nutrient composition of soybean, indicating improved soil fertility and plant nutrient availability. The discussion highlights the comparative effectiveness of different treatment combinations and their potential implications for sustainable soybean production.

Nutrient content

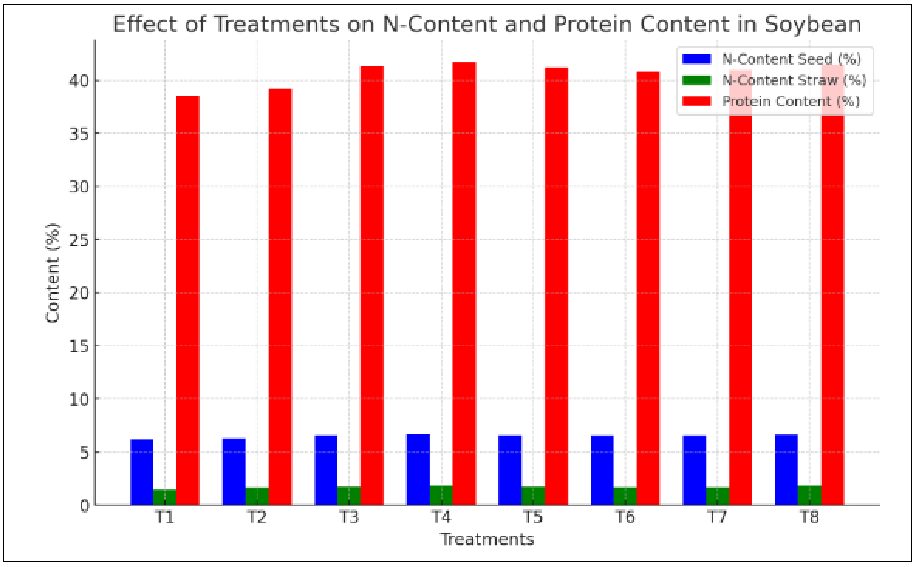
The nutrient content of soybean (*Glycine max* L.) seeds and straw was significantly influenced by the application of micronutrients, organics, and biofertilizers. The study examined the levels of nitrogen (N), phosphorus (P), and potassium (K) in both seeds and straw under different treatment conditions.

1. Nitrogen content (%)

The nitrogen content in soybean seeds and straw increased with the combined application of biofertilizers, organic amendments, and micronutrients. Treatments that included Rhizobium and phosphorus-solubilizing bacteria (PSB), along with organic fertilizers, resulted in a higher nitrogen uptake compared to control groups. This suggests that biofertilizers play a crucial role in nitrogen fixation, improving the overall nitrogen availability for the crop.

Table 1 (a): Effect of micronutrients, organics and biofertilizers on symbiotic traits, yield attributes, nutrient uptake and quality of soybean in N-content (%) in seed, straw and protein content (%).

	Treatments	N –Content seed (%)	N –Content straw (%)	Protein content (%)
T_1	RDF(20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})	6.17	1.43	38.56
T_2	RDF+*Rhizobium*+PSB inoculation	6.27	1.62	39.18
T_3	RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation	6.61	1.70	41.31
T_4	RDF+Ammo.Molyb.1g/kgseed+ *Rhizobium* + PSB inoculation	6.67	1.82	41.68
T_5	RDF+ Borax 5kg/ha+*Rhizobium*+PSB inoculation	6.59	1.70	41.18
T_6	RDF + $FeSO_4$ 10 kg/ha +*Rhizobium* +PSB inoculation	6.53	1.67	40.81
T_7	RDF+ $MnSO_4$ 25 kg/ha + *Rhizobium*+PSB inoculation	6.55	1.68	40.93
T_8	RDF +FYM 5t/ha +*Rhizobium* + PSB inoculation	6.63	1.80	41.43
	S.Em±	0.114	0.062	0.712
	CD at 5%	0.331	0.182	2.068



RDF = (Recommended dose of fertilizer (20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})
BF=Bio fertilizer (*Rhizobium* culture + Phosphorus solubilizing bacteria)
FYM= Farm Yard Manure
AM = Ammonium Molybdate
$ZnSO_4$ = Zinc Sulphate
$FeSO_4$ = Ferrous sulphate
$MnSO_4$ = Manganese sulphate

Nitrogen Content (%) In Soybean Seed

The data on N-content in seeds are presented in Table The data showed a significant effect on N content in soybean seed due to the effect of all the treatments (except T_2) over control. TreatmentsT_3,T_4 and T_8 recorded significantly higher N content over both T_1 and T_2. Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB recorded the highest N-content (6.67%) in seed followed by the treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation,T_8 (6.63%) and the treatment T_3 *viz.* RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation (6.61%).The lowest N-content in seed was recorded in RDF control (6.17%).

Nitrogen content (%) in soybean straw

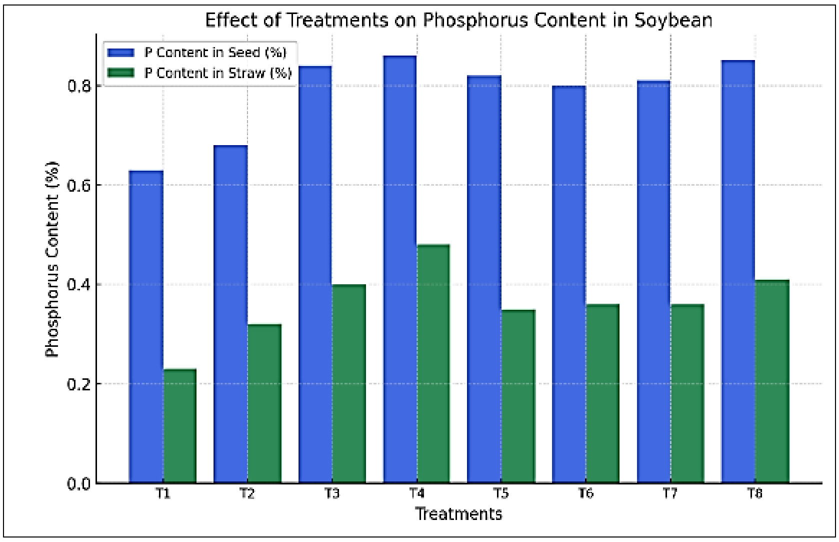
The data showed a significant effect on N content in soybean straw due to effect of all the treatments (except T_2) over control. TreatmentsT_3,T_4 and T_8 recorded significantly higher N content over both T_1 and T_2. Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB recorded the highest N-content (1.82%) in straw followed by the treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation, T_8 (1.80%) and the treatment T_3 *viz.*RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation (1.70%).The lowest N-content in straw was recorded in RDF control (1.43%).

2. Phosphorus content (%)

Phosphorus content in soybean seeds and straw was significantly enhanced in treatments where phosphorus-solubilizing bacteria were applied. The synergistic effect of organic amendments and biofertilizers facilitated greater phosphorus absorption, contributing to improved seed development and plant metabolism.

Table 2 (b): Effect of micronutrients, organics and biofertilizers on symbiotic traits, yield attributes, nutrient uptake and quality of soybean in P-content (%) in seed and straw

	Treatments	P-content seed (%)	P-content straw (%)
T_1	RDF(20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})	0.63	0.23
T_2	RDF+*Rhizobium*+PSB inoculation	0.68	0.32
T_3	RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation	0.84	0.40
T_4	RDF+Ammo.Molyb.1g/kgseed+ *Rhizobium* + PSB inoculation	0.86	0.48
T_5	RDF+ Borax 5kg/ha+*Rhizobium*+PSB inoculation	0.82	0.35
T_6	RDF + $FeSO_4$ 10 kg/ha +*Rhizobium* +PSB inoculation	0.80	0.36
T_7	RDF+ $MnSO_4$ 25 kg/ha + *Rhizobium*+PSB inoculation	0.81	0.36
T_8	RDF +FYM 5t/ha +*Rhizobium* + PSB inoculation	0.85	0.41
	S.Em±	0.044	0.029
	CD at 5%	0.12	0.087



RDF= (Recommended dose of fertilizer (20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})
BF=Bio fertilizer (*Rhizobium* culture + Phosphorus solubilizing bacteria)
FYM= Farm Yard Manure
AM = Ammonium Molybdate
$ZnSO_4$ = Zinc Sulphate
$FeSO_4$ = Ferrous sulphate
$MnSO_4$ = Manganese sulphate

Phosphorus Content (%) In Soybean Seed

It is evident from the data Table (b) that the phosphorus content in seeds was significantly influenced by different treatments. Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB recorded the highest P-content (0.86%) in seeds, which was significantly superior over T_1 and T_2 and found at par with the application of treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation T_8 (0.85%), T_3 (0.84%),T_5 (0.82) $T_{6,}$ (0.80%) and T_7 (0.81%). The lowest P -content in seed was recorded in T_1 i.e. RDF control (0.63%).

Phosphorus content (%) in soybean straw

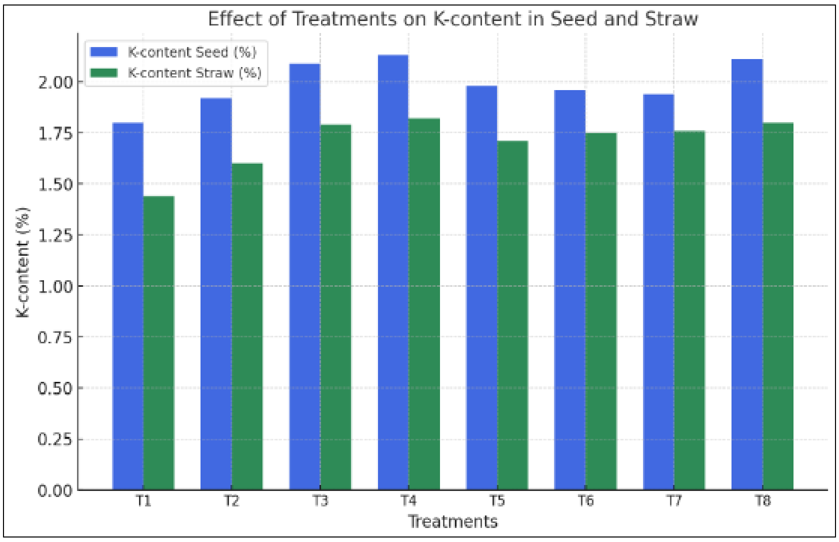
The data on P-content in straw are presented Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB recorded the highest P-content (0.48%) which was significantly superior over T_1 and T_2 and found at par with the application of treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation, T_8 (0.41%)and also with T_5,T_6, and T_7. The minimum P-content was observed in RDF control (0.23%)."

3. Potassium content (%)

The potassium content of soybean was also positively influenced by the treatments. The application of potassium-rich organic amendments, in combination with microbial inoculants, resulted in better potassium accumulation in both seeds and straw. This improvement in potassium uptake is crucial for soybean growth, as potassium plays a key role in enzymatic activities, water regulation, and overall plant health.

Table 3 (c): Effect of micronutrients, organics and biofertilizers on symbiotic traits, yield attributes, nutrient uptake and quality of soybean in K-content (%) in seed and straw. "

	Treatments	K-content seed (%)	K-content straw (%)
T_1	RDF(20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})	1.80	1.44
T_2	RDF+*Rhizobium*+PSB inoculation	1.92	1.60
T_3	RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation	2.09	1.79
T_4	RDF+Ammo.Molyb.1g/kgseed+ *Rhizobium* + PSB inoculation	2.13	1.82
T_5	RDF+ Borax 5kg/ha+*Rhizobium*+PSB inoculation	1.98	1.71
T_6	RDF + $FeSO_4$ 10 kg/ha +*Rhizobium* +PSB inoculation	1.96	1.75
T_7	RDF+ $MnSO_4$ 25 kg/ha + *Rhizobium*+PSB inoculation	1.94	1.76
T_8	RDF +FYM 5t/ha +*Rhizobium* + PSB inoculation	2.11	1.80
	S.Em±	0.055	0.067
	CD at 5%	0.161	0.195



RDF=(Recommended dose of fertilizer (20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})
BF=Bio fertilizer (*Rhizobium* culture + Phosphorus solubilizing bacteria)
FYM= Farm Yard Manure
AM = Ammonium Molybdate
$ZnSO_4$ = Zinc Sulphate
$FeSO_4$ = Ferrous sulphate
$MnSO_4$ = Manganese sulphate

Potassium Content (%) In Soybean Straw

The data on K-content in straw are presented in The K content in straw was significantly influenced by all the treatments (except T_2) over the control T_1. Maximum K-content in straw (1.82%%) was recorded by the application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB (T_4) which was significantly superior over T_1 and T_2 and found at par with the remaining treatments. The minimum K content was recorded with RDF control (1.44%).

Potassium content (%) in soybean seed

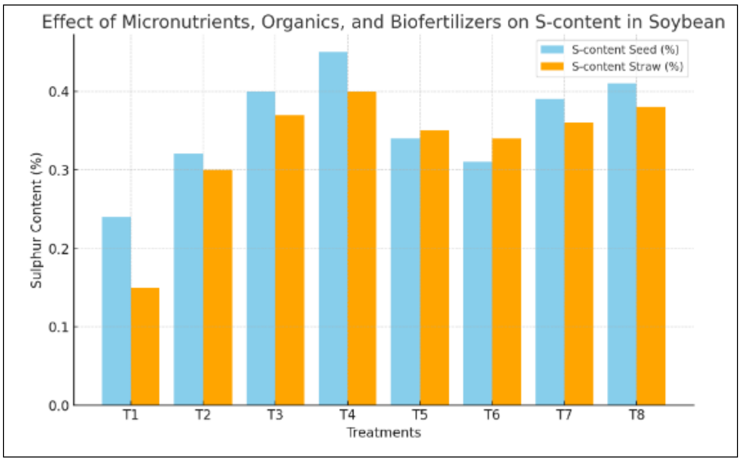
The K content in seed significantly influenced byT_3,T_4,T_5 and T_8 over the control T_1. Maximum K-content in seed (2.13%) was recorded by the application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB(T_4) which was significantly superior over T_1 and T_2 and found at par with T_3,T_5 and T_8.The minimum K content was recorded with RDF control (1.80)

4.3.8 Sulphur content (%)

Sulphur (S) is an essential nutrient for soybean growth, playing a critical role in protein synthesis, enzyme function, and chlorophyll formation. The study revealed that the sulphur content in both soybean seeds and straw was significantly influenced by the application of biofertilizers, organic amendments, and micronutrient treatments.

Table 4 (d): Effect of micronutrients, organics and biofertilizers on symbiotic traits, yield attributes, nutrient uptake and quality of soybean in S-content (%) in seed and straw

	Treatments	S-content seed (%)	S-content straw (%)
T_1	RDF(20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})	0.24	0.15
T_2	RDF+*Rhizobium*+PSB inoculation	0.32	0.30
T_3	RDF + $ZnSO_4$ 50 kg/ha + *Rhizobium* +PSB inoculation	0.40	0.37
T_4	RDF+Ammo.Molyb.1g/kgseed+ *Rhizobium* + PSB inoculation	0.39	0.37
T_5	RDF+ Borax 5kg/ha+*Rhizobium* +PSB inoculation	0.34	0.35
T_6	RDF + $FeSO_4$ 10 kg/ha +*Rhizobium* +PSB inoculation	0.39	0.37
T_7	RDF+ $MnSO_4$ 25 kg/ha + *Rhizobium*+PSB inoculation	0.39	0.36
T_8	RDF +FYM 5t/ha +*Rhizobium* + PSB inoculation	0.41	0.38
	S.Em±	0.029	0.013
	CD at 5%	0.085	0.040



RDF=(Recommended dose of fertilizer
(20:60:20:20,N:P_2O_5:K_20:S kg ha^{-1})
BF=Bio fertilizer (*Rhizobium* culture + Phosphorus solubilizing bacteria)
FYM= Farm Yard Manure
AM = Ammonium Molybdate
$ZnSO_4$ = Zinc Sulphate
$FeSO_4$ = Ferrous sulphate
$MnSO_4$ = Manganese sulphate

Sulphur content (%) in soybean straw

The data in table showed a significant effect of micronutrients, organics and biofertilizer sources on S-content of straw. Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB recorded the highest S-content (0.40%) in straw, which was significantly superior over other treatments and found at par with the application of treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation T_8 (0.38%). "

Sulphur Content (%) In Soybean Seed

The data showed a significant effect of different treatments on S-content of soybean seed. Application of RDF + Ammonium Molybdate (A.M.) @ 1g / kg seed +*Rhizobium* + PSB, recorded the highest S-content (0.39%) in seeds, which was significantly superior over the other treatments and found at par with the application of treatment RDF+FYM 5t/ha +*Rhizobium* + PSB inoculation T_8 (0.41%) and T_3 (0.40%).

Discussion

The application of different combinations of RDF, micronutrients, biofertilizers, and organic amendments significantly influenced the nutrient content of soybean seeds and straw. The highest nitrogen (N) content in seeds (6.67%) and straw (1.82%) was observed in the treatment with RDF + Ammonium Molybdate (1 g/kg seed) + Rhizobium + PSB inoculation (T4), which also resulted in the highest protein content (41.68%). This suggests that molybdenum enhances nitrogen fixation, thereby increasing protein synthesis. The incorporation of FYM (T8) also resulted in higher nitrogen content (6.63% in seed and 1.80% in straw), indicating the role of organic matter in nutrient availability.

Phosphorus (P) is essential for root development and energy transfer in plants. The highest P content in seeds (0.86%) and straw (0.48%) was recorded in T4, followed by the treatment with FYM (T8), where the P content in seed and straw was 0.85% and 0.41%, respectively. The increased phosphorus content in these treatments highlights the role of organic amendments and molybdenum in enhancing phosphorus uptake, possibly through improved microbial activity and root proliferation.

Potassium (K) plays a crucial role in enzyme activation, water regulation, and protein synthesis. The maximum K content in seeds (2.13%) and straw (1.82%) was observed in T4, followed closely by T8 (2.11% in seed and 1.80% in straw). The significant increase in potassium content in these treatments suggests improved nutrient solubilization and uptake facilitated by Rhizobium and PSB inoculation, as well as the beneficial effects of organic matter on soil structure and nutrient retention.

Sulfur (S) is essential for protein synthesis and enzyme activity in plants. The highest sulfur content in seeds (0.39%) and straw (0.40%) was recorded in T4, followed by T8 (0.41% in seed and 0.38% in straw). This indicates that sulfur uptake is enhanced with the addition of ammonium molybdate and FYM, which improve microbial activity and organic matter decomposition, leading to better sulfur availability.

The findings indicate that combining RDF with biofertilizers, micronutrients, and organic amendments significantly improves nutrient uptake and quality parameters in soybean. The treatment T4 (RDF + Ammonium Molybdate + Rhizobium + PSB) emerged as the most effective, likely due to improved nitrogen fixation and phosphorus solubilization, which in turn enhanced overall nutrient uptake. The role of FYM in improving soil organic matter and microbial activity was also evident in T8. These results suggest that integrating biofertilizers and organics with RDF can enhance soybean productivity in a sustainable manner.

Conclusion

The study demonstrated that the application of recommended doses of fertilizers (RDF) in combination with biofertilizers (Rhizobium and PSB), micronutrients, and organic amendments significantly improved the nutrient content and quality of soybean. Among all the treatments, T4 (RDF + Ammonium Molybdate + Rhizobium + PSB inoculation) was the most effective in enhancing nitrogen, phosphorus, potassium, and sulfur content in both seeds and straw, leading to the highest protein content. The addition of FYM (T8) also proved beneficial, indicating the positive role of organic amendments in nutrient availability. These findings highlight the importance of integrating chemical fertilizers with biofertilizers and organic amendments to enhance soybean yield, nutrient uptake, and overall soil health. This integrated approach not only improves crop productivity but also promotes sustainable agricultural practices by reducing dependence on synthetic fertilizers. Future research should focus on long-term field studies to assess the residual effects of such treatments on soil fertility and crop performance.

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