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Enhancing Soybean Quality, Nutrient Content and Uptake through Combined Soil and Foliar Nutrient Application under Vertisols

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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

This field experiment evaluated combined soil and foliar nutrient application for improving soybean quality, nutrient content and uptake under Vertisol conditions during the *kharif* season of 2022 at the Instructional Farm, College of Agriculture, Ummedganj-Kota, Rajasthan. The experiment used a randomized block design with three replications and ten treatments involving the recommended dose of fertiliser (RDF) and foliar applications of urea, DAP, NPK (18:18:18), Fe and Zn at 35 and 60 DAS. The treatment comprising RDF + 2% NPK (18:18:18) + 0.5% Fe + 0.5% Zn at 35 and 60 DAS produced the highest protein content (40.56%), protein yield (725.5 kg ha^{-1}), oil content (20.27%) and oil yield (362.6 kg ha^{-1}). It also recorded the highest N, P and K contents in seed and straw, together with the highest Fe and Zn contents. The same treatment recorded the maximum total uptake of N, P, K and S (181.3, 12.30, 108.5 and 15.8 kg ha^{-1}, respectively) and Fe, Zn, Mn and Cu (349.5, 82.5, 237.7 and 47.3 g ha^{-1}, respectively). Sulphur content and manganese and copper contents were not significantly influenced by the nutrient treatments. Under the conditions of this single-season experiment, supplementing RDF with foliar NPK, Fe and Zn improved soybean quality and nutrient acquisition relative to the tested treatments.

Keywords: Soybean; Glycine max; Vertisols; soil fertilisation; foliar nutrition; NPK; iron; zinc; seed quality; nutrient uptake.

1. Introduction

Soybean (*Glycine max* (L.) Merrill) is one of the most important oilseed-cum-legume crops globally, valued for its dual role as a source of edible oil and high-quality protein. Native to East Asia, soybean was introduced into India during the 1960s as a supplementary oilseed crop to address the country's edible oil deficit (Meena *et al*., 2018). From a nutritional perspective, soybean seeds contain approximately 38–42% protein and 18–20% oil, making them one of the richest plant-based sources of protein and energy (Messina, 2022). Globally, India ranks fifth in soybean area and production, following the United States, Brazil, Argentina, and China (ICAR–Indian Institute of Soybean Research, 2016). The latest final estimates indicate that soybean production in India reached 15.27 million tonnes during 2024–25, compared with 13.06 million tonnes in 2023–24. Rajasthan contributed about 1.18 million tonnes from 1.08 million ha during 2024–25, with an average productivity of 1089 kg ha^{-1}, indicating the continuing importance of soybean in the state's rainfed and semi-arid production systems (Department of Agriculture & Farmers Welfare, 2025). Recent literature also describes soybean as a multipurpose legume of broad nutritional and agronomic importance, supporting its continued relevance in crop and food systems (Mishra *et al*., 2024).

Despite its importance, soybean productivity in India remains suboptimal due to several constraints, among which nutrient deficiency and imbalance are major limiting factors. Soil application of the recommended dose of fertilisers (RDF) is fundamental for ensuring an adequate supply of essential macronutrients during the initial stages of crop growth. However, nutrient use efficiency is often limited due to losses through leaching, fixation and adverse soil conditions. Soil properties strongly influence nutrient availability and subsequent uptake by plants. This consideration is particularly important in Vertisols, which constitute an important soybean-growing soil group in central and south-eastern Rajasthan and adjoining soybean-producing regions. Vertisols generally have high clay content, high cation-exchange capacity and appreciable amounts of calcium carbonate in many locations. Such properties can restrict the availability of certain micronutrients, particularly Zn and Fe, even when their total concentrations in soil are not necessarily low. Studies conducted under Indian Vertisols have demonstrated that Zn availability and crop response can be limiting factors in soybean-based systems (Uike *et al*., 2013; Meena *et al*., 2022). Under such circumstances, foliar nutrition emerges as an effective complementary strategy for supplying nutrients directly to plant tissues during critical growth stages. Foliar application ensures rapid nutrient absorption and utilisation, thereby enhancing physiological efficiency and crop productivity. Recent studies have demonstrated that combined application of soil and foliar nutrients significantly improves soybean performance compared with sole soil fertilisation (Dass *et al*., 2022). Zinc is particularly relevant to soybean production because of its involvement in enzyme activation, membrane stability, protein synthesis, reproductive development and several physiological processes associated with seed formation. Field studies conducted on soybean have shown that soil application of Zn along with the recommended NPK fertilisation can increase seed and haulm yield as well as Zn uptake, demonstrating the importance of Zn nutrition under Rajasthan conditions (Jat *et al*., 2021). Similarly, experiments conducted in Vertisols of central India have reported significant improvements in soybean yield and Zn uptake following Zn fertilisation, confirming that the native Zn supply may not always satisfy crop demand in these soils. Recent field evidence further indicates that integrating zinc with a recommended fertiliser programme can improve soybean nutrient uptake and seed protein content (Rajendra *et al*., 2025). Longer-term field evidence in a soybean–wheat system further supports soil-test-based nutrient scheduling, including zinc-containing treatments, as an approach for improving system productivity and sustainability (Dwivedi *et al*., 2024).

Iron is another important micronutrient in soybean because of its direct involvement in chlorophyll formation, electron transport and several redox reactions associated with plant metabolism. The importance of Fe nutrition becomes more pronounced in alkaline and calcareous soils, where the concentration of plant-available Fe may be considerably lower than the total Fe present in the soil. Iron deficiency chlorosis has been specifically documented in soybean grown on calcareous Vertisols in India, demonstrating that total soil Fe does not necessarily represent Fe availability to the crop (Raj *et al*., 2019).

Foliar application of zinc and iron has been reported to significantly enhance protein and oil content in soybean seeds, as well as improve nutrient uptake efficiency under nutrient-deficient soils (Şahin & İşler, 2023). Moreover, combined application of Zn and Fe through foliar feeding has shown synergistic effects on yield and yield components, indicating improved metabolic activity and nutrient translocation within the plant system (Şahin & İşler, 2021). Recent field studies likewise indicate that foliar Zn-based treatments can increase Zn accumulation in soybean grain and can alter seed nutritional and oil-quality attributes, although the magnitude of response depends on treatment combination and experimental conditions (Han *et al*., 2024; Qureshi *et al*., 2026).

However, the literature summarised above does not fully resolve how the recommended soil-applied fertiliser dose performs when supplemented with foliar NPK together with Fe and Zn, applied individually or in combination, for simultaneous improvement of soybean seed quality and macro and micronutrient uptake under Vertisol conditions. A direct comparison of these combined nutrient options at the same critical growth stages is therefore needed within the conditions represented by the present experiment.

1.1 Objective

Considering the importance of balanced nutrient management for improving crop quality and nutrient acquisition, the present study was undertaken to investigate the effect of combined soil and foliar nutrient application on soybean quality, nutrient content, and nutrient uptake under Vertisol conditions.

2. Material and Methods

The experiment was conducted at the Instructional Farm, College of Agriculture, Ummedganj-Kota (Rajasthan) during the *Kharif* season of 2022. According to the Agro-ecological Region Map produced by the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Kota falls in Agro-ecological region No. 06. Geographically, the College of Agriculture, Ummedganj-Kota is situated in the south-eastern part of Rajasthan at 75°.25’ E longitude, 25°.13’ N latitude and an altitude of 258 metres above mean sea level. In Rajasthan, this region falls within Agro-Climatic Zone-V (Humid South Eastern Plain Zone). In the Kota region, the wet season is oppressive and mostly cloudy, the dry season is mostly clear and the climate is classified as hot throughout the year. Rainfall ranges from 550 mm to 1400 mm, most of which (80-85 per cent) is received from July to September through the south-west monsoon, whereas winter showers occur occasionally. There is a wide range of temperatures in both summer (22.1 to 45.6^{0}C), with hot winds and winter (4.0 to 23.5 ^{0}C), with some frost. The soil of the experimental field was clay loam in texture, with a moderately alkaline reaction, medium levels of available N, P_2O_5 and S, and a high level of available K_2O. The experiment was laid out in a randomised block design with three replications. The ten treatments were as follows, *viz.,* T_1- control, T_2-RDF + 2% urea spray at 35 and 60 DAS, T_3-RDF + 2% DAP spray at 35 and 60 DAS, T_4-RDF + 2% NPK (18:18:18) spray at 35 and 60 DAS, T_5-RDF + 0.5% Zn spray at 35 and 60 DAS, T_6-RDF + 0.5% Fe spray at 35 and 60 DAS, T_7-RDF + 0.5% Fe and 0.5% Zn spray at 35 and 60 DAS, T_8- RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 and 60 DAS, T_9-RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 and 60 DAS, and T_{10}- RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 and 60 DAS.

2.1 Quality Parameters

The crude protein content in seed was calculated by multiplying the nitrogen percentage in the seed by a factor of 6.25. The result was expressed as per cent protein content on a dry-weight basis.

Protein yield was worked out by using formula:

$$\text{Protein yield} = \frac{\text{protein content in seed (\%)} \times \text{seed yield}}{100}$$

Oil content was estimated as crude ether extract of the dry material using an automatic Soxhlet extraction unit (Association of Official Agricultural Chemists, 1965).

$$\text{Oil content} = \frac{W_2 - W_1}{\text{Sample weight}} \times 100$$

Where,

W_1 = Weight of empty beaker (g)
W_2 = Weight of dried extraction cup after oil extraction (g)

Oil yield was worked out by multiplying the seed yield by oil content for each corresponding treatment.

$$\text{Oil yield} = \frac{\text{oil content in seed (\%)} \times \text{seed yield}}{100}$$

2.2 Nutrient Content and Uptake

Nitrogen concentration in plant samples was determined by the Micro-Kjeldahl distillation method (Bremner, 1965). Phosphorus concentration was estimated by the vanado-molybdophosphoric acid yellow colour method (Jackson, 1967), while potassium concentration was determined using a flame photometer (Jackson, 1973). Sulphur concentration was estimated following di-acid digestion, with subsequent determination using a spectrophotometer.

For micronutrient analysis, plant samples were digested using a di-acid mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio. The concentrations of zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) were determined using an Atomic Absorption Spectrophotometer (AAS) following the procedure described by Lindsay and Norvell (1978). The uptake of individual nutrients, namely nitrogen, phosphorus, potassium, sulphur, zinc, iron, manganese and copper, at harvest was estimated using the following formula:

$$\text{Uptake} = \frac{\%\text{ content in seed or straw}}{100 \text{ x Yield (kg ha}^{-1}\text{) seed or straw}}$$

Nutrient uptake by the crop was then calculated by multiplying the per cent nutrient content in seed and straw by their respective dry matter yields and was expressed as kg ha^{-1}.

2.3 Statistical Analysis

The data recorded for different parameters were analysed using analysis of variance (ANOVA) for a randomised block design. The results are presented at the 5% level of significance (P = 0.05).

3. Results and Discussion

3.1 Quality Parameters

It is evident from the data that the protein content and protein yield of soybean were significantly influenced by various nutrient treatments (Table 1). Results showed that application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS gave significantly higher protein content (40.56 per cent) in seed and protein yield (725.5 kg ha^{-1}) of soybean compared with the rest of the treatments. The lowest protein content (34.27 per cent) and protein yield (352.7 kg ha^{-1}) were recorded under the control. The reported increases in protein concentration and protein yield were 18.33% and 105.71%, respectively. Thus, the improvement in protein yield was substantially greater than the improvement in protein concentration, indicating that increased seed production contributed considerably to the greater protein yield. The higher protein concentration may be associated with the more balanced nutrient supply provided by the treatment. Nitrogen supplied through the RDF and foliar NPK treatment provides a substrate for amino acid formation, while adequate phosphorus and potassium support energy metabolism, assimilate production and translocation during seed development. In soybean, seed protein accumulation is closely related to nitrogen acquisition and assimilation during reproductive growth (Epie *et al*., 2023). The increase in protein content might be due to iron and zinc, which are two important elements in enzyme structures involved in amino acid synthesis; amino acids form the basis of protein synthesis and protein content increased with the application of these micronutrients (Chavan *et al*., 2022). The increase in protein content could be attributed to the roles of iron and sulphur in enzyme activity and amino acid synthesis, which may help in the conversion of amino acids into high-quality protein (Biradar *et al*., 2022).

A critical examination of the data showed that the highest oil content (20.27 per cent) and oil yield (362.6 kg ha^{-1}) of soybean were recorded with the application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS and were significantly higher than those under the rest of the treatments (Table 1). Higher oil yield may be due to higher iron availability which ensured better biosynthesis of oil. Ferrous sulphate also contains sulphur in addition to iron. Sulphur is one of the important secondary nutrients required by crops; sulphur and iron might therefore have helped to obtain a higher oil yield of soybean (Kamble *et al*., 2021). The results are consistent with the findings of Kolekar *et al*. (2018).

3.2 Nutrient Content and Uptake

Results revealed that the nutrient content and uptake in soybean were influenced by the soil and foliar application of various nutrient treatments during the experiment. The results (Table 2 and Fig. 1) indicated that the highest nitrogen, phosphorus and potassium contents in seed (6.49, 0.318 and 1.70 per cent, respectively) and straw (2.04, 0.206 and 2.44 per cent, respectively) of soybean were obtained with the application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS and were significantly higher than those under the remaining treatments, while the minimum nitrogen, phosphorus and potassium contents in seed and straw were recorded under the control, whereas the various soil and foliar nutrient treatments did not significantly influence sulphur content in seed and straw of soybean.

The soil and foliar application of nutrients also showed significant effects on iron and zinc content (Table 3 and Fig. 2) in seed and straw of soybean. Application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS resulted in the highest iron and zinc contents in seed (41.23 and 20.35 ppm, respectively) and straw (86.11 and 14.21 ppm, respectively) and these values were significantly higher than those under the rest of the treatments, while the minimum values were recorded under the control during the experiment. Scrutiny of the data in Table 3 indicated that soil and foliar application of nutrients failed to show any significant effect on manganese and copper content of soybean seed and straw.

Data (Tables 4 and 5) clearly indicated that the maximum uptake values for nitrogen, phosphorus, potassium and sulphur by seed (116.1, 5.69, 30.5 and 7.5 kg ha^{-1}, respectively), straw (65.2, 6.61, 78 and 8.3 kg ha^{-1}, respectively) and total (181.3, 12.30, 108.5 and 15.8 kg ha^{-1} , respectively) of soybean were obtained with the application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS, while the minimum uptake values for seed, straw and total were recorded under the control.

The maximum uptake values for iron, zinc, manganese and copper (73.8, 36.4, 98.8 and 21.6 g ha^{-1}, respectively) by seed, straw (275.7, 46.1, 138.9 and 25.6 g ha^{-1}, respectively) and total (349.5, 82.5, 237.7 and 47.3 g ha^{-1}, respectively) were recorded with the application of RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS (Tables 6 and 7). However, the minimum values of micronutrient uptake by seed, straw and total of soybean were obtained under the control.

Table 1. Effect of soil and foliar application of nutrients on quality parameters of soybean

Treatments	Oil content (%)	Oil yield (kg ha^{-1})	Protein content (%)	Protein yield (kg ha^{-1})
T_1 : Control	18.84	193.6	34.27	352.7
T_2 : RDF + 2% urea spray at 35 & 60 DAS	19.58	282.3	37.90	546.0
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	19.59	287.7	37.38	548.7
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	19.62	308.0	38.21	599.3
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	19.24	249.7	36.83	478.9
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	19.12	240.9	36.67	461.9
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	19.43	262.4	37.00	499.3
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	19.69	313.9	38.44	612.8
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	19.71	316.1	38.69	620.2
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	20.27	362.6	40.56	725.5
SEm±	**0.18**	**11.2**	**0.61**	**22.2**
CD (P = 0.05)	**0.54**	**33.2**	**1.80**	**66.0**

Table 2. Effect of soil and foliar application of nutrients on nitrogen, phosphorus, potassium and sulphur content in seed and straw of soybean

Treatments	Nitrogen content (%)		Phosphorus content (%)		Potassium content (%)		Sulphur content (%)	
	Seed	**Straw**	**Seed**	**Straw**	**Seed**	**Straw**	**Seed**	**Straw**
T_1 : Control	5.48	1.67	0.182	0.175	1.55	2.27	0.393	0.235
T_2 : RDF + 2% urea spray at 35 & 60 DAS	6.06	1.90	0.288	0.190	1.60	2.33	0.404	0.244
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	5.98	1.89	0.296	0.196	1.61	2.34	0.407	0.245
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	6.11	1.91	0.294	0.194	1.62	2.35	0.410	0.247
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	5.89	1.82	0.270	0.188	1.58	2.31	0.398	0.239
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	5.87	1.79	0.267	0.187	1.57	2.30	0.396	0.238
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	5.92	1.83	0.279	0.189	1.59	2.32	0.401	0.243
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	6.15	1.92	0.300	0.197	1.63	2.36	0.413	0.248
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	6.19	1.93	0.304	0.198	1.64	2.37	0.416	0.252
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	6.49	2.04	0.318	0.206	1.70	2.44	0.419	0.258
SEm±	0.10	0.03	0.004	0.002	0.02	2.37	0.007	0.006
CD(P=0.05)	0.29	0.09	0.01	0.01	0.05	0.05	NS	NS

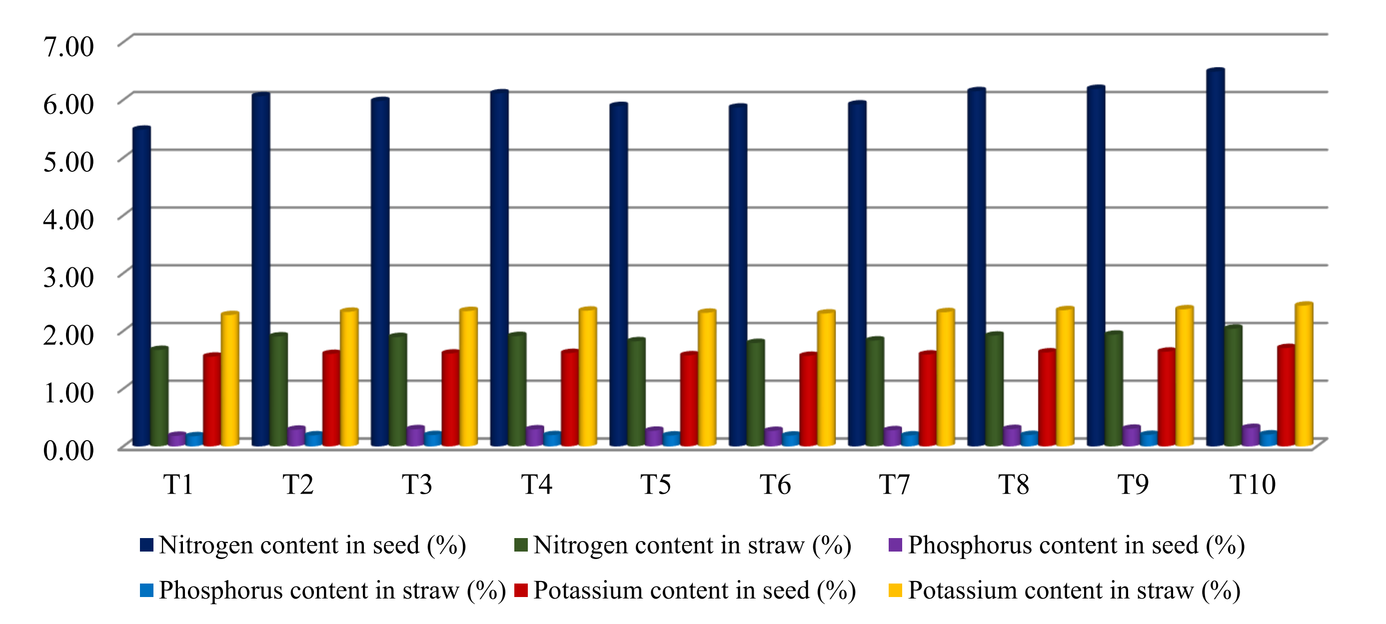

Fig. 1. Graph showing Effect of soil and foliar application of nutrients on N, P and K content in seed and straw of soybean

Table 3. Effect of soil and foliar application of nutrients on iron, zinc, manganese and copper content in seed and straw of soybean

Treatments	Iron content (ppm)		Zinc content (ppm)		Manganesecontent (ppm)		Copper content (ppm)	
	Seed	Straw	Seed	Straw	Seed	Straw	Seed	Straw
T_1 : Control	37.74	80.78	18.03	12.97	52.22	40.67	11.41	7.50
T_2 : RDF + 2% urea spray at 35 & 60 DAS	38.85	83.10	19.04	13.32	53.93	42.58	11.88	7.74
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	38.89	83.11	19.10	13.36	54.08	42.72	11.90	7.79
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	38.95	83.14	19.12	13.44	54.46	42.98	11.94	7.85
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	38.74	83.09	19.85	13.85	52.93	42.03	11.78	7.63
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	39.95	84.11	18.95	13.30	52.80	41.89	11.70	7.62
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	40.08	84.13	19.89	13.88	53.10	42.29	11.85	7.69
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	40.16	84.24	19.16	13.53	54.66	43.09	12.00	7.91
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	39.13	83.32	19.92	13.92	54.77	43.11	12.06	7.94
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	41.23	86.11	20.35	14.41	55.20	43.40	12.10	8.00
SEm±	**0.35**	**0.61**	**0.14**	**0.16**	**0.98**	**0.73**	**0.13**	**0.11**
CD(P=0.05)	**1.05**	**1.81**	**0.41**	**0.48**	**NS**	**NS**	**NS**	**NS**

Table 4. Effect of soil and foliar application of nutrients on nitrogen and phosphorus uptake by seed, straw and total of soybean crop

Treatments	Nitrogen uptake (kg ha^{-1})			Phosphorus uptake (kg ha^{-1})		
	Seed	**Straw**	**Total**	**Seed**	**Straw**	**Total**
T_1 : Control	56.4	34.4	90.8	1.87	3.61	5.49
T_2 : RDF + 2% urea spray at 35 & 60 DAS	87.4	53.2	140.5	4.15	5.31	9.46
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	87.8	53.5	141.3	4.36	5.53	9.88
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	95.9	54.4	150.3	4.61	5.52	10.12
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	76.6	46.8	123.4	3.51	4.82	8.32
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	73.9	45.0	118.9	3.37	4.69	8.06
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	79.9	48.2	128.1	3.77	4.94	8.72
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	98.0	54.9	152.9	4.78	5.63	10.41
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	99.2	55.7	155.0	4.88	5.70	10.58
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	116.1	65.2	181.3	5.69	6.61	12.30
SEm±	**3.6**	**2.5**	**5.5**	**0.17**	**0.22**	**0.34**
CD(P=0.05)	**10.6**	**7.4**	**16.3**	**0.50**	**0.65**	**1.02**

Table 5. Effect of soil and foliar application of nutrients on potassium and sulphur uptake by seed, straw and total of soybean crop

Treatments	Potassium uptake (kg ha^{-1})			Sulphur uptake (kg ha^{-1})		
	Seed	**Straw**	**Total**	**Seed**	**Straw**	**Total**
T_1 : Control	16.0	46.8	62.8	4.0	4.8	8.9
T_2 : RDF + 2% urea spray at 35 & 60 DAS	23.1	65.1	88.1	5.8	6.8	12.6
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	23.6	66.2	89.8	6.0	6.9	12.9
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	25.4	66.9	92.2	6.4	7.0	13.5
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	20.5	59.4	79.8	5.2	6.1	11.3
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	19.7	57.8	77.5	5.0	6.0	11.0
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	21.4	60.9	82.3	5.4	6.4	11.8
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	25.9	67.5	93.4	6.6	7.1	13.7
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	26.3	68.3	94.6	6.7	7.2	13.9
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	30.5	78.0	108.5	7.5	8.3	15.8
SEm±	**0.9**	**2.6**	**3.3**	**0.3**	**0.3**	**0.5**
CD(P=0.05)	**2.8**	**7.8**	**9.7**	**0.8**	**1.0**	**1.5**

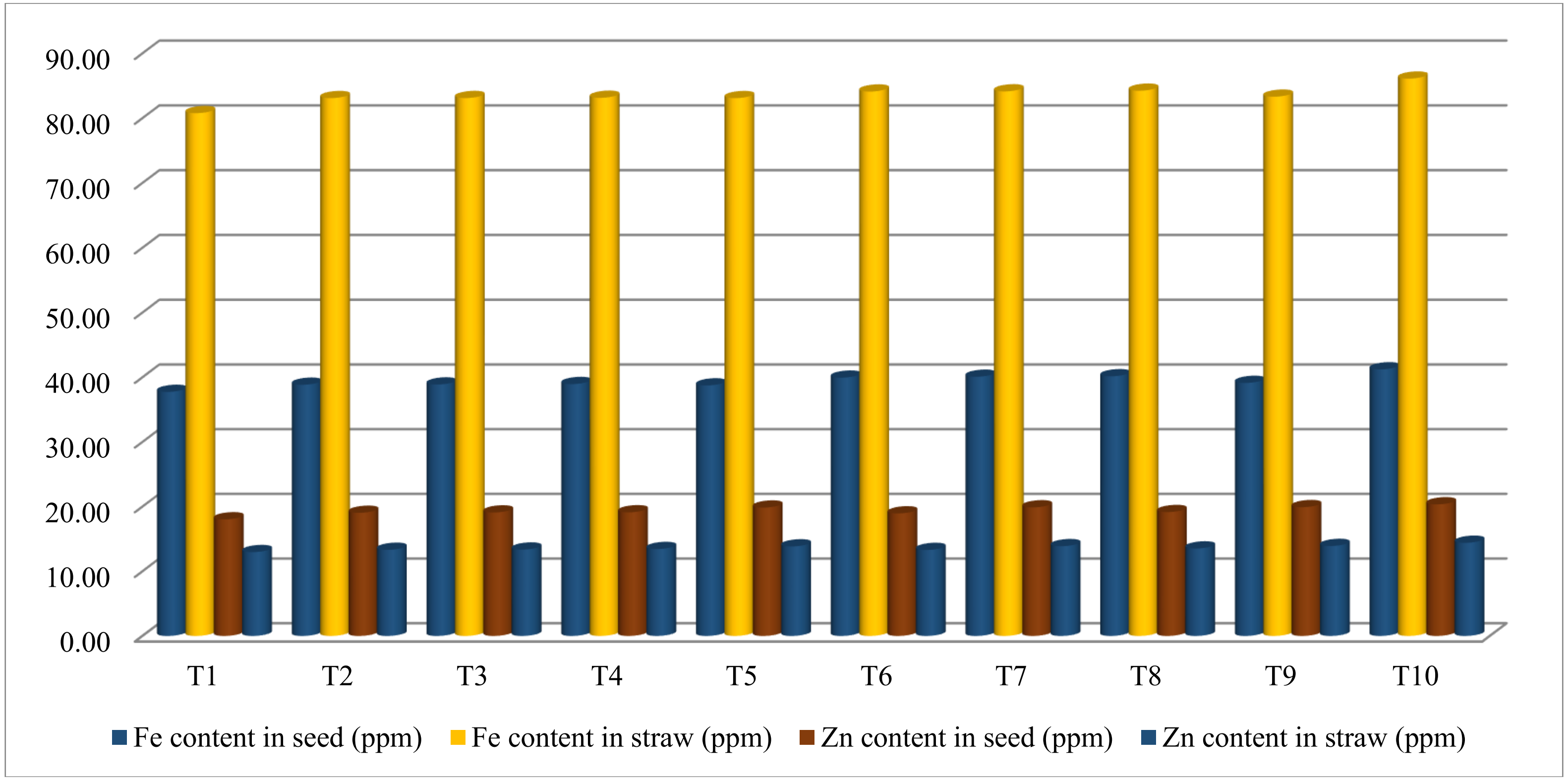

Fig. 2. Graph showing Effect of soil and foliar application of nutrients on Fe and Zn content in seed and straw of soybean

Table 6. Effect of soil and foliar application of nutrients on iron and zinc uptake by seed, straw and total of soybean crop

Treatments	**Iron (g ha^{-1})**			**Zinc (g ha^{-1})**		
	Seed	**Straw**	**Total**	**Seed**	**Straw**	**Total**
T_1 : Control	38.7	166.4	205.2	18.5	26.7	45.2
T_2 : RDF + 2% urea spray at 35 & 60 DAS	56.0	232.0	288.0	27.5	37.2	64.6
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	57.1	234.7	291.9	28.1	37.7	65.8
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	61.1	236.5	297.6	30.0	38.2	68.2
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	50.3	213.1	263.4	25.8	35.5	61.3
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	50.3	211.4	261.7	23.9	33.4	57.3
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	54.1	220.5	274.6	26.8	36.4	63.2
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	64.0	241.1	305.1	30.5	38.7	69.3
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	62.7	239.9	302.7	31.9	40.0	71.9
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	73.8	275.7	349.5	36.4	46.1	82.5
SEm±	**2.2**	**9.2**	**10.6**	**1.1**	**1.4**	**2.2**
CD(P=0.05)	**6.6**	**27.5**	**31.6**	**3.3**	**4.1**	**6.6**

Table 7. Effect of soil and foliar application of nutrients on manganese and copper uptake by seed, straw and total of soybean crop

Treatments	**Manganese (g ha^{-1})**			**Copper (g ha^{-1})**		
	Seed	**Straw**	**Total**	**Seed**	**Straw**	**Total**
T_1 : Control	53.7	83.8	137.4	11.7	15.5	27.2
T_2 : RDF + 2% urea spray at 35 & 60 DAS	77.7	118.9	196.7	17.1	21.6	38.7
T_3 : RDF + 2% DAP spray at 35 & 60 DAS	79.4	120.7	200.1	17.5	22.0	39.5
T_4 : RDF + 2% NPK (18:18:18) spray at 35 & 60 DAS	85.4	122.3	207.7	18.7	22.3	41.1
T_5 : RDF + 0.5% Zn spray at 35 & 60 DAS	68.7	108.0	176.7	15.3	19.5	34.9
T_6 : RDF + 0.5% Fe spray at 35 & 60 DAS	66.5	105.2	171.7	14.7	19.1	33.9
T_7 : RDF + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	71.7	110.3	182.0	16.0	20.1	36.1
T_8 : RDF + 2% NPK (18:18:18) + 0.5% Fe spray at 35 & 60 DAS	87.1	123.3	210.5	19.1	22.6	41.8
T_9 : RDF + 2% NPK (18:18:18) + 0.5% Zn spray at 35 & 60 DAS	87.8	124.3	212.1	19.3	22.9	42.2
T_{10} : RDF + 2% NPK (18:18:18) + 0.5% Fe and 0.5% Zn spray at 35 & 60 DAS	98.8	138.9	237.7	21.6	25.6	47.3
SEm±	**3.5**	**4.6**	**6.7**	**0.8**	**0.8**	**1.4**
CD(P=0.05)	**10.4**	**13.7**	**19.9**	**2.3**	**2.4**	**4.3**

Higher nutrient content in seed might be due to foliar application of nutrients that were directly absorbed by the crop and also due to the mobilisation of nutrients from leaves and stems to the seed. Foliar application of zinc and iron at critical stages such as pre-flowering, flowering and pod setting might have increased the transfer of photosynthetic products from source to sink, resulting in higher N, P, K, S, Zn and Fe uptake (Biradar *et al*., 2022). Foliar application of $FeSO_4$ may increase photosynthetic activity and the demand for essential elements, thereby enhancing both absorption and transportation of elements. Foliar zinc spray improved root growth and prevented nutritional disorders, consequently increasing Zn uptake; this response may also have been associated with the interaction between Zn and Fe (Hanwate *et al*., 2019). Higher yield ultimately leads to greater nutrient uptake by the crop. These findings are in close conformity with those of Kolekar *et al*. (2018), Kale *et al*. (2019), Rathod *et al*. (2020), Yadav *et al*. (2022) and Kamble *et al*. (2022).

4. Conclusion

The study indicated that combined soil and foliar nutrient application improved soybean quality and nutrient uptake under Vertisol conditions. The application of RDF + 2% NPK (18:18:18) + 0.5% Fe + 0.5% Zn as a foliar spray at 35 and 60 DAS resulted in the highest protein content, oil content, protein yield, oil yield and nutrient uptake among the tested treatments. The treatment also improved nitrogen, phosphorus, potassium, iron and zinc content in seed and straw. The superior performance of this treatment indicates that supplementation of the recommended soil-applied fertiliser with foliar NPK, Fe and Zn during crop growth can improve nutrient acquisition and seed quality under the conditions of the present experiment. However, the results are based on a single-season field experiment at one location and should not be generalised to all Vertisols or agro-climatic conditions. Multi-season and multi-location experiments are required to confirm the consistency, agronomic reliability and economic feasibility of this nutrient-management strategy before wider-scale recommendation.

5. Limitations

The study was conducted during a single kharif season at one location under the Vertisol conditions of Ummedganj-Kota, with three replications. Consequently, the observed treatment responses may be influenced by season-specific environmental conditions and site-specific soil characteristics, which restrict the broader generalisability of the findings. The consistency of the observed improvements in soybean quality, nutrient content and nutrient uptake should therefore be validated through multi-season and multi-location field experiments across representative Vertisol environments before wider agronomic recommendations are made.

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. Grammarly and ChatGPT 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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