



# **Influence of Different Micronutrient Grades on Nutrient Availability, Nutrient Use Efficiency, Nutrient Mining and Economics of French Bean (*Phaseolus vulgaris* L.)**

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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**

French bean (*Phaseolus vulgaris* L.) is an important leguminous vegetable crop valued for its dietary protein, minerals and role in improving farm income. Balanced micronutrient management is essential for sustaining soil fertility, improving nutrient-use efficiency and enhancing crop productivity. This study evaluated the

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influence of different micronutrient grades on post-harvest nutrient availability, nutrient-use efficiency, nutrient balance and economics of French bean (*Phaseolus vulgaris* L.) cv. 'Phule Vijaya'. The field experiment was conducted during the Rabi season of 2023–2024 at the Department of Soil Science, College of Agriculture, Vasantnao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra. The experiment was laid out in a randomised block design with ten treatments and three replications. The soil was clayey, calcareous, moderately alkaline, low in organic carbon, available nitrogen and available phosphorus, high in available potassium, sufficient in sulphur and deficient in DTPA-extractable Zn, Fe, Cu and Mn and available B. The treatment RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) recorded the highest post-harvest available N (204.89 kg ha<sup>-1</sup>), P (22.56 kg ha<sup>-1</sup>) and K (839.50 kg ha<sup>-1</sup>). The same treatment also recorded the highest apparent nutrient recovery and agronomic efficiency for nitrogen, phosphorus and potassium. The highest actual gains of nitrogen (72.91 kg ha<sup>-1</sup>), phosphorus (10.70 kg ha<sup>-1</sup>) and potassium (127.72 kg ha<sup>-1</sup>) were also observed under this treatment. Economically, RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> produced the highest yield (1105.41 kg ha<sup>-1</sup>), gross monetary return (₹72,711.17), net monetary return (₹43,226.17) and B:C ratio (2.47). The results indicate that gypsum-based soil-applied micronutrient formulation with RDF improved nutrient management and profitability in French bean under the study conditions.

*Keywords:* French bean; *Phaseolus vulgaris* L.; micronutrient grades; gypsum-based formulation; foliar fertilisation; soil application; nutrient availability; nutrient-use efficiency; nutrient balance; benefit:cost ratio.

## 1. Introduction

French bean (*Phaseolus vulgaris* L.) is an important vegetable crop belonging to the family Fabaceae. It is commonly known as rajmash, rajma, haricot bean, field bean, kidney bean, snap bean and pole bean. It is an inexpensive source of vegetable protein, vitamins and minerals, including calcium and iron. In India, 48, 12, 5, 4, 33, 13 and 41% of soils are affected by deficiencies of Zn, Fe, Mn, Cu, B, Mo and S, respectively (Shukla & Behera, 2011). The pattern of micronutrient deficiencies in India is changing from single-nutrient deficiency to clustered micronutrient deficiencies across large areas. Such multiple micronutrient deficiencies in soils and crops may reduce crop productivity and contribute to nutritional constraints. Micronutrient deficiencies are also difficult to diagnose. Recent studies on French bean and common bean have reported that foliar micronutrient fertilisation, including mixed nano-micronutrients and zinc-iron fertilisation, can influence growth, quality and yield-related responses (Maurya et al., 2024; Merkeb et al., 2024).

Foliar fertiliser application can be designed to meet specific plant requirements for one or more micro- and macronutrients, especially trace minerals, and can help correct deficiencies, strengthen weak or damaged crops, accelerate growth and improve plant performance. It can also be targeted to particular crop-development stages to achieve specific objectives and may serve as a useful method for fine-tuning a high-fertility programme. Nutrient availability and nutrient-use responses are also affected by rhizosphere processes, integrated fertiliser management and broader nutrient-use-efficiency mechanisms, indicating the need to evaluate formulation-specific nutrient behaviour under field conditions (Adal, 2023; Rosolem & Husted, 2024; Wabela et al., 2024). However, the relative performance of soil-applied gypsum- and bentonite-based micronutrient grades and chelated foliar formulations for post-harvest nutrient availability, nutrient mining, nutrient-use efficiency and economics in French bean remains inadequately documented under the present experimental conditions (Amrutkar et al., 2025). Therefore, the present investigation was undertaken to determine the effects of micronutrient grades on nutrient availability in soil after French bean harvest, nutrient mining, nutrient-use efficiency and the economics of micronutrient-grade use in French bean production.

## 2. Materials and Methods

The study was undertaken during the Rabi season of 2023–2024 at the research farm of the Department of Soil Science, College of Agriculture, Vasantnao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra. The experiment was arranged in a randomised block design comprising ten treatments, each replicated three times. The individual plot size was 5.40 × 4.50 m<sup>2</sup>.

The experimental soil was clayey in texture, calcareous and moderately alkaline in reaction. It was low in organic carbon (3.27 g kg<sup>-1</sup>), available nitrogen (131.98 kg ha<sup>-1</sup>) and available phosphorus (11.86 kg ha<sup>-1</sup>), but high in available potassium (711.78 kg ha<sup>-1</sup>). Available sulphur was sufficient (10.12 kg ha<sup>-1</sup>), whereas DTPA-

extractable zinc ( $0.68 \text{ mg kg}^{-1}$ ), iron ( $4.75 \text{ mg kg}^{-1}$ ), copper ( $1.33 \text{ mg kg}^{-1}$ ), manganese ( $2.58 \text{ mg kg}^{-1}$ ) and available boron ( $0.33 \text{ mg kg}^{-1}$ ) were deficient. The recommended fertiliser dose of 120:60:60 kg NPK  $\text{ha}^{-1}$  was applied. Half of the nitrogen, together with the full quantities of phosphorus and potassium, was applied as a basal dose, while the remaining nitrogen was supplied subsequently as a top dressing.

## 2.1 Preparation of Soil and Foliar Micro-nutrient Formulation Grades

In the present investigation, various micronutrient formulations were prepared in accordance with the nutrient standards presented in Table 1. The soil-applied micronutrient formulations, Grade-I(a) (gypsum-based) and Grade-I(b) (bentonite-based), comprised Zn 6%, Fe 5%, Mn 1%, B 1% and Cu 0.5%. The government-notified Grade-I(c) (gypsum-based) micronutrient formulation was prepared as per the recommendations of the Maharashtra State Department of Agriculture, containing Zn 5%, Fe 2%, Mn 1%, B 1.0% and Cu 0.5%.

Chelated foliar micronutrient formulations were prepared as Grade-II(a) with EDTA, Grade-II(b) with glycine, Grade-II(c) with EDTA and Grade-II(d) with citric acid, each containing Zn 4%, Fe 3%, Mn 1%, B 0.5%, Cu 0.2% and Mo 0.1%. In addition, Grade-II(e), chelated with EDTA, contained Zn 4.5%, Fe 3.5%, Mn 1%, B 0.5%, Cu 0.2% and Mo 0.1%. All formulations were prepared under laboratory conditions using laboratory-grade chemicals, including ferrous sulphate, zinc sulphate, manganese sulphate, copper sulphate, boric acid, sodium tetraborate and ammonium molybdate.

The nutrient sources used for soil and foliar micronutrient formulation are presented in Table 2.

**Table 1. Content of soil and foliar micro-nutrient grades**

Grade	Zn (%)	Fe (%)	Mn (%)	B (%)	Cu (%)	Mo (%)
<b>Soil application</b>						
Grade-I (a) and (b)	6	5	1	1	0.5	-
Govt. notified Grade-I (c)	5	2	1	1	0.5	-
<b>Foliar application</b>						
Grade-II (a) to (d)	4.5	3.5	1	0.5	0.2	0.1
Govt. notified Grade-II (e)	3	2.5	1	0.5	1	0.1

Source: Amrutkar et al., 2025

### Sources:

#### Soil application (Grade-I was prepared in 1 kg pack)

<b>Formulation-I</b>	
Grade-I (a)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (Gypsum based)
Grade-I (b)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (Bentonite based)
Govt. notified Grade-I (c)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (Gypsum based)

#### Foliar application (Grade-II was prepared in 1 liter capacity)

<b>Formulation-II</b>	
Grade-II (a)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ (Borax) + $\text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O} + (\text{NH}_4)_2\text{MoO}_4$ (Chelation with EDTA)
Grade-II (b)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O} + (\text{NH}_4)_2\text{MoO}_4$ (Chelation with glycine)
Grade-II (c)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3$ (Boric acid) + $\text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O} + (\text{NH}_4)_2\text{MoO}_4$ (Chelation with EDTA)
Grade-II (d)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O} + (\text{NH}_4)_2\text{MoO}_4$ (Chelation with citric acid)
Govt. notified Grade-II (e)	: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O} + \text{FeSO}_4 \cdot 7\text{H}_2\text{O} + \text{H}_3\text{BO}_3 + \text{MnSO}_4 \cdot \text{H}_2\text{O} + \text{CuSO}_4 \cdot 5\text{H}_2\text{O} + (\text{NH}_4)_2\text{MoO}_4$ (Chelation with EDTA)

**Table 2. Sources used for soil and foliar micronutrient formulation**

Sr. No.	Nutrient	Source	Nutrient content (%)
1	Fe	FeSO <sub>4</sub> .7H <sub>2</sub> O	20.10
2.	Mn	MnSO <sub>4</sub> .H <sub>2</sub> O	32.51
3.	Zn	ZnSO <sub>4</sub> .7H <sub>2</sub> O	22.75
4.	Cu	CuSO <sub>4</sub> .5H <sub>2</sub> O	25.47
5.	B	H <sub>3</sub> BO <sub>3</sub>	17.49
6.	B	Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> .10H <sub>2</sub> O	11.34
7.	Mo	(NH <sub>4</sub> ) <sub>2</sub> MoO <sub>4</sub>	54.35

Source: Amrutkar et al., 2025

The available nitrogen content was assessed by the alkaline potassium permanganate method described by Subbiah and Asija (1956). Available phosphorus was extracted from soil using 0.5 M sodium bicarbonate and measured colorimetrically at 820 nm following Olsen's method (Olsen et al., 1954). Available potassium was extracted using neutral normal ammonium acetate (NH<sub>4</sub>CH<sub>3</sub>CO<sub>2</sub>), and the potassium content in the extract was determined using a flame photometer according to Jackson (1973). Nutrient-use efficiency for nitrogen, phosphorus and potassium in the French bean field experiment was calculated using different measures of nutrient-use efficiency, namely apparent nutrient recovery, agronomic efficiency and physiological efficiency, as described below:

Apparent nutrient recovery (ANR) was calculated using nutrient uptake in the control and fertilised plots and the quantity of nutrient applied (Baligar et al., 2001).

$$\text{ANR (kg ha}^{-1}\text{)} = \frac{\text{Nutrient uptake from (fertilized plot - control plot) kg ha}^{-1}}{\text{Quantity of nutrient applied (kg ha}^{-1}\text{)}}$$

Agronomic efficiency (AE) was calculated using the yield of the fertilised plot, yield of the control plot and quantity of fertiliser applied according to the following formula (Baligar et al., 2001).

$$\text{AE (kg ha}^{-1}\text{)} = \frac{\text{Yield of fertilized plot - Yield of control plot) kg ha}^{-1}}{\text{Quantity of fertilizer applied (kg ha}^{-1}\text{)}}$$

Physiological efficiency (PE) was calculated using the yield of the fertilised plot, yield of the control plot, total uptake from the fertilised plot and total uptake from the control plot. It is defined as the yield increase in relation to the increase in nutrient uptake by the above-ground plant parts (Fixen et al., 2014).

$$\text{PE (kg ha}^{-1}\text{)} = \frac{\text{Yield of fertilized plot - Yield of control plot) kg ha}^{-1}}{\text{(Nutrient uptake from fertilized plot - Nutrient uptake from control plot) kg ha}^{-1}}$$

The economics of French bean cultivation were worked out using the following formulae:

- 1) Gross Monetary Return = Yield X selling price
- 2) Net Monetary Return = Gross Monetary Return – Cost of Cultivation
- 3) Benefit cost ratio =  $\frac{\text{Gross returns (Rs.)}}{\text{Cost of cultivation (Rs.)}}$

## 2.2 Statistical Analysis and Interpretation of Data

The data generated from the laboratory experiment were analysed using a randomised block design. Statistical analysis and interpretation were carried out following the procedures described in *Statistical Methods for Agricultural Workers* by Panse and Sukhatme (1985). Where required, the appropriate standard error (S.E.) and critical difference (C.D.) values at the 5% significance level were computed and used for interpreting the results.

### 3. Results and Discussion

#### 3.1 Results

##### 3.1.1 Effect of Different Micronutrient Grades on Availability of Macronutrients in Soil at Harvest Stage of French Bean

**Available nitrogen:** The available nitrogen content in the soil varied from 131.71 to 204.89 kg ha<sup>-1</sup> (Fig. 1). The highest available nitrogen content (204.89 kg ha<sup>-1</sup>) was observed in RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based), followed by RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based), with an available nitrogen content of 200.70 kg ha<sup>-1</sup>. However, the lowest soil nitrogen content was recorded in the absolute control (131.71 kg ha<sup>-1</sup>).

**Available phosphorus:** Available phosphorus content in the French bean-growing soil ranged from 13.75 to 22.56 kg ha<sup>-1</sup> (Fig. 1). The highest phosphorus content (22.56 kg ha<sup>-1</sup>) was observed in RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based), which was at par with RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based), i.e., 21.02 kg ha<sup>-1</sup>. Conversely, the lowest phosphorus content was recorded in the absolute control (11.13 kg ha<sup>-1</sup>).

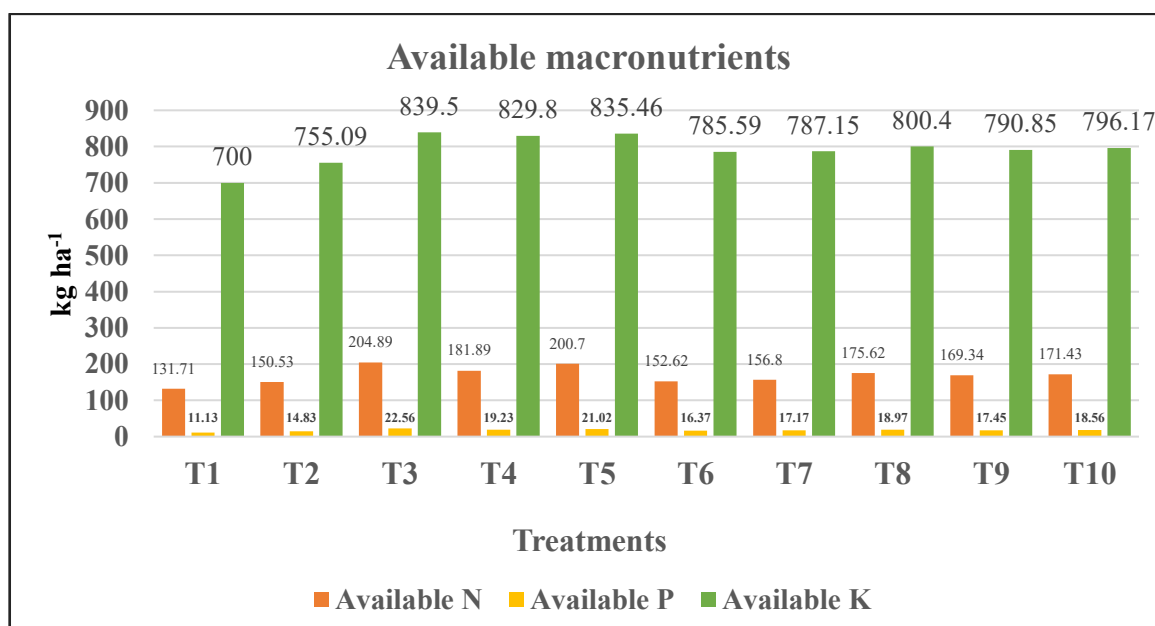


Fig. 1. Effect of different micro-nutrient grades on soil N, P and K after harvest of french bean

**Available potassium:** The available potassium content in the soil at harvest stage of French bean ranged from 700.00 to 839.50 kg ha<sup>-1</sup> (Fig. 1). Available potassium was maximum (839.50 kg ha<sup>-1</sup>) with the recommended dose of N, P and K along with micronutrient Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based). It was at par with all treatments except the absolute control and RDF. Treatments T4, T5, T6, T7, T8, T9 and T10 recorded 829.80, 835.46, 785.59, 787.15, 800.40, 790.85 and 796.17 kg ha<sup>-1</sup> available potassium, respectively, in French bean-growing soil. The minimum available potassium (700.00 kg ha<sup>-1</sup>) was recorded in the absolute control.

##### 3.1.2 Effect of Different Micro-nutrient Grades on Nutrient Use Efficiency

###### 3.1.2.1 Nitrogen Use efficiency

Among all treatments, application of RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) (T3) recorded the highest apparent nutrient recovery (9.61%), followed by T5, which included RDF + Govt. notified Grade-I(c) @ 25 kg

ha<sup>-1</sup> (gypsum-based), with 9.40%. This was significantly superior to RDF alone (T2), which recorded 2.45% (Table 3). These findings indicate that micronutrient application enhanced the ability of the French bean crop to absorb applied nitrogen more efficiently from the soil.

In terms of agronomic efficiency, which reflects the yield increase per unit of N applied, T3 [RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based)] again performed best, with 4.45 kg kg<sup>-1</sup>, followed closely by T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)], with 4.25 kg kg<sup>-1</sup>. Both treatments were statistically superior to RDF alone (T2), which recorded an agronomic efficiency of 1.92 kg kg<sup>-1</sup>. The increased agronomic-use efficiency in micronutrient treatments can be attributed to better solubilisation and mobilisation of native and applied nitrogen, resulting in improved uptake and productivity. Table 3 presents the variation in physiological efficiency across different treatments in French bean. Treatment T9 [RDF + Grade-II(d) @ 0.5 and 1% (chelation with citric acid)] recorded the highest physiological efficiency (78.19 kg kg<sup>-1</sup>), indicating strong internal conversion of absorbed nitrogen into economic yield. However, its apparent nutrient recovery and agronomic-use efficiency (3.68% and 3.25 kg kg<sup>-1</sup>, respectively) were moderate. The absolute control treatment (T1), which did not receive any nitrogen input, exhibited zero values for all efficiency parameters, establishing a baseline for comparison.

**Table 3. Effect of RDF and different micronutrient grades on nitrogen use efficiency**

Treatment details	Nitrogen Use Efficiency		
	Apparent Nutrient Recovery %	Agronomic Efficiency (Kg Kg <sup>-1</sup> )	Physiological Efficiency (Kg Kg <sup>-1</sup> )
T <sub>1</sub> : Absolute control	0.00	0.00	0.00
T <sub>2</sub> : RDF (As per crop)	2.45	1.92	58.57
T <sub>3</sub> : RDF+ Grade-I (a) @ 25kg ha <sup>-1</sup> (Gypsum based)	9.61	4.45	33.84
T <sub>4</sub> : RDF+ Grade-I(b) @ 25kg ha <sup>-1</sup> (Bentonite based)	7.59	3.69	39.24
T <sub>5</sub> : RDF+ Govt. notified Grade-I (c) @ 25 kg ha <sup>-1</sup> (Gypsum based)	9.40	4.25	35.46
T <sub>6</sub> : RDF+ Grade-II (a) @ 0.5&1% (Chelation with EDTA)	3.15	2.14	50.92
T <sub>7</sub> : RDF+ Grade-II (b) @ 0.5&1% (Chelation with glycine)	3.38	2.78	66.79
T <sub>8</sub> : RDF+ Grade-II (c) @ 0.5&1% (Chelation with EDTA)	5.74	3.60	56.58
T <sub>9</sub> : RDF+ Grade-II (d) @ 0.5&1% (Chelation with citric acid)	3.68	3.25	78.19
T <sub>10</sub> :RDF+ Govt. notified Grade-II (e) @ 0.5 & 1% (Chelation with EDTA)	5.23	3.42	55.35
SE ±	0.20	0.10	1.79
CD at 5%	0.58	0.30	5.31

### 3.1.2.2 Phosphorus Use Efficiency

Among all treatments, application of RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) (T3) recorded the highest apparent nutrient recovery (14.60%), followed by T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)], with 13.56%. This was significantly superior to RDF alone (T2), which recorded 4.30%. These findings indicate that gypsum-based micronutrient application enhanced the ability of French bean plants to absorb applied phosphorus more efficiently from the soil.

Table 4 presents the variation in agronomic efficiency among treatments in French bean. In terms of agronomic efficiency, which reflects the yield increase per unit of P applied, T3 [RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based)] again recorded the highest agronomic-use efficiency (8.91 kg kg<sup>-1</sup>), followed by T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)], with 8.51 kg kg<sup>-1</sup>. Both treatments were statistically superior to RDF alone (T2), which recorded an agronomic-use efficiency of 3.29 kg kg<sup>-1</sup>. The increased agronomic-use efficiency in micronutrient treatments can be attributed to better solubilisation and mobilisation of native and applied phosphorus, resulting in improved uptake and productivity.

Physiological efficiency, which indicates the efficiency of the crop in converting absorbed phosphorus into economic yield, was highest in T7 [RDF + Grade-II(b) @ 0.5 and 1% (chelation with glycine)], with 95.31 kg kg<sup>-1</sup>. This implies that although absolute phosphorus recovery was lower in T7, internal utilisation of the absorbed phosphorus was highly efficient.

### 3.1.2.3 Potassium Use Efficiency

Among all treatments, application of RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) (T3) recorded the highest apparent nutrient recovery (69.06%), followed by T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)], with 57.08%. This was significantly superior to RDF alone (T2), which recorded 15.18% (Table 5). These findings indicate that gypsum-based micronutrient application enhanced the ability of French bean plants to absorb applied potassium more efficiently from the soil.

Agronomic efficiency reflects the yield increase per unit of potassium applied. Treatment T3 [RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based)] recorded the highest agronomic-use efficiency (8.91 kg kg<sup>-1</sup>), followed by T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)], with 8.51 kg kg<sup>-1</sup>. Both treatments were statistically superior to RDF alone (T2), which recorded an agronomic-use efficiency of 3.29 kg kg<sup>-1</sup>. The increased agronomic-use efficiency in micronutrient treatments can be attributed to better solubilisation and mobilisation of native and applied potassium, resulting in improved uptake and productivity.

Physiological efficiency, which indicates the efficiency of the crop in converting absorbed potassium into economic yield, was highest in T7 [RDF + Grade-II(b) @ 0.5 and 1% (chelation with glycine)], with 29.61 kg kg<sup>-1</sup>. This implies that although absolute potassium recovery was lower in T7, internal utilisation of the absorbed potassium was highly efficient.

**Table 4. Effect of RDF and different micronutrient grades on phosphorous efficiency**

Treatment details	Phosphorous Use Efficiency		
	Apparent Nutrient Recovery %	Agronomic Efficiency (Kg Kg <sup>-1</sup> )	Physiological Efficiency (Kg Kg <sup>-1</sup> )
T1: Absolute control	0.00	0.00	0.00
T2: RDF (As per crop)	4.30	3.29	78.12
T3: RDF+ Grade-I (a) @ 25 kg ha <sup>-1</sup> (Gypsum based)	14.60	8.91	60.92
T4: RDF+ Grade-I(b) @ 25 kg ha <sup>-1</sup> (Bentonite based)	11.08	7.38	66.48
T5: RDF+ Govt. notified Grade-I (c) @ 25 kg ha <sup>-1</sup> (Gypsum based)	13.56	8.51	62.89
T6: RDF+ Grade-II (a) @ 0.5&1% (Chelation with EDTA)	5.25	3.73	78.20
T7: RDF+ Grade-II (b) @ 0.5&1% (Chelation with glycine)	6.04	5.57	95.31
T8: RDF+ Grade-II (c) 0.5&1% (Chelation with EDTA)	10.11	7.21	71.11
T9: RDF+ Grade-II (d) 0.5&1% (Chelation with citric acid)	6.93	6.50	93.82
T10: RDF+ Govt. notified Grade-II(e) @0.5&1% (Chelation with EDTA)	8.97	6.84	77.33
SE ±	0.34	0.14	3.48
CD at 5%	1.02	0.41	10.33

**Table 5. Effect of RDF and different micronutrient grades on potassium efficiency**

Treatment Details	Potassium Use Efficiency		
	Apparent Nutrient Recovery%	Agronomic Efficiency (Kg Kg <sup>-1</sup> )	Physiological Efficiency (Kg Kg <sup>-1</sup> )
T1: Absolute control	0.00	0.00	0.00
T2: RDF (As per crop)	15.18	3.29	23.13
T3: RDF+ Grade-I (a) @ 25kg ha <sup>-1</sup> (Gypsum based)	69.06	8.91	13.00
T4: RDF+ Grade-I(b) @ 25kg ha <sup>-1</sup> (Bentonite based)	44.02	7.38	16.78
T5: RDF+ Govt. notified Grade-I (c) @ 25 kg ha <sup>-1</sup> (Gypsum based)	57.08	8.51	15.17
T6: RDF+ Grade-II (a) @ 0.5&1% (Chelation with EDTA)	19.93	3.73	21.49
T7: RDF+ Grade-II (b) @ 0.5&1% (Chelation with glycine)	21.03	5.57	29.61
T8: RDF+ Grade-II (c) @ 0.5&1% (Chelation with EDTA)	39.47	7.21	18.73
T9: RDF+ Grade-II (d) @ 0.5&1% (Chelation with citric acid)	23.08	6.50	29.05
T10: RDF+ Govt. notified Grade-II (e) @ 0.5&1% (Chelation with EDTA)	33.58	6.84	20.36
SE ±	1.47	0.14	0.91
CD at 5%	4.35	0.41	2.71

**Table 6. Effect of different micro-nutrient grades on nutrient balance of available N, P and K in soil**

Treatments	N		P		K	
	Apparent loss/gain (kg ha <sup>-1</sup> )	Actual gain/loss (kg ha <sup>-1</sup> )	Apparent loss/gain (kg ha <sup>-1</sup> )	Actual gain/loss (kg ha <sup>-1</sup> )	Apparent loss/gain (kg ha <sup>-1</sup> )	Actual gain/loss (kg ha <sup>-1</sup> )
T <sub>1</sub> : Absolute control	-108.7	-0.27	-58.12	-0.73	-34.4	-0.73
T <sub>2</sub> : RDF (As per crop)	-87	18.55	-53.22	2.97	18.75	43.31
T <sub>3</sub> : RDF+ Grade-I (a) @ 25kg ha <sup>-1</sup> (Gypsum based)	-23.87	72.91	-39.51	10.7	135.49	127.72
T <sub>4</sub> : RDF+ Grade-I(b) @ 25kg ha <sup>-1</sup> (Bentonite based)	-50.35	49.91	-44.88	7.37	110.76	118.02
T <sub>5</sub> : RDF+ Govt. notified Grade-I (c) @ 25kg ha <sup>-1</sup> (Gypsum based)	-28.49	68.72	-41.68	9.16	124.26	123.68
T <sub>6</sub> : RDF+ Grade-II (a) @ 0.5&1% (Chelation with EDTA)	-84.06	20.64	-51.17	4.51	52.1	73.81
T <sub>7</sub> : RDF+ Grade-II (b) @ 0.5&1% (Chelation with glycine)	-79.52	24.82	-50	5.31	54.32	75.37
T <sub>8</sub> : RDF+ Grade-II (c) 0.5&1% (Chelation with EDTA)	-56.4	43.64	-46.06	7.11	78.64	88.62
T <sub>9</sub> : RDF+ Grade-II (d) 0.5&1% (Chelation with citric acid)	-65.56	37.36	-49.44	5.59	59.25	79.07
T <sub>10</sub> : RDF+ Govt. notified Grade-II (e) @ 0.5 & 1% (Chelation with EDTA)	-61.74	39.45	-47.22	6.7	70.87	84.39

**Table 7. Benefit cost ratio as influenced by different micro-nutrient grades in french bean**

Treatment details	Yield (kg ha <sup>-1</sup> )	GMR (Rs)	Cost of cultivation (Rs.)	NMR (Rs.)	B:C ratio
T <sub>1</sub> : Absolute control	571.00	37632.67	25338	12294.67	1.49
T <sub>2</sub> : RDF (As per crop)	735.11	48414.15	26996	21418.15	1.79
T <sub>3</sub> : RDF+ Grade-I (a) @ 25kg ha <sup>-1</sup> (Gypsum based)	1105.41	72711.17	29485	43226.17	2.47
T <sub>4</sub> : RDF+ Grade-I(b) @ 25kg ha <sup>-1</sup> (Bentonite based)	1013.60	66659.15	29284	37375.15	2.28
T <sub>5</sub> : RDF+ Govt. notified Grade-I (c) @ 25kg ha <sup>-1</sup> (Gypsum based)	1081.37	71139.9	29345	41794.9	2.42
T <sub>6</sub> : RDF+ Grade-II (a) @ 0.5&1% (Chelation with EDTA)	761.47	50146.72	29141	21005.72	1.72
T <sub>7</sub> : RDF+ Grade-II (b) @ 0.5&1% (Chelation with glycine)	905.02	59485.14	29226	30259.14	2.04
T <sub>8</sub> : RDF+ Grade-II (c) @ 0.5&1% (Chelation with EDTA)	1003.54	65994.1	29546	36448.1	2.23
T <sub>9</sub> : RDF+ Grade-II (d) @ 0.5&1% (Chelation with citric acid)	961.15	63145.92	29443	33702.92	2.14
T <sub>10</sub> : RDF+ Govt. notified Grade-II (e) @0.5&1% (Chelation with EDTA)	981.38	64533.67	29945	34588.67	2.16

### 3.1.3 Effect of Different Micro-nutrient Grades on Nutrient Balance in Soil

The data on the effects of micronutrient grades along with RDF on available nitrogen, phosphorus and potassium status after harvest of French bean are presented in Table 6. The data showed a definite loss in available soil nitrogen status after harvest of the French bean crop, irrespective of treatment combination. The nitrogen-balance data indicated a clear trend, where integration of Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) with RDF resulted in improved nitrogen utilisation compared with RDF alone. The data also showed actual gain or loss in available soil phosphorus status after harvest. Soil phosphorus balance indicated a clear trend in which integration of different micronutrient grades with RDF resulted in improved phosphorus utilisation compared with RDF alone. All treatments showed apparent phosphorus losses, but those receiving micronutrient grades performed better in terms of actual gain. The data further revealed a positive balance of available potassium in soil after harvest of the French bean crop. The plot receiving RDF + Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based) recorded the highest actual gains of nitrogen (72.91 kg ha<sup>-1</sup>), phosphorus (10.70 kg ha<sup>-1</sup>) and potassium (127.72 kg ha<sup>-1</sup>), followed by RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based), with 68.72 kg ha<sup>-1</sup> nitrogen, 9.16 kg ha<sup>-1</sup> phosphorus and 123.68 kg ha<sup>-1</sup> potassium. The absolute control (T1) recorded a net nitrogen loss of -0.27 kg ha<sup>-1</sup> due to the absence of external N inputs. The lowest and negative actual gain of phosphorus was recorded in the absolute control (T1) (-0.73 kg ha<sup>-1</sup>). The absolute control (T1) also showed a negative potassium balance (-0.73 kg ha<sup>-1</sup>), indicating depletion.

### 3.1.4 Effect of Different Micro-nutrient Grades on Economics of French Bean

Among the micronutrient Grade-I treatments, the gypsum-based formulation (T3) demonstrated the highest yield (1105.41 kg ha<sup>-1</sup>) and economic returns, with a GMR of ₹72,711.17, an NMR of ₹43,226.17 and the highest B:C ratio (2.47) across all treatments (Table 7). This suggests that the gypsum-based Grade-I formulation was effective in enhancing productivity and profitability under the present experimental conditions. Similarly, T5 [RDF + Govt. notified Grade-I(c) @ 25 kg ha<sup>-1</sup> (gypsum-based)] yielded 1081.37 kg ha<sup>-1</sup>, with a net return of ₹41,794.90 and a B:C ratio of 2.42, comparable to T3. Treatment T4 [RDF + Grade-I(b) @ 25 kg ha<sup>-1</sup> (bentonite-based)] also performed well, with a yield of 1013.60 kg ha<sup>-1</sup> and a B:C ratio of 2.28, although it was slightly lower than the gypsum-based treatments. The absolute control (T1), which received no fertilisation, recorded the lowest yield (571.00 kg ha<sup>-1</sup>). Correspondingly, the gross return was ₹37,632.67, with a net return of ₹12,294.67 and a B:C ratio of 1.49, indicating the economic limitations of nutrient omission.

## 3.2 Discussion

Available soil N content increased with soil or foliar application of micronutrients. The balanced supply of nutrients might have improved root growth and added root litter to the soil, thereby increasing nutrient status in the post-harvest soil. Similar results were reported by Anitha and Kadalli (2019), Krishnasree et al. (2022) and Poonam et al. (2023). The increase in available P content in the present study may be due to solubilisation of native phosphorus through the release of organic acids and increased mineralisation following the addition of chemical fertilisers. Comparable findings were reported by Singh et al. (2017), Anitha and Kadalli (2019) and Poonam et al. (2023). Available potassium was maximum (839.50 kg ha<sup>-1</sup>) with application of the recommended dose of N, P and K along with micronutrient Grade-I(a) @ 25 kg ha<sup>-1</sup> (gypsum-based). These findings showed that the optimum dose of inorganic fertilisers increased available potassium in soil. Potassium application appears to have a beneficial effect in overcoming soil moisture stress and increasing physiological parameters and carbon partitioning in food legumes. Band et al. (2007) also supported the present results. The results were in accordance with Changkiri et al. (2024), who reported that T3 produced the highest available potassium (126.80 kg ha<sup>-1</sup>); the slight increase might be due to the addition of NPK through organic and inorganic fertilisers.

Application of RDF along with micronutrient grades enhanced nitrogen-use efficiency in French bean by improving root development, enzymatic activity, such as nitrate reductase activity, and overall nutrient balance, leading to better nitrogen uptake and assimilation and reduced losses. Similar results were reported by Patil et al. (2019), who observed that nitrogen-use efficiency ranged from 26.3 to 37.9%. The application of 50% NPK was also beneficial in improving nitrogen-use efficiency. The balanced use of chemical fertiliser was also beneficial for higher nitrogen-use efficiency (31%). Sandeep et al. (2024) showed that significantly higher internal utilisation efficiency of nitrogen (16.42 kg seed yield kg<sup>-1</sup> nutrient uptake) was recorded with 75% RDF, followed by 100% RDF (15.51 kg seed yield kg<sup>-1</sup> nutrient uptake), while lower internal utilisation efficiency of nitrogen (14.57 kg seed yield kg<sup>-1</sup> nutrient uptake) was recorded with nutrient application at 150% RDF.

Application of RDF along with micronutrient grades increased phosphorus-use efficiency in French bean by enhancing root growth, improving soil microbial activity and reducing phosphorus fixation in soil. Micronutrients such as zinc and boron facilitate phosphorus mobilisation and uptake, resulting in improved plant utilisation. The results are in conformity with Manjunath et al. (2006), who concluded that phosphorus-use efficiency of French bean on Vertisol improved when rock phosphate was applied with FYM or vermicompost at a 1:2 ratio along with phosphate-solubilising bacteria. Patil et al. (2020) recorded the highest phosphorus-use efficiency in T5 (green manuring of sun hemp + 50% recommended dose of NP through fertiliser + foliar spray of 0.5% of 1000 ppm nano P suspension at tillering and flowering stage) in wheat, i.e., 35.82%, which was statistically superior to all other treatments.

Although absolute potassium recovery was lower in T7, internal utilisation of the absorbed potassium was highly efficient. The results are corroborated by Kumar et al. (2022), who found that integration of macro- and micronutrient fertilisation significantly increased nutrient-use efficiency in *Lens culinaris* Medik. Fertiliser-use efficiency, i.e., agronomic efficiency (AE), apparent recovery efficiency (RE) and physiological efficiency, increased with the combined application of fertiliser, biofertiliser and micronutrients in chickpea. Patil et al. (2019) indicated that potassium-use efficiency ranged from 74 to 126%. However, the highest nutrient-use efficiency was registered under integrated use of chemical fertiliser and organic manures. Application of 50% NPK was also beneficial in improving potassium-use efficiency, which was 99%.

Nitrogen is subject to loss through volatilisation, denitrification and surface run-off during heavy rain; therefore, the theoretical balance of N in tropical soil may have limited practical utility. In general, application of different micronutrient grades along with RDF decreased the loss of available nitrogen status in soil after harvest of the French bean crop. Overall, the results indicated that application of micronutrient grades along with RDF improved growth and yield of French bean and the available nutrient balance in soil. Similar results were reported by Band et al. (2007), who showed a gain in available nitrogen with the application of 75% RN + 50% N through FYM or vermicompost, as well as 50% RN + 50% N through FYM, vermicompost or biofertiliser treatment in French bean. Similar observations were reported by Deshbhratar et al. (2010), who found a gain in available nitrogen with the application of 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> through DAP, whereas all other treatments showed losses in available nitrogen in redgram. Similar findings were also reported by Daphade et al. (2019).

Band et al. (2007) showed gains in available phosphorus and potassium with the application of 75% RN + 50% N through FYM or vermicompost, as well as 50% RN + 50% N through FYM, vermicompost or biofertiliser treatment in French bean. Similar findings were reported by Deshbhratar et al. (2010), who found gains in available phosphorus and potassium with the application of 25, 50 and 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> through DAP, as well as in the control, in redgram. Daphade et al. (2019) found losses of available phosphorus and potassium with RDF, RDF + ZnSO<sub>4</sub>, RDF + FeSO<sub>4</sub> and RDF + borax, whereas gains in available phosphorus and potassium were observed in the other treatments in maize.

The data indicate that nutrient fortification, particularly gypsum-based Grade-I formulations, improved the economic performance of French bean cultivation under the present experimental conditions. The higher B:C ratios under these treatments indicate their profitability, making them promising options for nutrient management. Similar economic responses of French bean to nutrient levels were reported by Sharma et al. (2013). Rathod et al. (2016) reported that application of 100% RDF + ZnSO<sub>4</sub> @ 15 kg ha<sup>-1</sup> along with RDF recorded higher gross returns (₹59,039 ha<sup>-1</sup>) and a B:C ratio of 2.83 compared with the absolute control and other micronutrient combinations. Maurya et al. (2024) showed that the total cost of cultivation (₹53,790.53 ha<sup>-1</sup>), gross income (₹225,120.00 ha<sup>-1</sup>), net return (₹171,329.47 ha<sup>-1</sup>) and maximum B:C ratio (3.18) were obtained with the application of boric acid 0.1% (T6). In contrast, the minimum values for the above parameters were recorded under T1 (control).

#### 4. Conclusion

The study showed that application of the recommended dose of fertiliser along with micronutrient grades improved post-harvest nutrient availability, nutrient-use efficiency, nutrient balance, yield and economics of French bean. Among the tested treatments, RDF + Grade-I(a) at 25 kg ha<sup>-1</sup> (gypsum-based) consistently performed better than the other treatments. This treatment recorded higher available nitrogen and phosphorus in soil, improved apparent nutrient recovery and agronomic efficiency, and produced the highest positive nutrient gains for nitrogen, phosphorus and potassium. It also resulted in the highest yield and B:C ratio, indicating

better economic feasibility. The government-notified Grade-I(c) gypsum-based formulation also showed comparable performance and may be considered a useful alternative. Overall, the findings suggest that soil application of gypsum-based micronutrient formulations with RDF can improve nutrient management and profitability in French bean cultivation. However, the recommendation should be validated across additional seasons and locations before wider field adoption.

## 5. Limitations

This study was conducted during one Rabi season at a single research farm; therefore, the findings may not fully represent different soils, climates or production systems. The work focused mainly on macronutrient availability, nutrient-use efficiency, nutrient balance and economics. Micronutrient uptake, pod quality and long-term soil-health effects were not fully assessed. Multi-season and multi-location trials are needed before wider recommendation.

## Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that no competing interests exist.

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