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## Soil Properties and Nutrient Uptake by Cowpea with Nutrient Management Strategies in the Vertisols of the Northern Transition Zone of Karnataka, India

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### ABSTRACT

Cowpea (*Vigna unguiculata* L. Walp) is a short-duration, multipurpose legume suitable for diverse agroecological conditions and is commonly grown under rainfed farming systems. It fixes atmospheric nitrogen and contributes to soil nutrient cycling, making it important for sustainable cropping systems. However, declining soil fertility and an imbalanced nutrient supply can limit nutrient availability and uptake and thus crop productivity. Therefore, nutrient management strategies are very important in improving soil fertility, nutrient utilization and crop performance. This experiment was therefore undertaken to know the effect of nutrient management practices on soil properties and nutrient uptake by cowpea during the post-rainy (*rabi*) season of 2025–26 at the ICAR-IIPR, RRS, Dharwad. This study was carried out in a randomized block design with eight treatments in three replications using the cowpea variety DC-15. The treatments comprised 100% and 75% recommended rates of fertilizer (RRF) with FYM (1.0 and 2.0 t ha<sup>-1</sup>, respectively), microbial consortium seed treatment and foliar sprays of ZnSO<sub>4</sub> and FeSO<sub>4</sub>. The outcome of this experiment indicated that applying 100% RRF (recommended rate of fertilizer) + FYM at 2.0 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> of seed + two 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub> foliar sprays prior to flowering and at beginning pod formation stage (T<sub>8</sub> treatment) produced significantly higher N, P, K, Zn and Fe uptake by cowpea seed (43.75, 7.08, 20.54 kg ha<sup>-1</sup>, 35.58 and 123.44 g ha<sup>-1</sup>, respectively) and haulm (37.24, 6.10, 49.22 kg ha<sup>-1</sup>, 67.02 and 285.21 g ha<sup>-1</sup>, respectively), higher soil available Zn (0.56 ppm) and Fe (2.70 ppm) and dehydrogenase activity (44.0 µg TPF g<sup>-1</sup> soil day<sup>-1</sup>) in the soil at harvest of cowpea. Applying 100% RRF + FYM at 2.0 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> of seed application (T<sub>6</sub> treatment) recorded significantly more amounts of available N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O (228.54, 35.17 and 229.58 kg ha<sup>-1</sup>, respectively) in soil at cowpea harvest. Hence, T<sub>8</sub> is recommended for greater uptake of both macro- and micronutrients by cowpea, whereas T<sub>6</sub> is recommended for improving nutrient availability in the soil.

## INTRODUCTION

Among the pulses, cowpea (*Vigna unguiculata* (L.) Walp.) is an important crop widely cultivated in tropical and subtropical regions as it is wide adaptability, short growth duration and diverse uses, such as food, green manure, fodder and cover crop (Rai and Chandravanshi, 2025; Sindha et al., 2024). In Karnataka, the crop is grown during both the *kharif* and the *rabi* seasons, particularly in rainfed and moisture-deficit regions (Ashoka et al., 2025). However, cowpea production is constrained by the cultivation of varieties with limited yield potential and declining soil fertility. Many tropical soils are naturally characterized by low availability of essential plant nutrients, and repeated cultivation in these soils, especially where nutrient inputs are inadequate, can further accelerate nutrient depletion and contribute to reduced soil fertility and crop yields (Usman et al., 2020 and Danso et al., 2025). Prolonged cultivation with insufficient nutrient replacement can reduce soil nutrient availability and fertility, whereas excessive reliance on mineral fertilizers with limited organic inputs may adversely affect soil organic matter and nutrient use efficiency (Jat et al., 2023). Deficiencies in micronutrients can further limit plant productivity (Jat et al., 2026).

Therefore, nutrient management (NM), involving balanced mineral fertilization, organic manures, microbial consortia and micronutrients, provides an effective approach to improve nutrient availability and uptake in cowpea. The complementary action of these nutrient sources enhances nutrient mobilization and use efficiency, thus improving soil fertility and promoting healthy crop growth, and contributing to sustainable crop production (Kaur et al., 2024). The use of diverse nutrient sources supports crop nutrient requirements while sustaining soil microbial activity and enhancing nutrient cycling processes (Shah and Wu, 2019 and Krishna et al., 2025). Chemical fertilizer application leads to immediate nutrient availability for crop uptake. Chemical fertilizers application along with FYM improved the soil physical, chemical and biological properties in the soil thus increase organic carbon and moisture retention, availability of nutrients and microbial activity (Ushasri et al., 2023). The use of microbial consortia in nutrient management leads to improvement in soil fertility, better nutrient utilization and sustainable crop performance (Miljakovic et al., 2024 and Vanikyal et al., 2025).

Iron (Fe) and zinc (Zn) are the important essential mi-

cronutrients for better plant growth, yet their deficiencies are widespread in agricultural systems. Iron plays important roles in various enzymatic and metabolic processes, whereas Zn is involved in enzyme activation, antioxidant defense and overall plant development (Jat et al., 2026). However, the availability of these micronutrients to plants is often limited by their fixation in soil and the formation of less soluble compounds, particularly under well-aerated conditions. Therefore, improving Fe and Zn availability through appropriate fertilization practices has attracted considerable attention. Foliar application of Fe and Zn is a promising approach, as it delivers nutrients directly to the plant canopy and facilitates their absorption during critical growth stages. In legume crops such as cowpea (*Vigna unguiculata* L. Walp.), combined Fe and Zn supplementation may improve nutrient uptake and thus improve growth, yield and yield-attributing traits. Hence, evaluating suitable rates and timings of Fe and Zn foliar application is important for enhancing cowpea productivity (Dhaliwal et al., 2022).

Although the effects of individual nutrient sources on cowpea performance have been extensively investigated, the influence of their integrated application on soil fertility and plant nutrient acquisition remains poorly understood, particularly under the agroecological conditions of the northern transition zone of Karnataka. Integrating organic, inorganic and biological nutrient sources may improve soil chemical properties, increase nutrient availability and promote more efficient uptake of essential nutrients by cowpea, thereby supporting sustainable soil fertility management. Hence, this experiment was taken up to know the improved nutrient management practices and their effects on soil properties and uptake of nutrients in cowpea in the northern transition zone of Karnataka, India.

## MATERIALS AND METHODS

This study was taken up from October 2025 to February 2026 at the ICAR-Indian Institute of Pulses Research, Regional Research Station, Dharwad, India. Dharwad is located in the northern transition zone, i.e., zone-8, of Karnataka. The experiment was situated at 15° 49' north latitude and 74° 59' east longitude at an altitude of 678 m above msl. The area received a mean maximum temperature varied from 31.3°C (February 2026) to 28.8°C (December 2025), while the mean minimum temperature varied from 20.3°C (October 2025) to 11.8°C (December 2025) at different stages of crop growth from sowing till harvest. The rainfall that fell

Table 1

| Table 1. Soil physical and chemical properties of experimental site |                                                                              |           |           |                                                                  |
|---------------------------------------------------------------------|------------------------------------------------------------------------------|-----------|-----------|------------------------------------------------------------------|
| S.No.                                                               | Particulars                                                                  | Values    |           | Method employed                                                  |
| I. Particle size distribution                                       |                                                                              |           |           |                                                                  |
| 1                                                                   | Coarse sand (%)                                                              | 6.82      |           | International pipette method Piper (2002)                        |
| 2                                                                   | Fine sand (%)                                                                | 13.23     |           |                                                                  |
| 3                                                                   | Silt (%)                                                                     | 26.68     |           |                                                                  |
| 4                                                                   | Clay (%)                                                                     | 53.27     |           |                                                                  |
| 5                                                                   | Textural class                                                               | Clay soil |           |                                                                  |
| II. Chemical properties                                             |                                                                              |           |           |                                                                  |
| 1                                                                   | pH (1:2.5 soil: water extract)                                               | 7.15      | Neutral   | Potentiometric method using pH meter Piper (2002)                |
| 2                                                                   | EC (1:2.5 soil: water extract) (dS m <sup>-1</sup> )                         | 0.42      | Nonsaline | Conductivity method using EC bridge Piper (2002)                 |
| 3                                                                   | Organic carbon (g kg <sup>-1</sup> )                                         | 4.9       | Low       | Wet oxidation method Piper (2002)                                |
| 4                                                                   | Available nitrogen (N) (kg ha <sup>-1</sup> )                                | 218.3     | Low       | Modified alkaline permanganate method Piper (2002)               |
| 5                                                                   | Available phosphorus (P <sub>2</sub> O <sub>5</sub> ) (kg ha <sup>-1</sup> ) | 34.8      | Medium    | Olsen’s method Piper (2002)                                      |
| 6                                                                   | Available potassium (K <sub>2</sub> O) (kg ha <sup>-1</sup> )                | 227.1     | Medium    | Neutral normal ammonium acetate ex- traction method Piper (2002) |
| 7                                                                   | Available zinc (ppm)                                                         | 0.54      | Deficient | DTPA extractable method (Lindsay and Norvell, 1978)              |
| 8                                                                   | Available iron (ppm)                                                         | 2.66      | Deficient |                                                                  |

during 2025 was 1030.1 mm and was distributed on 74 rainy days. During the cropping season, the actual rainfall was 110.2 mm. We observed soils were deep black with moderate depth at the experimental site, low in organic carbon content (4.9 g kg<sup>-1</sup>), low in available nitrogen (218.3 kg ha<sup>-1</sup>), medium in available phosphorus (34.8 kg ha<sup>-1</sup>) and available potassium (227.1 kg ha<sup>-1</sup>), and deficient in available zinc (0.54 ppm) and available iron (2.66 ppm) (Table 1).

### Experimental details

This experiment was done during the postrainy (*rabi*) season using the cowpea variety DC-15. All the study plots were deep ploughed and twice harrowed prior to sowing. Each study plot measured 6.0 m × 5.4 m = 32.4 m<sup>2</sup>. Cowpea seeds were manually sown by line sowing at 45 cm × 10 cm spacing. Cowpea was harvested by two pickings at 1-week intervals. This study was conducted in a randomized block design in three replications. Two rounds of irrigation are provided at the flowering and pod initiation stages of the crop.

The present study consisted of eight treatments, viz., 75% RRF and 100% RRF with FYM at 1 and 2 t ha<sup>-1</sup>, Microbial consortia seed treatment at 8 ml kg<sup>-1</sup> and two foliar sprays of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub> before the start of flowering and at the initial pod formation stage of cowpea (Table 2).

### Nutrient management (NM)

The NPK fertilizers were applied at sowing. For cowpea, the RRF was applied, i.e., 25:50:25 kg ha<sup>-1</sup> of N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O, using urea, diammonium phosphate (DAP) and muriate of potash (MOP) as the respective sources in treatments T<sub>5</sub> to T<sub>8</sub>, whereas 75% RRF was applied in treatments T<sub>1</sub> to T<sub>4</sub>. Farmyard manure (FYM) was applied to individual plots at a rate of 2.0 t ha<sup>-1</sup> in the 100% RRF treatments and 1.0 t ha<sup>-1</sup> in the 75% RRF treatments 15 days prior to sowing. In treatments T<sub>2</sub>, T<sub>4</sub>, T<sub>6</sub> and T<sub>8</sub>, prior to sowing, seed treatment with rhizosphere microbial consortium at 8 ml kg<sup>-1</sup> and Trichoderma to cowpea seeds was done at sowing. The rhizosphere consortium consisted of *Rhizobium* (nitrogen fixer), *Pseudomonas striata* (phosphate-solubilizing bacteria), *Bacillus* sp. (potassium-solubilizing bacteria), efficient strains of zinc-solubilizing bacteria (ZnSB), silica-solubilizing bacteria (SiSB), Actinobacteria (JK-16), pink-pigmented facultative methylotrophs (PPFM-33) and lactic acid bacteria (LAB75). The liquid formulation of the rhizosphere microbial consortium contained a minimum population of 3.8 × 10<sup>8</sup> cells mL<sup>-1</sup> of each strain, and this product was commercialized by the UAS, Dharwad, Karnataka and Agri-Innovate India DARE (ICAR), India.

Table 2

| Table 2. Soil chemical properties (pH, EC and OC) in the experimental plots after harvest of cowpea as influenced by nutrient management practices                                                             |                   |                          |                          |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|--------------------------|--------------------------|
| Treatments                                                                                                                                                                                                     | pH                | EC (dS m <sup>-1</sup> ) | OC (g kg <sup>-1</sup> ) |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                         | 7.12 <sup>a</sup> | 0.37 <sup>a</sup>        | 5.5 <sup>a</sup>         |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                | 7.09 <sup>a</sup> | 0.38 <sup>a</sup>        | 5.6 <sup>a</sup>         |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                          | 7.11 <sup>a</sup> | 0.38 <sup>a</sup>        | 5.7 <sup>a</sup>         |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5% | 7.07 <sup>a</sup> | 0.39 <sup>a</sup>        | 5.9 <sup>a</sup>         |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                             | 7.06 <sup>a</sup> | 0.40 <sup>a</sup>        | 5.8 <sup>a</sup>         |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                    | 7.04 <sup>a</sup> | 0.40 <sup>a</sup>        | 5.9 <sup>a</sup>         |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                              | 7.05 <sup>a</sup> | 0.41 <sup>a</sup>        | 6.1 <sup>a</sup>         |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%     | 7.02 <sup>a</sup> | 0.41 <sup>a</sup>        | 6.2 <sup>a</sup>         |
| <b>Prior to sowing</b>                                                                                                                                                                                         | <b>7.15</b>       | <b>0.42</b>              | <b>4.9</b>               |
| S.Em. ±                                                                                                                                                                                                        | 0.12              | 0.017                    | 0.22                     |
| LSD at 5%                                                                                                                                                                                                      | NS                | NS                       | NS                       |

Table 3

| Table 3. Soil available nutrients (N, P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, Zn and Fe) and dehydrogenase enzyme activity in the experimental plots after harvest of cowpea as influenced by nutrient management practices |                          |                                                      |                                         |                    |                    |                                                                                |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|------------------------------------------------------|-----------------------------------------|--------------------|--------------------|--------------------------------------------------------------------------------|
| Treatments                                                                                                                                                                                                                            | N (kg ha <sup>-1</sup> ) | P <sub>2</sub> O <sub>5</sub> (kg ha <sup>-1</sup> ) | K <sub>2</sub> O (kg ha <sup>-1</sup> ) | Zn (ppm)           | Fe (ppm)           | Dehydrogenase enzyme activity (µg TPF g <sup>-1</sup> soil day <sup>-1</sup> ) |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                                                | 220.29 <sup>ab</sup>     | 31.29 <sup>b</sup>                                   | 221.50 <sup>ab</sup>                    | 0.47 <sup>b</sup>  | 2.51 <sup>b</sup>  | 29.2 <sup>f</sup>                                                              |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                                       | 222.15 <sup>ab</sup>     | 32.70 <sup>ab</sup>                                  | 224.49 <sup>ab</sup>                    | 0.49 <sup>ab</sup> | 2.53 <sup>ab</sup> | 34.3 <sup>de</sup>                                                             |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                                                 | 219.20 <sup>b</sup>      | 30.85 <sup>b</sup>                                   | 220.60 <sup>b</sup>                     | 0.52 <sup>ab</sup> | 2.62 <sup>ab</sup> | 32.4 <sup>ef</sup>                                                             |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                        | 221.13 <sup>ab</sup>     | 31.95 <sup>ab</sup>                                  | 223.17 <sup>ab</sup>                    | 0.53 <sup>ab</sup> | 2.65 <sup>ab</sup> | 36.8 <sup>cd</sup>                                                             |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                                                    | 226.80 <sup>ab</sup>     | 34.03 <sup>ab</sup>                                  | 227.79 <sup>ab</sup>                    | 0.50 <sup>ab</sup> | 2.56 <sup>ab</sup> | 35.4 <sup>de</sup>                                                             |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                                           | 228.54 <sup>a</sup>      | 35.17 <sup>a</sup>                                   | 229.58 <sup>a</sup>                     | 0.51 <sup>ab</sup> | 2.58 <sup>ab</sup> | 41.7 <sup>ab</sup>                                                             |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                                                     | 224.50 <sup>ab</sup>     | 33.29 <sup>ab</sup>                                  | 225.13 <sup>ab</sup>                    | 0.55 <sup>a</sup>  | 2.68 <sup>ab</sup> | 39.5 <sup>bc</sup>                                                             |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                            | 227.71 <sup>ab</sup>     | 34.58 <sup>ab</sup>                                  | 228.48 <sup>ab</sup>                    | 0.56 <sup>a</sup>  | 2.70 <sup>a</sup>  | 44.0 <sup>a</sup>                                                              |
| <b>Prior to sowing</b>                                                                                                                                                                                                                | 218.28                   | 34.78                                                | 227.14                                  | 0.54               | 2.66               | 27.3                                                                           |
| S.Em. ±                                                                                                                                                                                                                               | 2.60                     | 1.14                                                 | 2.47                                    | 0.02               | 0.06               | 1.1                                                                            |
| LSD at 5%                                                                                                                                                                                                                             | 7.87                     | 3.47                                                 | 7.49                                    | 0.07               | 0.17               | 3.2                                                                            |

Table 4

| Table 4. Nutrient content in cowpea seed and haulm (N, P and K) as influenced by nutrient management practices                                                                                                 |                     |                    |                      |                      |                    |                     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|--------------------|----------------------|----------------------|--------------------|---------------------|
| Treatments                                                                                                                                                                                                     | N content (%)       |                    | P content (%)        |                      | K content (%)      |                     |
|                                                                                                                                                                                                                | Seed                | Haulm              | Seed                 | Haulm                | Seed               | Haulm               |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                         | 2.86 <sup>e</sup>   | 1.09 <sup>f</sup>  | 0.482 <sup>e</sup>   | 0.170 <sup>f</sup>   | 1.22 <sup>e</sup>  | 1.43 <sup>e</sup>   |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                | 2.91 <sup>e</sup>   | 1.13 <sup>ef</sup> | 0.489 <sup>de</sup>  | 0.177 <sup>ef</sup>  | 1.27 <sup>de</sup> | 1.49 <sup>de</sup>  |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                          | 3.01 <sup>de</sup>  | 1.15 <sup>de</sup> | 0.497 <sup>c-e</sup> | 0.181 <sup>d-f</sup> | 1.30 <sup>de</sup> | 1.51 <sup>de</sup>  |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5% | 3.08 <sup>cd</sup>  | 1.19 <sup>cd</sup> | 0.506 <sup>b-d</sup> | 0.187 <sup>c-e</sup> | 1.35 <sup>cd</sup> | 1.56 <sup>cd</sup>  |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                             | 3.12 <sup>b-d</sup> | 1.22 <sup>bc</sup> | 0.511 <sup>b-d</sup> | 0.195 <sup>b-d</sup> | 1.41 <sup>bc</sup> | 1.59 <sup>b-d</sup> |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                    | 3.18 <sup>a-c</sup> | 1.27 <sup>ab</sup> | 0.519 <sup>a-c</sup> | 0.201 <sup>a-c</sup> | 1.48 <sup>ab</sup> | 1.65 <sup>a-c</sup> |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                              | 3.25 <sup>ab</sup>  | 1.28 <sup>a</sup>  | 0.526 <sup>ab</sup>  | 0.208 <sup>ab</sup>  | 1.51 <sup>a</sup>  | 1.68 <sup>ab</sup>  |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%     | 3.32 <sup>a</sup>   | 1.30 <sup>a</sup>  | 0.537 <sup>a</sup>   | 0.213 <sup>a</sup>   | 1.56 <sup>a</sup>  | 1.72 <sup>a</sup>   |
| S.E.m. ±                                                                                                                                                                                                       | 0.04                | 0.02               | 0.007                | 0.005                | 0.03               | 0.04                |
| LSD at 5%                                                                                                                                                                                                      | 0.14                | 0.05               | 0.020                | 0.014                | 0.09               | 0.11                |

### Collection and processing of soil and plant samples

Representative soil samples (0 to 30 cm depth) at the experimental site were collected prior and after the experiment, and the basic physico-chemical properties were determined to analyse the changes in the nutrient status of soil. The collected soil samples were dried in the shade, powdered, sieved through a 2.0 mm sieve and used for analysis.

The plant leaves and stem together and grains from individual treatment after the harvest of crop were oven dried at 70°C and powdered for analysis. These plant samples were used for the estimation of nitrogen, phosphorus, potassium, zinc and iron. After estimation of the nutrient content, the nutrient uptake was calculated and expressed in kg ha<sup>-1</sup>.

### Nutrient analysis in soil samples

The soil pH was measured in digital pH meter and EC using a conductivity bridge. Soil organic carbon was estimated by Walkley and Black wet oxidation method and is expressed in g kg<sup>-1</sup>. The modified alkaline permanganate method, Olsen's method and flame photometer were used for estimation of available nitrogen, available phosphorus and available potassium (Piper, 2019). Zinc and iron contents were estimated by an atomic absorption spectrophotometer (DTPA extract) (Lindsay and Norvell, 1978).

### Nutrient analysis in plant samples

In the plant samples, nitrogen content was determined by the micro-Kjeldahl method, phosphorus content estimated by the vanado-molybdate phosphoric acid yellow colour method and the potassium content was determined by atomizing the diluted digest using flame

photometer and are expressed as a percentage (%) as outlined by Piper (2019). The Zn and Fe contents were estimated by DTPA extractant using AAS (Lindsay and Norvell, 1978). Nutrient uptake was determined by multiplying nutrient content with biomass yield and is expressed in kg ha<sup>-1</sup> for N, P and K and/or g ha<sup>-1</sup> for Zn and Fe.

### Statistical analysis

The observations recorded in this experiment at harvest were statistically analysed using the methodology as detailed by Gomez and Gomez (1984). The significance level for 'F' and 't' tests was P=0.05. The Least Significance difference (LSD) values were determined at the 5% probability level if the F test is significant. Mean values of treatments and their interactions were separately subjected to the Duncan multiple range test (DMRT) using the corresponding error mean sum of squares and degrees of freedom. Statistical analysis was done by using Microsoft Excel and OPSTAT software.

## RESULTS AND DISCUSSION

### Effects of nutrient management on basic soil properties

At harvest, the soil pH and EC ranged from 7.02–7.12 and 0.37–0.41 dS m<sup>-1</sup>, respectively, with mean values of 7.07 and 0.39 dS m<sup>-1</sup>, respectively and did not vary with NM practices (Table 2). This stability is due to the buffering capacity and inherent soil properties and is largely influenced due to parent material and climatic conditions (Mukati *et al.*, 2021) in chickpea. Organic carbon increased marginally with increase in FYM application and did not vary significantly at the cowpea

Table 5

| Table 5. Nutrient content in cowpea seed and haulm (Zn and Fe) as influenced by nutrient management practices                                                                                                  |                                   |                     |                                   |                      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|---------------------|-----------------------------------|----------------------|
| Treatments                                                                                                                                                                                                     | Zn content (mg kg <sup>-1</sup> ) |                     | Fe content (mg kg <sup>-1</sup> ) |                      |
|                                                                                                                                                                                                                | Seed                              | Haulm               | Seed                              | Haulm                |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                         | 19.54 <sup>f</sup>                | 15.98 <sup>f</sup>  | 75.42 <sup>e</sup>                | 83.42 <sup>e</sup>   |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                | 20.67 <sup>ef</sup>               | 16.68 <sup>ef</sup> | 77.93 <sup>e</sup>                | 85.18 <sup>de</sup>  |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                          | 23.86 <sup>cd</sup>               | 20.54 <sup>c</sup>  | 85.65 <sup>bc</sup>               | 91.76 <sup>bc</sup>  |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5% | 24.57 <sup>bc</sup>               | 21.68 <sup>bc</sup> | 89.19 <sup>ab</sup>               | 94.69 <sup>ab</sup>  |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                             | 21.97 <sup>de</sup>               | 17.96 <sup>de</sup> | 80.16 <sup>de</sup>               | 87.64 <sup>c-e</sup> |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                    | 22.76 <sup>cd</sup>               | 18.53 <sup>d</sup>  | 83.47 <sup>cd</sup>               | 89.28 <sup>cd</sup>  |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                              | 25.97 <sup>ab</sup>               | 22.39 <sup>ab</sup> | 91.42 <sup>a</sup>                | 96.82 <sup>ab</sup>  |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%     | 27.01 <sup>a</sup>                | 23.41 <sup>a</sup>  | 93.75 <sup>a</sup>                | 99.65 <sup>a</sup>   |
| S.Em. ±                                                                                                                                                                                                        | 0.61                              | 0.53                | 1.66                              | 1.68                 |
| LSD at 5%                                                                                                                                                                                                      | 1.84                              | 1.61                | 5.04                              | 5.10                 |

Table 6

| Table 6. Nutrient uptake (N, P and K) by cowpea as influenced by nutrient management practices                                                                                                                 |                                 |                      |                      |                                 |                    |                     |                                 |                      |                     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|----------------------|----------------------|---------------------------------|--------------------|---------------------|---------------------------------|----------------------|---------------------|
| Treatments                                                                                                                                                                                                     | N uptake (kg ha <sup>-1</sup> ) |                      |                      | P uptake (kg ha <sup>-1</sup> ) |                    |                     | K uptake (kg ha <sup>-1</sup> ) |                      |                     |
|                                                                                                                                                                                                                | Seed                            | Haulm                | Total                | Seed                            | Haulm              | Total               | Seed                            | Haulm                | Total               |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                         | 26.46 <sup>f</sup>              | 23.15 <sup>e</sup>   | 49.61 <sup>f</sup>   | 4.46 <sup>e</sup>               | 3.61 <sup>e</sup>  | 8.07 <sup>f</sup>   | 11.28 <sup>f</sup>              | 30.39 <sup>e</sup>   | 41.67 <sup>f</sup>  |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                | 28.59 <sup>ef</sup>             | 25.43 <sup>de</sup>  | 54.02 <sup>ef</sup>  | 4.80 <sup>de</sup>              | 3.94 <sup>e</sup>  | 8.74 <sup>ef</sup>  | 12.47 <sup>ef</sup>             | 33.23 <sup>de</sup>  | 45.70 <sup>ef</sup> |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                          | 31.81 <sup>d-f</sup>            | 27.56 <sup>c-e</sup> | 59.37 <sup>d-f</sup> | 5.26 <sup>c-e</sup>             | 4.31 <sup>de</sup> | 9.57 <sup>de</sup>  | 13.77 <sup>de</sup>             | 35.86 <sup>c-e</sup> | 49.63 <sup>de</sup> |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5% | 33.76 <sup>c-e</sup>            | 29.65 <sup>b-d</sup> | 63.41 <sup>c-e</sup> | 5.55 <sup>cd</sup>              | 4.66 <sup>cd</sup> | 10.21 <sup>cd</sup> | 14.82 <sup>d</sup>              | 38.84 <sup>b-d</sup> | 53.66 <sup>d</sup>  |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                             | 34.70 <sup>cd</sup>             | 30.53 <sup>bc</sup>  | 65.23 <sup>cd</sup>  | 5.69 <sup>cd</sup>              | 4.92 <sup>cd</sup> | 10.62 <sup>cd</sup> | 15.62 <sup>cd</sup>             | 40.11 <sup>bc</sup>  | 55.73 <sup>cd</sup> |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                    | 37.66 <sup>bc</sup>             | 32.81 <sup>ab</sup>  | 70.47 <sup>bc</sup>  | 6.14 <sup>bc</sup>              | 5.28 <sup>bc</sup> | 11.42 <sup>bc</sup> | 17.51 <sup>bc</sup>             | 43.60 <sup>ab</sup>  | 61.11 <sup>bc</sup> |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                              | 41.70 <sup>ab</sup>             | 35.62 <sup>a</sup>   | 77.32 <sup>ab</sup>  | 6.75 <sup>ab</sup>              | 5.82 <sup>ab</sup> | 12.57 <sup>ab</sup> | 19.39 <sup>ab</sup>             | 47.05 <sup>a</sup>   | 66.44 <sup>ab</sup> |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%     | 43.75 <sup>a</sup>              | 37.24 <sup>a</sup>   | 80.99 <sup>a</sup>   | 7.08 <sup>a</sup>               | 6.10 <sup>a</sup>  | 13.18 <sup>a</sup>  | 20.54 <sup>a</sup>              | 49.22 <sup>a</sup>   | 69.76 <sup>a</sup>  |
| S.Em. ±                                                                                                                                                                                                        | 1.65                            | 1.46                 | 3.01                 | 0.28                            | 0.22               | 0.40                | 0.69                            | 1.98                 | 2.08                |
| LSD at 5%                                                                                                                                                                                                      | 5.02                            | 4.43                 | 9.14                 | 0.85                            | 0.65               | 1.20                | 2.08                            | 6.01                 | 6.30                |

Table 7

| Table 7. Nutrient uptake (Zn and Fe) by cowpea as influenced by nutrient management practices                                                                                                                  |                                 |                     |                     |                                 |                      |                     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------|---------------------|---------------------------------|----------------------|---------------------|
| Treatments                                                                                                                                                                                                     | Zn uptake (g ha <sup>-1</sup> ) |                     |                     | Fe uptake (g ha <sup>-1</sup> ) |                      |                     |
|                                                                                                                                                                                                                | Seed                            | Haulm               | Total               | Seed                            | Haulm                | Total               |
| T <sub>1</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup>                                                                                                                                                         | 18.08 <sup>d</sup>              | 33.95 <sup>d</sup>  | 52.03 <sup>d</sup>  | 69.77 <sup>d</sup>              | 177.20 <sup>d</sup>  | 246.97 <sup>c</sup> |
| T <sub>2</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                | 20.29 <sup>cd</sup>             | 37.17 <sup>d</sup>  | 57.46 <sup>d</sup>  | 76.47 <sup>cd</sup>             | 190.19 <sup>cd</sup> | 266.66 <sup>c</sup> |
| T <sub>3</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                          | 25.24 <sup>b</sup>              | 48.82 <sup>bc</sup> | 74.06 <sup>bc</sup> | 90.87 <sup>bc</sup>             | 217.93 <sup>bc</sup> | 308.80 <sup>b</sup> |
| T <sub>4</sub> : 75% RRF + FYM at 1 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5% | 26.93 <sup>b</sup>              | 54.05 <sup>b</sup>  | 80.98 <sup>b</sup>  | 97.79 <sup>b</sup>              | 235.78 <sup>b</sup>  | 333.57 <sup>b</sup> |
| T <sub>5</sub> : RRF + FYM at 2 t ha <sup>-1</sup>                                                                                                                                                             | 24.43 <sup>bc</sup>             | 45.24 <sup>c</sup>  | 69.67 <sup>c</sup>  | 88.96 <sup>bc</sup>             | 221.16 <sup>b</sup>  | 310.12 <sup>b</sup> |
| T <sub>6</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed                                                                    | 26.91 <sup>b</sup>              | 48.69 <sup>bc</sup> | 75.60 <sup>bc</sup> | 98.84 <sup>b</sup>              | 234.03 <sup>b</sup>  | 332.87 <sup>b</sup> |
| T <sub>7</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%                                                                                              | 33.38 <sup>a</sup>              | 62.81 <sup>a</sup>  | 96.19 <sup>a</sup>  | 117.49 <sup>a</sup>             | 271.00 <sup>a</sup>  | 388.49 <sup>a</sup> |
| T <sub>8</sub> : RRF + FYM at 2 t ha <sup>-1</sup> + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg <sup>-1</sup> of seed + ZnSO <sub>4</sub> and FeSO <sub>4</sub> foliar spray at 0.5%     | 35.58 <sup>a</sup>              | 67.02 <sup>a</sup>  | 102.60 <sup>a</sup> | 123.44 <sup>a</sup>             | 285.21 <sup>a</sup>  | 408.65 <sup>a</sup> |
| S.Em. ±                                                                                                                                                                                                        | 1.37                            | 2.66                | 3.27                | 4.79                            | 9.26                 | 9.73                |
| LSD at 5%                                                                                                                                                                                                      | 4.15                            | 8.06                | 9.91                | 14.53                           | 28.08                | 29.51               |

harvest. However, compared with that in the initial treatment (4.9 g kg<sup>-1</sup>), the OC content in the soil in the T<sub>8</sub> treatment (100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> + two foliar sprays of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub>) was higher (6.2 g kg<sup>-1</sup>) (Table 2). This is attributed to greater organic carbon addition through the FYM and enhanced crop biomass and root-derived carbon resulting from improved nutrient availability. Similar increases in soil OC with integrated organic, inorganic and microbial nutrient management were earlier reported by Kaur *et al.* (2024) and Bhakti *et al.* (2021).

#### Nutrient management effects on soil macro nutrients availability

The soil nutrients availability after the cowpea harvest was influenced by the balance between nutrients applied through fertilizers and FYM, which increased nutrient transformation and release by the microbial consortium and increased the nutrient availability and removal of nutrients by the crop through uptake. Among the NM treatments, applying 100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> (T<sub>6</sub>) resulted in significantly greater amounts of available macro-nutrients, *i.e.*, N (228.54 kg ha<sup>-1</sup>), P<sub>2</sub>O<sub>5</sub> (35.17 kg ha<sup>-1</sup>) and K<sub>2</sub>O (229.58 kg ha<sup>-1</sup>) in the soil at crop harvest than with applying 75% RRF + FYM at 1 t ha<sup>-1</sup> + 2 foliar sprays of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub> (T<sub>3</sub>). The microbial consortia with the recommended rate of chemical fertilizers application contributed to the higher soil nutrient availability observed in T<sub>6</sub> after cowpea harvest, and due to the increased microbial activity that enhanced nutrient solubilization, mobilization and mineralization. These processes improve nu-

trient cycling and maintain greater amounts of nutrients available in the soil after harvest of the cowpea crop (Apate *et al.*, 2025 and Kaur *et al.*, 2024). The applying microbial consortia likely increased soil nitrogen availability by stimulating nitrogen mineralization and biological nitrogen fixation; in addition, phosphate- and potassium-solubilizing microorganisms in the consortium may have increased the availability of these nutrients by releasing organic acids/other metabolites that solubilized fixed forms of phosphorus and potassium. Further, the residual effect of FYM application has increased the soil cation exchange capacity and nutrient retention, thus resulting in greater soil nutrient availability after crop harvest and same was earlier seen in chickpea (Jakhar *et al.*, 2020).

#### Soil available zinc and iron as influenced by nutrient management

Compared with those in the T<sub>1</sub> treatment, the available Zn (0.56 ppm) and Fe (2.70 ppm) in the soil after cowpea harvest in the T<sub>8</sub> treatment (100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> + two foliar sprays of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub>) were significantly greater (Table 3), which might be due to the combined effects of the FYM, microbial consortia and foliar ZnSO<sub>4</sub> and FeSO<sub>4</sub> application. The applied FYM adds Zn and Fe, as it contains appreciable amounts of these micronutrients; it forms soluble organo-metal complexes and reduces their fixation, whereas the microbial consortium produces organic acids and siderophores, enhancing the mobilization of native micronutrients. Foliar Zn and Fe application may have contributed to increased soil availability of Zn and Fe through leaf fall and root exudates (Fouda

and Elhamied-Abd, 2017, Mane *et al.*, 2020 and Patel *et al.*, 2025).

### **Effects of NM on dehydrogenase enzyme activity in soil after cowpea harvest**

Dehydrogenase activity in the soil at harvest of cowpea was significantly higher in T<sub>8</sub> treatment, which comprised 100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortia seed treatment at 8 ml kg<sup>-1</sup> + two foliar applications of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub> before flowering and at the initial stages of pod formation, showing a 50.7% increase over T<sub>1</sub>, with a value of 44 µg TPF g<sup>-1</sup> soil day<sup>-1</sup> (Table 3). The greater dehydrogenase activity in the T<sub>8</sub> treatment is due to the contribution of FYM, microbial consortia and micronutrient application. Organic manure supplies carbon substrates that favour microbial growth, whereas microbial inoculation enhances beneficial microbial activity. Improved nutrient availability, including that of micronutrients *such as* zinc and iron, may further stimulate root growth, nodulation and rhizosphere processes, collectively favouring microbial activity in the soil and thus increasing dehydrogenase enzyme activity in soil (Kaur *et al.*, 2024).

### **Effects of NM on plant nutrient status and nutrient uptake**

Nutrient content and uptake in cowpea were varied significantly with NM management practices, with T<sub>8</sub> (100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortium seed treatment at 8 ml kg<sup>-1</sup> + two foliar sprays of 0.5% ZnSO<sub>4</sub> and 0.5% FeSO<sub>4</sub>) producing higher values of N, P, K, Zn and Fe contents (3.32%, 0.537%, 1.56%, 27.01 mg kg<sup>-1</sup> and 93.75 mg kg<sup>-1</sup>, respectively) in the seeds, representing increases of 16.1, 11.4, 27.9, 38.2 and 24.3% over T<sub>1</sub> (75% RRF + FYM at 1 t ha<sup>-1</sup>). The corresponding haulm nutrient contents were 1.30%, 0.213%, 1.72%, 23.41 mg kg<sup>-1</sup> and 99.65 mg kg<sup>-1</sup>, with increases of 19.3, 25.3, 20.3, 46.5 and 19.5%, respectively (Tables 4 and 5). Similarly, compared with T<sub>1</sub>, T<sub>8</sub> resulted in significantly greater total N, P, K, Zn and Fe uptake (80.99, 13.18, 69.76 kg ha<sup>-1</sup>, 102.60 and 408.65 g ha<sup>-1</sup>, respectively), with increases of 63.3, 63.3, 67.4, 97.2 and 65.5%, respectively. Seed and haulm contributed 43.75 and 37.24 kg ha<sup>-1</sup>, 7.08 and 6.10 kg ha<sup>-1</sup>, 20.54 and 49.22 kg ha<sup>-1</sup>, 35.58 and 67.02 g ha<sup>-1</sup>, and 123.44 and 285.21 g ha<sup>-1</sup> to N, P, K, Zn and Fe uptake, respectively (Tables 6 and 7). Higher nutrient concentrations in cowpea were recorded under improved fertility management in the T<sub>8</sub> treatment is due to greater nutrient availability in the rhizosphere and higher plant nutrient uptake. An adequate nutrient supply supports physiological and metabolic processes, leading to increased accumulation

of N, P, K, Zn and Fe in plant tissues and their efficient movement to reproductive parts during crop growth. In addition, the higher nutrient concentrations with increased seed and haulm yields contributed to greater overall uptake of nutrients with INM involving fertilizers, organic manures, micronutrients and microbial consortia (Pargi *et al.*, 2023 and Apate *et al.*, 2025).

In cowpea, higher N content and uptake in seeds and haulm with T<sub>8</sub> treatment is due to a supply of balanced nutrients, improvement in soil properties, reduced N losses and increased microbial activity. Integrating fertilizers with organic amendments and microbial inoculants improves root growth and N availability, thereby increasing N uptake and use efficiency by the crop (Thakur *et al.*, 2024) in blackgram.

Applying mineral fertilizers, organic manures and microbial inoculants in the T<sub>8</sub> treatment increased P availability and its uptake in cowpea. Chemical fertilizers immediately increase readily available P, whereas organic manures supply P gradually and improve its retention in soil. Phosphate-solubilizing microorganisms in consortia further increase P availability by converting insoluble forms of phosphorus into plant-available forms through the release of organic acids and other metabolites, resulting in more P availability and uptake by cowpea (Vineela and Dawson, 2021).

Applying fertilizers, organic amendments and microbial inoculants increased the K content and uptake in cowpea in the T<sub>8</sub> treatment with more nutrient availability. Potassium-solubilizing microorganisms release organic acids and dissolve more mineral-bound K, and increase its availability in the soil solution for absorption by plants (Olaniyan *et al.*, 2022).

The higher Zn and Fe uptake in T<sub>8</sub> treatment is due to the combined effects of foliar absorption, microbial activity and FYM application. Foliar sprays provided a rapid micronutrient supply, whereas microbial inoculants increased Zn and Fe availability in soil through organic acids and siderophores. FYM further improved micronutrient retention and availability, promoting their uptake and translocation within the plant (Dhaliwal *et al.*, 2022).

## **CONCLUSION**

Results from this study demonstrated that integrated nutrient management increased the soil nutrient availability and cowpea nutrient uptake. In treatment T<sub>6</sub>, with 100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortium seed treatment at 8 ml kg<sup>-1</sup>, significantly higher soil available N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O were recorded, whereas

in treatment T<sub>8</sub>, with 100% RRF + FYM at 2 t ha<sup>-1</sup> + microbial consortium seed treatment at 8 ml kg<sup>-1</sup> + two foliar sprays of ZnSO<sub>4</sub> and FeSO<sub>4</sub>, significantly higher soil available Zn and Fe were recorded. T<sub>8</sub> also resulted in higher nutrient concentrations and uptake by cowpea seeds and haulm, highlighting the complementary effects of balanced fertilization with chemical fertilizer, organic manure, microbial inoculation and micronutrient application. Finally, the results of this study indicate that integrated nutrient management increases soil nutrient status and nutrient acquisition in cowpea. Long-term studies are recommended to know the residual effects of these INM practices on soil nutrient dynamics and crop productivity.

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## AUTHORS' CONTRIBUTIONS

Conceptualization: Anila, P., S.L. Patil; Literature collection: Anila, P., S.L. Patil; Supervision: S.L. Patil; Visualization: S.L. Patil; Writing – original draft: Anila, P., S.L. Patil; Writing – review & editing: S.L. Patil,

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