

Yield and nutrient uptake in maize and chickpea cropping sequences as influenced by integrated nutrient management practices

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Research Article

Keywords: Cropping system, Micronutrient, Nutrient concentration, Nutrient uptake, Rhizosphere microbial consortia, Vertisols

Posted Date: September 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10701516/v1>

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Additional Declarations: No competing interests reported.

Abstract

Integrated nutrient management (INM) with the application of chemical fertilizers, farmyard manure (FYM), micronutrients and rhizosphere microbial consortia as a seed treatment is a sustainable approach for enhancing crop productivity and nutritional quality. A field experiment was conducted in a randomized complete block design with eight treatments and three replications during the monsoon and winter seasons of 2024-25 at the ICAR-Indian Institute of Pulses Research, Regional Research Station, Dharwad, India, to determine the effects of INM practices on grain and straw yields, nutrient concentration and uptake in a maize–chickpea sequential cropping system in the Vertisols of southern India. The application of the recommended rate of fertilizer + *Rhizosphere* microbial consortia seed treatment at 8 ml kg⁻¹ of seed + zinc sulphate and ferrous sulphate at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ (T₈) resulted in a significantly greater maize grain yield of 8006 kg ha⁻¹ and a straw yield of 7044 kg ha⁻¹ during the rainy season of 2024. During the winter season of 2024–25, the RRF + *Rhizosphere* microbial consortia seed treatment with 8 ml kg⁻¹ of seed + Zn and Fe foliar spray at 0.5% (T₈) resulted in significantly greater chickpea seed yield (2642 kg ha⁻¹) and haulm yield (2950 kg ha⁻¹). The higher grain and straw yields of maize in the T₈ treatment were attributed to greater nutrient uptake of N (138.47 kg ha⁻¹), P (38.98 kg ha⁻¹) and K (100.71 kg ha⁻¹). Similarly, the higher yields of chickpea in the T₈ treatment resulted from the higher uptake of N (110.6 kg ha⁻¹), P (33.88 kg ha⁻¹) and K (69.70 kg ha⁻¹). A similar trend toward greater Zn and Fe uptake was observed in the T₈ treatment for both the maize and the chickpea crops. INM addresses the research gap concerning the synergistic effects of microbial consortia and macro- and micronutrients with organic materials on sequential maize–chickpea productivity in Vertisols, where nutrient imbalances limit sustainability. The INM T₈ treatment increased maize–chickpea system productivity by 36%, with balanced nutrient uptake in Dharwad Vertisols. Farmers should practice the T₈ treatment for sustainable soil and crop productivity and higher net returns.

1 Introduction

Global food demand is projected to increase by 35–56% by 2050 because of population growth, necessitating significant improvements in crop productivity [1]. Intensive agricultural practices have led to soil degradation, micronutrient deficiency, and unsustainable nutrient mining [2]. The major challenges confronting global agriculture include increasing food production with environmental sustainability, thus reducing chemical fertilizer dependency and addressing widespread micronutrient malnutrition [3].

Maize and chickpea represent critical staple food crops in many developing countries, particularly in South Asia and sub-Saharan Africa, and contribute substantially to global food security and nutrition [4]. Maize supplies essential carbohydrates and energy, whereas chickpea provides high-quality plant-based protein, dietary fibre and essential micronutrients [5]. Maize–chickpea sequential cropping dominated the rainfed Vertisols of southern India, especially in Karnataka, where it occupied ~ 2.5 Mha, with a system productivity of 20–30% below the potential because of Zn/Fe deficiencies and nutrient mining. Cereals and pulses, when cultivated together in a cropping system, provide complementary nutritional profiles and offer advantages in nutrient cycling through nitrogen fixation by legumes, as chickpea residue enhances succeeding crop N availability via fixation carryover of ~ 20–40 kg N ha⁻¹ [6].

The conventional approach of applying solely synthetic chemical fertilizers has led to several problems, including soil acidification, micronutrient depletion, reduced soil biological activity and accelerated nutrient loss through leaching and volatilization [7]. Earlier studies have indicated that in many Asian soils, particularly in India, widespread deficiencies in micronutrients such as zinc (Zn) and iron (Fe) have emerged because of intensive cultivation and imbalanced nutrient management [8]. Vertisols with high pH (7.5–8.5), CaCO₃ (20–40%), and montmorillonite clays fix Zn/Fe, reducing availability by 50–70% during submergence.

Integrated nutrient management (INM) is now recognized as a holistic approach that combines organic, chemical and microbial nutrient sources to achieve sustainable crop production while maintaining soil health and ecological balance [9]. This approach operates on the principle of utilizing all possible sources of plant nutrients to meet crop production needs sustainably [10]. In this study, the INM follows the 4R principle (right rate, source, time and place): 100% RRF + 2 t FYM (slow-release) + RMC (solubilization) + Zn/Fe (targeted) for Vertisol sustainability. The FAO and other international organizations have advocated for INM as a core strategy for achieving the Sustainable Development Goals related to food security, zero hunger and climate change.

Recent advances in agricultural microbiology have demonstrated that rhizosphere microbial consortia (RMC) containing plant growth-promoting rhizobacteria (PGPR) with diverse functional capabilities can significantly increase nutrient availability and plant growth [11]. These beneficial microorganisms solubilize insoluble nutrients, produce phytohormones and increase plant resistance to biotic and

abiotic stresses [12]. The application of such consortia along with chemical fertilization and organic amendments offers a synergistic pathway for nutrient management. Novel use of multi-strain RMC (PGPR + solubilizers) in maize-chickpea fills the yield gap in Vertisols.

Agronomic biofortification through the foliar application of micronutrients has emerged as an effective strategy for increasing micronutrient concentrations in crop grains and addressing the widespread problem of hidden hunger [13][14]. Zinc and iron are particularly critical micronutrients, as their deficiency affects billions of people globally, with children and women in developing countries being most vulnerable [15].

Despite the recognized potential of integrated nutrient management approaches, comprehensive field-scale studies evaluating the combined effects of chemical fertilizers, organic materials, microbial inoculants and micronutrient fortification in maize–chickpea cropping systems are limited. In this study, we evaluated the efficacy of systematically integrated nutrient management strategies on crop productivity, nutrient accumulation and nutrient uptake in a maize–chickpea cropping system.

The hypothesis of this study was that compared with the T_1 practice adopted by the farmers in southern India, the T_8 treatment would result in increased grain yield, improved nutrient concentration and greater nutrient uptake efficiency.

2 Materials and methods

2.1 Location and site characteristics

A field experiment was conducted during the rainy (*kharif*) season of 2024 and post–rainy/winter (*rabi*) season of 2024–25 at ICAR-IIPR, Regional Research Station, Dharwad, India, which represents a semiarid agroclimatic zone with typical black soil (Vertisol) characteristics and is situated at 15° 49′ north latitude and 74° 99′ east longitude at an altitude of 678 m above mean sea level. The experimental soil was classified as clay textured with a pH of 7.30 [16]; an organic carbon content of 5.0 g kg⁻¹ [17]; and available nitrogen [18], phosphorus [19] and potassium [20], Zn, and Fe [21] contents of 210.5 kg ha⁻¹, 38.0 kg ha⁻¹ and 340.3 kg ha⁻¹, 0.51 ppm and 4.23 ppm, respectively (Table 1). The crop-season rainfall recorded during maize cultivation was 714.4 mm, and sufficient soil moisture in the profile led to better maize growth and development. The cumulative rainfall for the chickpea crop growth period was only 4.6 mm. Since there was no rainfall during the initial stages of crop growth, an external source of 75 mm of irrigation was applied to ensure early germination and crop establishment. Two irrigations of 75 mm were applied at 30 days after sowing (DAS) and at the initial stages of pod filling.

2.2 Experimental design and treatments

The experiments were laid out in a randomized complete block design (RCBD) with three replications, and each plot measured 5.4 m × 6.0 m (32.4 m²), with a spacing of 60 cm × 20 cm for maize and 30 cm × 10 cm for chickpea. Eight nutrient management treatments were evaluated for both the maize and chickpea crops (Table 2). The eight integrated nutrient management treatments in the experiment included a 75% recommended rate of fertilizer, i.e., RRF: 100:50:50 N:P:K kg ha⁻¹ for maize and 25:50 N:P kg ha⁻¹ for chickpea; rhizosphere microbial consortia seed treatment at 8 ml kg⁻¹; micronutrient application at 25 kg ha⁻¹ ZnSO₄ and FeSO₄ for maize; and 0.5% foliar spray of ZnSO₄ and FeSO₄ for chickpea and farmyard manure (FYM) at 1.0 t ha⁻¹ and 2.0 t ha⁻¹, respectively, for maize.

2.3 Rhizosphere microbial consortia preparation and application

The rhizosphere microbial consortia are composed of plant growth-promoting rhizobacteria (PGPR) with multiple functional capabilities, including nitrogen fixation, phosphate solubilization, potassium release and the production of growth-promoting substances. The beneficial microbial strains were obtained from the Department of Agricultural Microbiology, University of Agricultural Sciences, Dharwad, India. The microbial strains used were *Pseudomonas striata* (PSB: phosphate solubilizer), KSB-27 (*Bacillus megaterium*: K-solubilizer), ZnSB (*Pseudomonas fluorescens*: Zn-solubilizer), JK-16 (action-bacterium/PGPR), PPFM-33 (*Methylobacterium* sp.: methyl-troph) and LAB-75 (*Leuconostoc* sp.: lactic acid bacterium). The nitrogen fixer for the legume was *Rhizobium*; for cereals, it was *Azospirillum*. Liquid formulations of equal volume were mixed in sterile water with glycerol to determine their viability. The shelf life exceeds 180 days at 28°C with a mixture of 0.5% PVP + glycerol. The consortium formulated at a concentration of 10⁸ CFU ml⁻¹ was seed treated at 8 ml kg⁻¹.

2.4 Sample selection and data acquisition

At harvest, five representative plant samples, including cobs, were randomly collected from each treatment. The samples were washed sequentially with tap water and distilled water to remove adhering soil and dust, air-dried, and then oven-dried at 60–70°C for eight hours. The dried grain and stover samples were separately ground into a fine powder using a Willey mill and stored in polyethylene bags. Total nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and zinc (Zn) contents in seed and straw were determined using standard analytical procedures. Specifically, N concentration was determined via Micro kjeldahl digestion-distillation method [17]; P content was measured using vanadomolybdo-phosphoric yellow color method [17]; and K content was quantified via flame photometry [17]. Zinc and Fe contents were determined using atomic absorption spectroscopy (AAS) following diethylene triamine pentaacetic acid (DTPA) extraction [21]. Nutrient uptake was calculated on a dry matter basis using Eq. 1:

$$\text{Total nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient Content (\%)} \times \text{Biomass yield (kg ha}^{-1}\text{)}}{100}$$

(1)

2.5 Statistical analysis

The data collected at harvest were subjected to statistical analysis as described by Gomez and Gomez [22]. The means were compared using Duncan's multiple range test i.e., DMRT at the 5% probability level. The data were analysed using the standard statistical software OPSTAT, and the results are presented as the standard error of the mean and least significant difference at the 5% probability level.

3 Results

3.1 Maize productivity

A significantly greater maize grain yield of 8006 kg ha⁻¹ was recorded in the RRF + Rhizosphere microbial consortia seed treatment at 8 ml kg⁻¹ of seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ (T₈) and was significantly greater than that in the other treatments except T₇ (7836 kg ha⁻¹) and T₆ (7780 kg ha⁻¹) (Table 3). The 75% RRF + FYM treatment at 1.0 t ha⁻¹ resulted in a lower grain yield of 5882 kg ha⁻¹. The T₈ treatment was 36.1% greater than the T₁ treatment was and 14.7% greater than the T₅ treatment was. The stover yield showed similar trends, ranging from as low as 5832 kg ha⁻¹ (T₁) to as high as 7044 kg ha⁻¹ (T₈), with statistical significance observed between the treatments.

3.2 Chickpea productivity

The chickpea seed yield of the 2642 kg ha⁻¹ treatment and the haulm yield of the 2950 kg ha⁻¹ treatment were significantly greater than those of the RRF + Rhizosphere microbial consortia seed treatment at 8 ml kg⁻¹ of seed + Zn and Fe foliar spray at 0.5% (T₈), and the results were statistically similar between the T₇ to T₃ treatments. A lower haulm yield of 2321 kg ha⁻¹ was recorded in the T₁ treatment, which received only 75% of the recommended rate of fertilizer. A significantly greater biological yield (5592 kg ha⁻¹) was recorded in the T₈ treatment than in the other treatments, except for T₆ (5168 kg ha⁻¹) and T₇ (5242 kg ha⁻¹). A lower biological yield of 4265 kg ha⁻¹ was recorded with the addition of 75% RRF (T₁) (Table 4).

3.3 Nutrient concentrations in maize and chickpea

3.3.1 Maize

Nutrient concentrations in maize grain and straw varied significantly with INM practices (Table 5). Significantly higher grain nutrient concentrations, i.e., N 1.22%, P 0.332%, K 0.477%, Zn 0.171%, and Fe 0.682%, and stover concentrations, i.e., N 0.58%, P 0.176%, K 0.888%, Zn 0.271%, and Fe 0.325%, were recorded in the T₈ treatment than in the 75% RRF + FYM treatment at 1.0 t ha⁻¹ (T₁). Compared with the T₈ treatment, the T₁ treatment resulted in lower nutrient concentrations in the grain (i.e., N 1.09%, P 0.295%, K 0.411%, Zn 0.107%, and Fe 0.382%) and straw (i.e., N 0.54%, P 0.131%, K 0.777%, Zn 14.17 mg kg⁻¹ and Fe 17.20 mg kg⁻¹).

3.3.2 Chickpea

The T₈ treatment resulted in significantly higher nutrient concentrations in the seeds, i.e., N 3.34%, P 0.505%, K 1.082%, Zn 26.20 mg kg⁻¹ and Fe 36.66 mg kg⁻¹, and in the haulm, i.e., N 1.07%, P 0.974%, K 1.952%, and RRF greater than 75%, which resulted in lower nutrient concentrations in the seeds, i.e., N 3.13%, P 0.436%, K 0.722%, Zn 14.07 mg kg⁻¹ and Fe 17 mg kg⁻¹, and in the haulm, i.e., N 0.79%, P 0.915%, K 1.570%, Zn 12.90 mg kg⁻¹ and Fe 72.43 mg kg⁻¹ (Table 8).

3.4 Uptake of nutrients in maize and chickpea

3.4.1 Maize

Nitrogen uptake in the maize grain, straw, and total material varied significantly with INM practices. The grain, straw and total N uptake were significantly greater in the T₈ treatment, with values of 97.59, 40.89 and 138.47 kg ha⁻¹, respectively, and were significantly greater in all the treatments except the T₇ treatment, i.e., 94.15, 39.33 and 133.48 kg ha⁻¹, respectively, and in the T₆ treatment, i.e., 92.05, 38.44 and 130.49 kg ha⁻¹, respectively (Table 6). Lower N uptakes of 63.99, 31.55 and 95.34 kg ha⁻¹ in maize grain, straw and total plants, respectively, were recorded in the 75% RRF + FYM treatment at 1.0 t ha⁻¹.

Phosphorus uptake in maize varied significantly across the INM treatments. Compared with that in the other treatments, the P uptake in the grain and straw in the T₈ treatment was significantly greater, i.e., 26.55 and 12.43 kg ha⁻¹, respectively, with a total uptake of 38.98 kg ha⁻¹. The total P uptake in the T₆ (35.80 kg ha⁻¹) and T₇ (35.72 kg ha⁻¹) treatments was statistically similar to that in the T₈ treatment (Table 6). A lower P uptake in the grain (17.38 kg ha⁻¹), straw (7.62 kg ha⁻¹) and total uptake (25.00 kg ha⁻¹) occurred in the 75% RRF + FYM treatment at 1.0 t ha⁻¹.

High grain, straw and total K uptake rates of 38.17, 62.55 and 100.71 kg ha⁻¹, respectively, were recorded in the T₈ treatment, which were significantly greater than those in the other treatments except for T₇, i.e., 35.64, 60.83 and 96.48 kg ha⁻¹, and T₆, i.e., 34.97, 60.21 and 95.17 kg ha⁻¹, respectively, for maize (Table 6). Lower K uptakes of 24.19, 45.34 and 69.53 kg ha⁻¹, respectively, were recorded in the 75% RRF + FYM treatment at 1.0 t ha⁻¹.

The zinc uptake in grain, straw and total was significantly influenced by INM practices (Table 7). Compared with those in the other treatments, the grain, straw and total Zn uptake in the T₈ treatment were significantly greater (34.27, 54.27 and 88.53 mg kg⁻¹, respectively). Lower Zn uptakes of 21.33, 28.33 and 49.67 mg kg⁻¹ were detected in the grain, straw and total, respectively, with the application of 75% RRF + FYM at 1.0 t ha⁻¹.

Iron uptake in grain, straw and the total was significantly greater under the INM practices. Compared with those in the other treatments, the grain, straw and total Fe uptake in the T₈ treatment was significantly greater (136.40, 65.00 and 201.4 mg kg⁻¹, respectively) (Table 7). Lower Fe uptake was observed in the T₁ treatment, i.e., 76.47, 34.40 and 110.87 mg kg⁻¹, respectively.

3.4.2 Chickpea

N uptake was significantly greater in the seed and haulm treatments and in the total N uptake in the T₈ treatment, with values of 88.11, 22.48 and 110.60 kg ha⁻¹, respectively (Table 9). N uptake was lower (60.72, 13.09 and 73.81 kg ha⁻¹) in the seed and haulm treatments and the total treatment, respectively, at the 75% RRF.

A higher total P uptake of 33.88 kg ha⁻¹ was recorded in the T₈ treatment, which was statistically similar to that in the T₇ treatment, i.e., 31.46 kg ha⁻¹ (Table 9). The P uptake of the seeds and haulm was significantly greater in the T₈ treatment (13.55 and 20.53 kg ha⁻¹, respectively). A lower P uptake of 8.47 kg ha⁻¹ was detected in the seeds, whereas in the haulm, it was 15.18 kg ha⁻¹, and the total P uptake was 23.65 kg ha⁻¹ in the 75% RRF plots.

Compared with those in the other treatments, the seed (28.58 kg ha⁻¹), haulm (41.12 kg ha⁻¹) and total K uptake (69.70 kg ha⁻¹) in the T₈ treatment were significantly greater (Table 9). A lower K uptake of 14.03 kg ha⁻¹ in the seed, 26.04 kg ha⁻¹ in the haulm and 40.07 kg ha⁻¹ in the total was observed at the 75% RRF.

Zinc uptake by the seeds, haulm, and total material varied significantly with INM practices (Table 10). Compared with those in the other treatments, the seed, haulm and total Zn uptake in the treatments involving the RRF + Rhizosphere microbial consortia seed treatment

were 39.20, 35.40 and 74.60 mg kg⁻¹, respectively, at 8 ml kg⁻¹ of seed + Zn and Fe foliar spray at 0.5% (T₈). Lower Zn uptakes of 28.13, 25.80 and 53.93 mg kg⁻¹ in the seed, haulm and total treatments, respectively, were observed in the 75% RRF treatment.

Significantly greater seed, haulm and total Fe uptake was recorded in the RRF + Rhizosphere microbial consortia seed treatment at 8 ml kg⁻¹ of seed + Zn and Fe foliar spray at 0.5% (T₈), with values of 73.33, 233.51 and 306.85 mg kg⁻¹, respectively (Table 10). Low Fe uptake values of 34.00, 144.85 and 178.85 mg kg⁻¹ in the seed, haulm and total treatments, respectively, were observed in the T₁ treatment.

4 Discussion

4.1 Effect of Integrated Nutrient Management on Maize and Chickpea Productivity

The results from the T₈ treatment indicate that compared with the T₅ and T₁ treatments, the combined nutrient management, chemical fertilizer, organic material, and *rhizosphere* microbial consortia seed treatments and micronutrient application improved maize grain yield by 14.7% and 36.1% and chickpea seed yield by 16.3% and 36.0%, respectively. This enhanced productivity with the INM approach was similar to the findings of earlier studies indicating that the combined use of chemical fertilizers with organic inputs improved soil nutrient availability, nutrient uptake and crop productivity in maize and chickpea [23][24]. The synergistic effects observed are attributed to multiple mechanisms: chemical fertilizers supply readily available nutrients for immediate crop requirements; organic materials increase the soil structure and water-holding capacity; and rhizosphere microbial consortia increase nutrient availability through solubilization and mineralization processes [25].

The rhizosphere microbial consortia application was particularly effective, with treatments incorporating biological inoculants (T₂, T₄, T₆, and T₈) consistently outperforming their non-inoculated counterparts. Rhizosphere bacteria produce plant growth-promoting substances such as auxins, gibberellins and cytokinins, which regulate physiological processes to improve plant development [26]. Additionally, these microorganisms solubilize insoluble nutrients and make them easily available for plant uptake and release siderophores that chelate iron and other micronutrients, thus improving their bioavailability [27].

The increased level of FYM in the treatments receiving 2.0 t ha⁻¹ (T₅–T₈) compared with those receiving 1.0 t ha⁻¹ (T₁–T₄) contributed significantly to the productivity improvements. Farmyard manure has multiple functions: it adds organic content to the soil, which improves soil physical properties, provides slow-release nutrients, enhances microbial biomass and their activity and further increases the soil water-holding capacity [28][29]. The results validate the importance of organic amendments in sustainable intensification strategies.

4.2 Effect of integrated nutrient management on plant nutrient status and uptake in maize

The RRF + *Rhizosphere* microbial consortia seed treatments with 8 ml kg⁻¹ of seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ (T₈) resulted in higher concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the grain (1.22, 0.332 and 0.477%, respectively) and straw (0.58, 0.176 and 0.888%, respectively) (Table 5). This increase might be attributed to the combined effect of readily available N from RRF, slow mineralization of N from farmyard manure and the nitrogen-fixing activity of rhizosphere microbial consortia [30][31]. Increased P availability results from multiple mechanisms. Organic acid production during FYM decomposition solubilizes fixed native soil phosphorus, while microbial consortia contain phosphate-solubilizing bacteria (PSB) that convert insoluble phosphates into plant-available forms. The PSB achieve phosphorus solubilization through acidolysis, enzyme lysis and chelation mechanisms, secreting organic acids, enzymes and siderophores that mobilize bound phosphorus [32]. The potassium content, particularly in the straw, was higher in the treatments receiving RRF and 2.0 t ha⁻¹ FYM (0.888%) in the T₈ treatment. The FYM helps to improve soil cation exchange capacity, reduce potassium leaching and increase retention for plant uptake. This synergistic effect of organic and inorganic materials on K nutrition is observed in sustainable agricultural systems [33][34].

High zinc and iron concentrations were recorded in the grain and straw in the T₈ treatment (Table 5). The higher uptake of Zn and Fe is due to microbial siderophores further mobilizing Fe and Zn in the *rhizosphere*, whereas the humic substances in the FYM function as natural chelators, thus decreasing micronutrient fixation and increasing uptake by roots [35].

In the grain (97.59 kg ha^{-1}), straw (40.89 kg ha^{-1}) and total ($138.47 \text{ kg ha}^{-1}$) nitrogen uptake were greater in the T_8 treatment than in the other treatments, except for the T_7 and T_6 treatments, which included micronutrients and microbial amendments. The nearly 20% and 45% increases in total N uptake in the T_8 treatment over those in the T_5 and T_1 treatments, respectively, are attributed to the contributions of farmyard manure, inorganic fertilizer for sustained N release and rhizosphere microbes to biological N fixation and root proliferation. Similarly, higher N uptake in maize with INM [35], where compared with chemical fertilizer application alone, farmyard manure combined with biofertilizers increased total N recovery by 25–30%. The total phosphorus uptake in the grain and straw was 26.55 and 12.43 kg ha^{-1} , respectively, and it was 56% greater in the T_8 treatment than in the T_1 treatment. This increase in the T_8 treatment is attributed to the increase in microbial P availability through the solubilization of applied and native P and the release of organic acids from farmyard manure [36]. Compared with those in the T_1 treatment, a higher grain K uptake of 38.17 kg ha^{-1} , a straw uptake of 62.55 kg ha^{-1} and a total of $100.71 \text{ kg ha}^{-1}$ were recorded in the T_8 treatment. The total uptake of K was greater by 17.3% and 45% in the T_8 treatment than in the T_5 and T_1 treatments, respectively (Table 6). The greater amount of farmyard manure applied improved the soil cation exchange capacity and microbial exudates that mobilized the exchangeable K, which might have resulted in greater K uptake. Compared with NPK fertilization alone, integrated farmyard manure and bioinoculant treatments increased maize K uptake by 30–35% [37].

Compared with those in the T_5 and T_1 treatments, the grain and total zinc uptake in the T_8 treatment were 32.5% and 45.9% and 60.7% and 78.2% greater, respectively. Soil-derived ZnSO_4 and farmyard manure release humic substances, coupled with microbial siderophore production, leading to increased Zn solubility and root uptake [38]. Compared with the T_1 treatment, the T_8 treatment resulted in a 78.4% increase in Fe uptake in the grain and an 81.7% increase in total uptake (Table 7). The application of FeSO_4 , an organic chelator from farmyard manure with microbial siderophores, facilitated Fe mobilization and absorption. Compared with chemical fertilization alone, the combination of soil and foliar Fe with organic material application increased maize grain Fe uptake by 50% [39].

Greater application of nutrients through organic, inorganic (macro- and micronutrients) and microbial consortia might have resulted in greater nutrient release and increased nutrient availability, thus resulting in greater uptake of nitrogen, phosphorus, potassium, zinc and iron with better plant growth and higher crop yields under lower nutrient application through organic, inorganic and no application of microbial consortia.

4.3 Effect of integrated nutrient management on the plant nutrient status and uptake of chickpea

Among the integrated nutrient management practices, the RRF + *Rhizosphere* microbial consortia seed treatment with 8 ml kg^{-1} of seed + Zn and Fe foliar spray at 0.5% (T_8) resulted in significantly higher nutrient concentrations in the seeds and haulm than the 75% RRF treatment did (T_1). The concentrations of nitrogen, phosphorus, potassium, zinc, and iron in the seeds were higher by 6.7, 15.8, 49.9, 39 and 115.9%, respectively, whereas the concentrations in the haulm were 35.4, 6.4, 24.3, 38.5 and 61.3% greater, respectively, in the T_8 treatment than in the T_1 treatment (Table 8). The substantial increases in micronutrient concentrations, particularly for zinc and iron, represent significant achievements for addressing micronutrient malnutrition. The 115.9% increase in iron concentration in chickpea seeds with the integrated approach demonstrates the powerful potential of agronomic biofortification. These results align with the principles of agronomic biofortification, which uses soil or foliar nutrient application to increase micronutrient concentrations in edible crop parts [14]. The foliar application approach used for chickpea was particularly effective, as it allows direct supply of nutrients to the site of accumulation and bypasses soil-related limitations such as low nutrient availability, pH-induced precipitation or reduced availability because of antagonistic nutrient interactions. The balanced supply of macronutrients (N, P, and K) through RRF and microbial activity creates an optimal nutritional environment that enhances the uptake and utilization of micronutrients applied through foliar spray, as observed in the T_8 treatment [40]. The improved vigour resulting from adequate macronutrient supply increases the sink strength of developing plants, leading to increased translocation of nutrients from vegetative to reproductive parts [41][42]. An integrated nutrient management strategy improves individual nutrient concentrations and enhances the overall nutritional quality of chickpea, thus making it more valuable in terms of nutrition for human consumption and feed for livestock [43][44].

Compared with those in the T_1 treatment, nitrogen (N) uptake in the seed, haulm and total N was significantly greater by 45.1, 71.7 and 49.8%, respectively, in the T_8 treatment (Table 9). The *rhizosphere* microbial consortia increased N fixation and mineralization, while a sustained N supply from fertilizers maintained high N availability throughout critical crop growth stages. This synergism between

biological and chemical sources optimizes root growth and nodule function, thereby increasing N assimilation in reproductive and vegetative parts [45][46].

Compared with those in the T₁ treatment, phosphorus (P) uptake in the seed, haulm and total treatments was greater by 57.6, 35.2 and 43.2%, respectively (Table 9). Phosphate-solubilizing bacteria in the microbial consortium release organic acids and phosphatases that mobilize native and applied P, whereas foliar Zn and Fe sprays mitigate P fixation in the soil, thus increasing P uptake [47][48].

Compared with those in the T₁ treatment, the potassium (K) uptake in the seed, haulm and total uptake in the T₈ treatment were 103.8, 57.9 and 73.9% greater, respectively (Table 9). The potassium-solubilizing microbes produced organic acids that released K from mineral matrices and improved root proliferation, which enhanced K uptake kinetics in INM modules [49].

Compared with those in the T₁ treatment, the zinc uptake in seed, haulm and total in T₈ treatment increased by 39.4, 37.2 and 38.3%, respectively. Foliar zinc application ensures immediate Zn availability during reproductive stages, and microbial siderophore production improves root-mediated Zn acquisition, thus collectively increasing Zn partitioning into pods and stover at harvest [50]. Like zinc, even iron uptake by the seed, haulm, and total uptake was greater in the T₈ treatment (115.7, 61.2 and 71.6%, respectively) than in the T₁ treatment (Table 10). Foliar Fe sprays prevent soil Fe immobilization, and the rhizobacteria produce chelators that maintain Fe in soluble forms for greater Fe uptake by roots. Thus, enhanced vegetative vigour and phloem translocation with INM practices facilitate greater Fe uptake into the seed [44].

4.4 Implications for Sustainable Agriculture and Food Security

The demonstrated success of integrated nutrient management has significant implications for the sustainable intensification of agriculture in developing countries. The results show that it is possible to substantially increase productivity (36% for both maize and chickpea) without increasing chemical fertilizer rates beyond the recommended levels through optimized combinations with organic and biological inputs.

4.5 This approach addresses several global challenges simultaneously

Food security: Substantial yield increases directly contribute to increased food production and farm income for producers.

Nutrition security: Dramatic increases in micronutrient concentrations (particularly iron and zinc concentrations) contribute to addressing hidden hunger and micronutrient malnutrition, which affects billions of people worldwide.

Environmental sustainability: By improving soil health through organic amendment integration and reducing reliance on chemical inputs through biological nutrient cycling, this approach can minimize environmental degradation and pollution.

Economic viability: The integration of biofertilizers and organic amendments typically reduces the total cost of nutrient provision compared with exclusive reliance on chemical fertilizers, improving farmer profitability.

Climate resilience: Improved soil structure and microbial activity increase soil water retention and nutrient cycling, increasing crop resilience to drought and other climate-related stresses [51].

5 Conclusion

The results of the present investigation conclusively demonstrated that INM—which combines RRF with FYM, rhizosphere microbial consortia, and micronutrients of Zn and Fe application—significantly increased yield, nutrient concentration and nutrient uptake in a maize–chickpea sequential cropping system for Vertisols. The synergistic interaction among organic, inorganic and biological components improved soil–plant nutrient dynamics, leading to increased productivity, improved nutrient use efficiency and superior grain nutritional quality.

Farming communities should adopt the INM strategy in maize–chickpea cropping systems with the application of 2.0 t ha⁻¹ farmyard manure in crop lines every year for maize crops along with the recommended rates of chemical fertilizers, i.e., NPK and Zn and Fe, as soil application for maize crops and 0.5% Zn and Fe spray prior to the flowering and pod formation stages for chickpea along with microbial consortium seed treatment; i.e., the T₈ treatment improves soil and crop productivity on a sustainable basis and income for farmers, especially resourceful farmers. Resource-poor farmers can adopt 75% of the recommended rate of chemical fertilizers (T₄) for a greater Benefit:cost ratio. The results from this study provide practical guidance for farmers, extension professionals, and policy

makers seeking to increase crop productivity, improve nutritional quality, and achieve agricultural sustainability in maize–chickpea systems and similar cereal–legume cropping patterns across developing countries.

Declarations

Ethics approval and consent to participate

Maize (*Zea mays* L.) variety DEKALB DKC 9133 (a high-yielding hybrid maize seed from Bayer CropScience India) and Chickpea (*Cicer arietinum* L.) variety BGD 111-1 (a high-yielding chickpea variety, released by UAS, Dharwad), seeds were procured from authentic seed sellers and UAS Dharwad, respectively. The methods followed in the study complies with local and national guidelines.

Consent for publication

Yes. All the authors agreed to publish the manuscript.

Competing interests

The authors declare that they have no competing interests.

Funding

None.

Author Contribution

Author contributions: Conceptualization of research; V.B.B, S.L.P; Literature collection: V.B.B, S.L.P; Supervision; S.L.P, M.S.V; Data Analysis; V.B.B, S.L.P, S; Writing - original draft; V.B.B, S.L.P, C.R.P, M.N.R, S.B.G, S; Writing - review and editing: S.L.P, C.R.P, M. N.R, S.B.G, S. All the authors reviewed the manuscript.

Acknowledgement

The authors are grateful to the Director, ICAR-IIPR, Kanpur, India, for their encouragement in conducting this research at ICAR-IIPR, RRS, Dharwad. Help rendered by Ms. Anusha B and Mr. Manjunath Amminabhavi for data collection and Mrs. Priya Patil for data entry and compilation of data is highly appreciated.

Data Availability

The data presented in this study are available on request from the corresponding author.

Code availability

Not applicable.

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Tables

Table 1 Soil physical and chemical properties at the experimental site and plant nutrient uptake			
S. No.	Particulars	Values	Method employed
Soil particle size distribution			
1.	Coarse sand (%)	6.43	International pipette method [16]
2.	Fine sand (%)	13.23	
3.	Silt (%)	26.68	
4.	Clay (%)	53.27	
5.	Textural class	Clay soil	
Soil chemical properties			
1.	pH (1:2.5 soil: water extract)	7.30	Potentiometric method using pH meter [16]
2.	EC (1:2.5 soil: water extract) (dS m ⁻¹)	0.42	Conductivity method using EC bridge [16]
3.	Organic carbon (%)	0.50	Wet oxidation method by Walkley and Black [17]
4.	Available nitrogen (N) (kg ha ⁻¹)	210.5	Modified alkaline permanganate method [18]
5.	Available phosphorus (P ₂ O ₅) (kg ha ⁻¹)	38	Olsen's method [19]
6.	Available potassium (K ₂ O) (kg ha ⁻¹)	340.3	Neutral normal ammonium acetate extraction method [20]
7.	Available Zinc (mg kg ⁻¹)	0.51	DTPA extractable method [21]
8.	Available iron (mg kg ⁻¹)	4.23	
Plant nutrient uptake			
1.	Nitrogen content (%)		Micro Kjeldahl digestion-distillation method [17]
2.	Phosphorus content (%)		Vanadomolybdo-phosphoric yellow color method [17]
3.	Potassium content (%)		Flame photometry [17]
4.	Zinc content (%)		Atomic absorption spectroscopy (AAS) following diethylene triamine pentaacetic acid (DTPA) extraction [21]
5.	Iron content (%)		

Table 2 Treatment details for maize and chickpea crops

Treatments	Maize-Rainy season (DKC-9133)	Chickpea-Winter season (BDG-111-1)
T ₁	75% RRF + FYM at 1.0 t ha ⁻¹	75% RRF
T ₂	75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed
T ₃	75% RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1 t ha ⁻¹	75% RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%
T ₄	75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%
T ₅	RRF + FYM at 2.0 t ha ⁻¹	RRF
T ₆	RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed
T ₇	RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%
T ₈	RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%

FYM - Farmyard manure

The recommended rate of fertilizer (RRF) for maize was 100:50:50 N:P:K kg ha⁻¹, and for chickpea, it was 25:50 N:P kg ha⁻¹

Table 3 Grain yield, straw yield and biological yield of maize as influenced by integrated nutrient management practices

Treatments	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)
T ₁ : 75% RRF + FYM at 1.0 t ha ⁻¹	5882 ^d	5832 ^b	11714 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	6271 ^{cd}	6094 ^b	12365 ^{cd}
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	6519 ^{cd}	6455 ^{ab}	12974 ^{cd}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	7073 ^{a-c}	6448 ^{ab}	13521 ^{bc}
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	6980 ^{bc}	6548 ^{ab}	13528 ^{bc}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	7780 ^{ab}	6944 ^a	14724 ^{ab}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	7836 ^{ab}	6936 ^a	14772 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	8006 ^a	7044 ^a	15050 ^a
S.Em. ±	297	219	429
LSD at 5%	900	664	1300

FYM - Farmyard manure

RRF - Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 4 Seed yield, haulm yield and biological yield of chickpea as influenced by integrated nutrient management

Treatments	Seed yield (kg ha ⁻¹)	Haulm yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)
T ₁ : 75% RRF	1943 ^c	2321 ^c	4265 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	2078 ^{bc}	2403 ^{bc}	4482 ^{cd}
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	2195 ^{bc}	2617 ^{a-c}	4813 ^{b-d}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	2287 ^{a-c}	2764 ^{ab}	5051 ^{a-c}
T ₅ : RRF	2272 ^{a-c}	2752 ^{ab}	5025 ^{a-c}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	2350 ^{a-c}	2818 ^a	5168 ^{a-c}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	2410 ^{ab}	2832 ^a	5242 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed+ ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	2642 ^a	2950 ^a	5592 ^a
S.Em. ±	125	121	213
LSD at 5%	380	366	640

RRF - Recommended rate of fertilizer for chickpea, i.e., 25:50 N:P kg ha⁻¹

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 5 Effect of integrated nutrient management on nutrient concentrations in maize grain and straw

Treatments	N (%)		P (%)		K (%)		Zn (mg kg ⁻¹)		Fe (mg kg ⁻¹)	
	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover
T ₁ : 75% RRF + FYM at 1.0 t ha ⁻¹	1.09 ^d	0.54 ^c	0.295 ^c	0.131 ^e	0.411 ^d	0.777 ^c	10.67 ^c	14.17 ^d	38.23 ^c	17.20 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	1.11 ^{cd}	0.54 ^c	0.300 ^c	0.136 ^{de}	0.416 ^d	0.793 ^{bc}	12.63 ^{bc}	15.33 ^{cd}	40.63 ^{bc}	19.23 ^{cd}
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1 t ha ⁻¹	1.12 ^{b-d}	0.54 ^c	0.307 ^{bc}	0.138 ^{de}	0.418 ^{cd}	0.842 ^{ab}	13.53 ^{bc}	16.63 ^{cd}	52.80 ^{a-c}	27.90 ^{a-c}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	1.14 ^{a-d}	0.54 ^c	0.320 ^{ab}	0.145 ^{cd}	0.419 ^{cd}	0.848 ^{ab}	15.17 ^{ab}	16.97 ^{cd}	56.13 ^{ab}	29.87 ^{ab}
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	1.14 ^{a-d}	0.55 ^{bc}	0.322 ^{ab}	0.149 ^{cd}	0.429 ^c	0.856 ^a	12.93 ^{bc}	17.40 ^{cd}	42.33 ^{bc}	19.87 ^{cd}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	1.18 ^{a-c}	0.55 ^{bc}	0.323 ^{ab}	0.154 ^{bc}	0.449 ^b	0.867 ^a	12.90 ^{bc}	18.33 ^c	45.13 ^{bc}	22.53 ^{b-d}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	1.20 ^{ab}	0.57 ^{ab}	0.312 ^{a-c}	0.163 ^b	0.455 ^b	0.877 ^a	15.33 ^{ab}	22.53 ^b	64.07 ^a	28.77 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	1.22 ^a	0.58 ^a	0.332 ^a	0.176 ^a	0.477 ^a	0.888 ^a	17.13 ^a	27.13 ^a	68.20 ^a	32.50 ^a
S.Em. ±	0.02	0.008	0.006	0.004	0.003	0.017	0.92	1.19	5.16	2.67
LSD at 5%	0.08	0.024	0.018	0.012	0.011	0.053	2.78	3.60	15.63	8.11

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 6 Plant macro nutrient (NPK) uptake by maize as influenced by different integrated nutrient management practices

Treatments	N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			K uptake (kg ha ⁻¹)		
	Grain	Stover	Total	Grain	Stover	Total	Grain	Stover	Total
T ₁ : 75% RRF + FYM at 1.0 t ha ⁻¹	63.99 ^e	31.35 ^d	95.34 ^d	17.38 ^d	7.63 ^f	25.00 ^d	24.19 ^c	45.34 ^d	69.53 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	70.07 ^{de}	32.71 ^d	102.78 ^{cd}	18.81 ^d	8.27 ^{ef}	27.08 ^d	26.10 ^{bc}	48.32 ^{cd}	74.41 ^{cd}
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	73.29 ^{de}	34.66 ^{cd}	107.95 ^{cd}	20.02 ^{cd}	8.89 ^{de}	28.91 ^{cd}	27.20 ^{bc}	54.38 ^{bc}	81.58 ^{bc}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	80.39 ^{b-d}	34.64 ^{cd}	115.03 ^{bc}	22.63 ^{bc}	9.32 ^{de}	31.96 ^{bc}	29.64 ^b	54.89 ^b	84.53 ^b
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	79.92 ^{cd}	35.85 ^{b-d}	115.78 ^{bc}	22.54 ^{bc}	9.74 ^{cd}	32.28 ^{bc}	29.93 ^b	55.93 ^{ab}	85.86 ^b
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	92.05 ^{a-c}	38.44 ^{a-c}	130.49 ^{ab}	25.13 ^{ab}	10.67 ^{bc}	35.80 ^{ab}	34.97 ^a	60.21 ^{ab}	95.17 ^a
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	94.15 ^{ab}	39.33 ^{ab}	133.48 ^a	24.43 ^{ab}	11.29 ^b	35.72 ^{ab}	35.64 ^a	60.83 ^{ab}	96.48 ^a
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	97.59 ^a	40.89 ^a	138.47 ^a	26.55 ^a	12.43 ^a	38.98 ^a	38.17 ^a	62.55 ^a	100.71 ^a
S.Em. ±	4.34	1.36	4.96	1.14	0.35	1.26	1.26	2.03	2.52
LSD at 5%	13.17	4.13	15.04	3.46	1.05	3.82	3.82	6.17	7.65

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 7 Zinc (Zn) and iron (Fe) uptake of maize as influenced by different integrated nutrient management practices

Treatments	Zn uptake (mg kg ⁻¹)			Fe uptake (mg kg ⁻¹)		
	Grain	Straw	Total	Grain	Straw	Total
T ₁ : 75% RRF + FYM at 1.0 t ha ⁻¹	21.33 ^c	28.33 ^d	49.67 ^d	76.47 ^c	34.40 ^d	110.87 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	25.27 ^{bc}	30.67 ^{cd}	55.93 ^{cd}	81.27 ^{bc}	38.47 ^{cd}	119.73 ^d
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	27.07 ^{bc}	33.27 ^{cd}	60.33 ^c	105.60 ^{a-c}	55.80 ^{a-c}	161.4 ^{bc}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	30.33 ^{ab}	33.93 ^{cd}	64.27 ^c	112.27 ^{ab}	59.73 ^{ab}	172 ^{ab}
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	25.87 ^{bc}	34.80 ^{cd}	60.67 ^c	90.00 ^{bc}	39.73 ^{cd}	129.73 ^{cd}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	25.80 ^{bc}	36.67 ^c	62.47 ^c	84.67 ^{bc}	45.07 ^{b-d}	130 ^{cd}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	30.67 ^{ab}	45.07 ^b	75.73 ^b	128.13 ^a	57.53 ^{ab}	185.67 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	34.27 ^a	54.27 ^a	88.53 ^a	136.40 ^a	65.00 ^a	201.4 ^a
S.Em. ±	1.83	2.37	3.05	10.36	5.35	11.77
LSD at 5%	5.56	7.20	9.25	31.43	16.22	35.69

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 8 Effect of integrated nutrient management on nutrient concentrations in chickpea seeds and haulm

Treatments	N (%)		P (%)		K (%)		Zn (mg kg ⁻¹)		Fe (mg kg ⁻¹)	
	Seed	Haulm	Seed	Haulm	Seed	Haulm	Seed	Haulm	Seed	Haulm
T ₁ : 75% RRF	3.13 ^g	0.79 ^b	0.436 ^h	0.915 ^h	0.722 ^e	1.570 ^d	14.07 ^d	12.90 ^b	17.00 ^c	72.43 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	3.18 ^f	0.80 ^b	0.447 ^g	0.922 ^g	0.800 ^d	1.630 ^{cd}	15.00 ^{cd}	13.47 ^b	17.83 ^{bc}	70.61 ^d
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	3.22 ^e	0.91 ^{ab}	0.454 ^f	0.931 ^f	0.836 ^d	1.683 ^{b-d}	17.30 ^{bc}	16.10 ^{ab}	31.03 ^a	100.33 ^b
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	3.26 ^d	1.00 ^a	0.465 ^e	0.938 ^e	0.904 ^c	1.697 ^{b-d}	18.57 ^b	16.73 ^{ab}	32.63 ^a	116.00 ^a
T ₅ : RRF	3.31 ^c	1.00 ^a	0.474 ^d	0.945 ^d	0.918 ^c	1.633 ^{cd}	15.67 ^{cd}	14.07 ^{ab}	24.20 ^b	78.42 ^{cd}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	3.33 ^b	1.04 ^a	0.487 ^c	0.960 ^c	1.005 ^b	1.748 ^{bc}	16.20 ^{b-d}	14.23 ^{ab}	31.00 ^a	85.27 ^c
T ₇ : RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	3.33 ^b	1.05 ^a	0.495 ^b	0.965 ^b	1.070 ^a	1.808 ^b	18.53 ^b	17.70 ^a	34.93 ^a	114.67 ^a
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	3.34 ^a	1.07 ^a	0.505 ^a	0.974 ^a	1.082 ^a	1.952 ^a	26.20 ^a	17.87 ^a	36.66 ^a	116.67 ^a
S.Em. ±	0.002	0.05	0.0005	0.0007	0.012	0.039	0.78	1.15	2.10	3.96
LSD at 5%	0.007	0.16	0.0018	0.0022	0.039	0.120	2.38	3.49	6.38	12.01

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 9 Plant macro nutrient (NPK) uptake by chickpea as influenced by different integrated nutrient management practices

Treatments	N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			K uptake (kg ha ⁻¹)		
	Seed	Haulm	Total	Seed	Haulm	Total	Seed	Haulm	Total
T ₁ : 75% RRF	60.72 ^d	13.09 ^d	73.81 ^c	8.47 ^d	15.18 ^e	23.65 ^e	14.03 ^f	26.04 ^d	40.07 ^f
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	66.04 ^{cd}	13.79 ^{cd}	79.83 ^c	9.28 ^{cd}	15.84 ^{de}	25.12 ^{de}	16.63 ^{ef}	27.99 ^{cd}	44.62 ^{ef}
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	70.70 ^{b-d}	17.17 ^{bc}	87.87 ^{bc}	9.96 ^{b-d}	17.41 ^{cd}	27.37 ^{cd}	18.34 ^{de}	31.47 ^{bc}	49.82 ^{de}
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	74.65 ^{a-d}	19.70 ^{ab}	94.35 ^b	10.63 ^{bc}	18.53 ^{bc}	29.16 ^{bc}	20.68 ^{cd}	33.49 ^b	54.17 ^{cd}
T ₅ : RRF	75.27 ^{a-c}	19.63 ^{ab}	94.91 ^b	10.76 ^{bc}	18.58 ^{bc}	29.34 ^{bc}	20.86 ^{cd}	32.16 ^{bc}	53.03 ^{cd}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	78.16 ^{a-c}	20.90 ^a	99.06 ^{ab}	11.44 ^b	19.32 ^{abc}	30.76 ^b	23.62 ^{bc}	35.16 ^b	58.78 ^{bc}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	80.40 ^{ab}	21.22 ^a	101.61 ^{ab}	11.93 ^{ab}	19.52 ^{ab}	31.46 ^{ab}	25.76 ^{ab}	36.58 ^{ab}	62.34 ^b
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	88.11 ^a	22.48 ^a	110.60 ^a	13.35 ^a	20.53 ^a	33.88 ^a	28.59 ^a	41.12 ^a	69.70 ^a
S.Em. ±	4.09	1.12	4.44	0.59	0.59	0.94	1.26	1.57	2.28
LSD at 5%	12.39	3.41	13.45	1.79	1.79	2.84	3.83	4.77	6.92

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)

Table 10 Zinc (Zn) and iron (Fe) uptake of chickpea as influenced by different integrated nutrient management practices

Treatments	Zn uptake (mg kg ⁻¹)			Fe uptake (mg kg ⁻¹)		
	Grain	Halum	Total	Grain	Halum	Total
T ₁ : 75% RRF	28.13 ^d	25.80 ^b	53.93 ^c	34.00 ^c	144.85 ^d	178.85 ^d
T ₂ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	30.00 ^d	26.93 ^b	56.93 ^c	35.67 ^{bc}	141.21 ^d	176.88 ^d
T ₃ : 75% RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	34.60 ^{bc}	32.20 ^{ab}	66.80 ^{ab}	62.07 ^a	200.90 ^b	262.97 ^b
T ₄ : 75% RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	37.13 ^{ab}	33.47 ^{ab}	70.60 ^a	65.27 ^a	232.73 ^a	297.99 ^a
T ₅ : RRF	31.33 ^{cd}	28.13 ^{ab}	59.47 ^{bc}	48.40 ^b	156.85 ^{cd}	205.25 ^{cd}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed	32.4 ^{cd}	28.47 ^{ab}	60.87 ^{bc}	62.00 ^a	170.53 ^c	232.53 ^c
T ₇ : RRF + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	37.07 ^{ab}	35.73 ^a	72.80 ^a	69.87 ^a	229.93 ^a	299.80 ^a
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 ml kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ foliar spray at 0.5%	39.20 ^a	35.40 ^a	74.60 ^a	73.33 ^a	233.51 ^a	306.85 ^a
S.Em. ±	1.28	2.30	2.95	4.21	7.93	9.66
LSD at 5%	3.89	6.97	8.95	12.75	24.04	29.31

FYM - Farmyard manure

RRF- Recommended rate of fertilizer (100:50:50 N:P:K kg ha⁻¹) for maize

Means followed by the same letter (s) within a column are not significantly different by DMRT (P=0.05)