



OPEN ACCESS

EDITED BY

Vimala D. Nair,
University of Florida, United States

REVIEWED BY

Atanu Mukherjee,
Kentucky State University, United States
Dalia Soliman,
Arish University, Egypt

*CORRESPONDENCE

Sanjeev Kumar
✉ bhanusanjeev@gmail.com

RECEIVED 02 August 2025

ACCEPTED 24 October 2025

PUBLISHED 19 November 2025

CITATION

Onte S, Fiskey VV, Dadhich DK, Guglawath AK, Rajkumari P, Kothuru B, Veda TV, Yadav R, Singh H, Puttaswamaiah P, Singh M, Kumar D, Boregowda YS, Kumar S, Garg K, Halagundegowda GR, Singh AG, Pyati PS, Kanwat M, Chandra R, Mukherjee S and Kumar S (2025) Effect of integrated organic nutrient management on growth, yield, and soil fertility under a maize–berseem–cowpea cropping system.
Front. Sustain. Food Syst. 9:1678536.
10.3389/fsufs.2025.1678536

COPYRIGHT

© 2025 Onte, Fiskey, Dadhich, Guglawath, Rajkumari, Kothuru, Veda, Yadav, Singh, Puttaswamaiah, Singh, Kumar, Boregowda, Kumar, Garg, Halagundegowda, Singh, Pyati, Kanwat, Chandra, Mukherjee and Kumar. This is an open-access article distributed under the terms of the [Creative Commons Attribution License \(CC BY\)](#). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Effect of integrated organic nutrient management on growth, yield, and soil fertility under a maize–berseem–cowpea cropping system

Santosh Onte^{1,2}, Vrusabh Vijay Fiskey³,
Devendra Kumar Dadhich³, Ashwin Kumar Guglawath³,
Preety Rajkumari³, Bhanusri Kothuru³, T. V. Veda³, Rohit Yadav³,
Harjeet Singh³, Praveen Puttaswamaiah⁴, Magan Singh³,
Dileep Kumar⁵, Yogananda Shivalli Boregowda⁴, Sudhir Kumar⁶,
Kamal Garg³, Gopikunte Ramegowda Halagundegowda⁷,
Akash Gaurav Singh⁸, Prasanna S. Pyati⁹, Manish Kanwat¹⁰,
Ramesh Chandra³, Sabyasachi Mukherjee³ and Sanjeev Kumar^{3*}

¹ICAR-Krishi Vigyan Kendra, University Agricultural Sciences, Dharwad, Karnataka, India, ²Centre for Water Resources Development and Management (CWRDM), Calicut, India, ³ICAR-National Dairy Research Institute, Karnal, Haryana, India, ⁴College of Agriculture, VC Farm, Mandya, Karnataka, India, ⁵ICAR-Indian Institute of Sugarcane Research, Lucknow, Uttar Pradesh, India, ⁶ICAR-Indian Agricultural Research Institute, New Delhi, India, ⁷Statistics Section, Central Silk Board, Bengaluru, Karnataka, India, ⁸Acharya Narendra Dev University of Agriculture and Technology, Kumarganj, Uttar Pradesh, India, ⁹Tocklai Tea Research Institute, Jorhat, Assam, India, ¹⁰ICAR-CAZRI Krishi Vigyan Kendra, Bhuj, Gujarat, India

Intensive cropping systems in South Asia, particularly those focused on year-round fodder supply, are increasingly constrained by soil fertility decline, nutrient imbalance, and reduced biological activity due to the overreliance on inorganic fertilizers. To address this challenge, the present study evaluated the effects of integrated organic nutrient management (IONM) involving farmyard manure (FYM), plant growth-promoting rhizobacteria (PGPR), and Panchagavya on crop performance and soil health under a maize (*Zea mays* L.) (M)–berseem (*Trifolium alexandrinum* L.) (B)–cowpea (*Vigna unguiculata* L.) (C) sequential fodder system. A field experiment was conducted over three consecutive years (2018–2021) with seven nutrient management treatments, including fully organic, partially organic, and inorganic fertilizer-based regimes. Research findings revealed that the T₇ treatment, involving 100% Recommended dose of nitrogen (RDN) through FYM + PGPR + 3% foliar spray of Panchagavya (M) – PGPR + 3% foliar spray of Panchagavya (B) – PGPR + 3% foliar spray of Panchagavya (C), yielded significant improvements in both green fodder of maize (35.4, 37.0, and 38.6 t ha⁻¹), berseem (58.2, 60.0, and 60.6 t ha⁻¹) and cowpea (25.7, 27.5, and 28.3 t ha⁻¹) during 2018–19, 2019–20 and 2020–21, respectively. Results revealed that T₇ significantly enhanced plant growth attributes from 20.7–34.4% in all three crops. Nutrient concentrations (N, P, K, Zn, Fe) and uptake were consistently higher under T₇ across all crops. Additionally, T₇ recorded the improvement in soil nutrient availability after each crop cycle, reflecting cumulative benefits over time. The findings indicate that the integrated application of FYM, PGPR, and Panchagavya can serve as a sustainable alternative to inorganic fertilizers by improving both crop productivity and soil fertility. The study supports the adoption of IONM strategies for enhancing the resilience and

sustainability of intensive fodder production systems, offering a viable pathway for reducing chemical input dependency while maintaining high yields.

KEYWORDS

farmyard manure, fodder yield, Panchagavya, PGPR, nutritive quality

Introduction

The sustainability of intensive cropping systems is under increasing scrutiny due to declining soil fertility, over-dependence on chemical fertilizers, and stagnation in crop productivity (Kansanga et al., 2019; Gollin et al., 2021). Continuous application of inorganic fertilizers, although effective in increasing yields in the short term, has been associated with long-term soil degradation, nutrient imbalance, and reduced biological activity (Onte et al., 2025). This unsustainable trend has raised concerns over the future viability of such systems, as they have become increasingly reliant on costly external inputs. Therefore, the development of alternative nutrient management strategies that maintain crop productivity while improving soil health is a critical need in modern agriculture.

Organic nutrient sources, particularly FYM, have long been recognized for their potential to enhance soil physical, chemical, and biological properties. FYM improves soil structure, moisture retention, and microbial activity, and provides a slow but steady release of nutrients (Abrol et al., 2024; Garg et al., 2024). However, its mineralization rate is often inadequate to meet the immediate nutrient demands of high-yielding crops, especially during critical growth stages. This limitation can be addressed through the use of biological inputs such as PGPR and traditional organic formulations like Panchagavya, which have received growing attention in sustainable agriculture.

PGPR are beneficial microbes that colonize the plant rhizosphere and enhance plant growth through mechanisms such as atmospheric nitrogen fixation, phosphorus solubilization, and synthesis of phytohormones like auxins and cytokinins (Shah et al., 2021; Shilpa et al., 2024). These organisms also improve nutrient uptake efficiency and stimulate root development, thereby improving overall crop vigor. Panchagavya, a traditional Indian bio-formulation prepared from cow-based products (milk, curd, ghee, urine, and dung), is rich in macro- and micro-nutrients, amino acids, enzymes, and beneficial microorganisms. It is reported to promote plant metabolism, enhance resistance to pests and diseases, and stimulate growth (Golakiya et al., 2019). We hypothesize that FYM provides a slow-release nutrient base and improves soil structure, creating a favorable habitat for PGPR. The PGPR, in turn, enhance nutrient solubilization and fixation, while the growth-promoting compounds in Panchagavya (e.g., hormones, microbes) further stimulate root development and microbial activity, creating a positive feedback loop that boosts nutrient availability beyond the sum of individual applications. The synergistic application of FYM with PGPR and Panchagavya has the potential to improve nutrient availability, boost microbial activity, and enhance soil fertility and crop performance more effectively than individual applications.

Fodder production is a crucial component of integrated farming systems, particularly in South Asia, where livestock contributes significantly to rural livelihoods. A major challenge faced by livestock farmers is the year-round availability of nutritious green fodder. Sequential cropping systems such as

maize–berseem–cowpea are commonly practiced to ensure continuous fodder supply across seasons. Maize (*Zea mays* L.), a fast-growing cereal cultivated during the rainy season, is valued for its high biomass and energy-rich fodder. Berseem (*Trifolium alexandrinum* L.), a winter-season legume, is highly palatable and rich in protein and contributes to soil nitrogen through biological fixation. Cowpea (*Vigna unguiculata* L.), a short-duration summer legume, is known for its drought tolerance, soil fertility enhancement, and quality green fodder. Together, these three crops form a biologically diverse and nutrient-responsive system that supports both productivity and sustainability. However, to sustain high yields and preserve soil health in such a system, balanced and integrated nutrient management is essential.

While several studies have evaluated the effects of organic nutrient management strategies in cereal and grain legume systems, research focusing on their performance under fodder-based cropping systems remains limited. Moreover, long-term, field-based evidence evaluating the combined use of FYM, PGPR, and Panchagavya in terms of growth, yield, nutrient uptake, and soil fertility parameters in sequential cropping systems is scarce. Therefore, the present study hypothesizes that the integrated application of 100% nitrogen through FYM, along PGPR, and foliar spray of Panchagavya would produce green fodder yields statistically equivalent to 100% inorganic fertilization, while significantly enhancing post-harvest soil available N, P, and K levels compared to all other treatments over a three-year cycle. The objective of this research was to evaluate the impact of IONM on the growth performance, productivity, and soil fertility in a maize–berseem–cowpea cropping system.

Materials and methods

Research location and treatment specifications

The research was carried out at the Agronomy Section's experimental farm under ICAR–National Dairy Research Institute, located in Karnal, Haryana. The study spanned three cropping seasons rainy, winter, and summer between 2018 and 2021. Situated in the Trans Indo-Gangetic Plains, the site lies at 29.45° N latitude, 76.58° E longitude, and an elevation of 245 meters above sea level. The area is characterized by a subtropical climate with hot, arid summers and chilly winters. The topsoil (0–15 cm) at the study site was identified as clay loam in texture. It exhibited an electrical conductivity of 0.23 dS m⁻¹ and a pH of 7.52. The soil contains organic carbon 0.601%, available N (nitrogen) 188.4 kg ha⁻¹, available P (phosphorus) 28.54 kg ha⁻¹ and available K (potassium) 190.2 kg ha⁻¹. The experiment was conducted on a fixed plot with a gross plot size of 8 meters in length and 6 meters in breadth (Supplementary Figure S1).

A field study was conducted following a crop rotation involving maize, berseem and cowpea, using a randomized complete block

TABLE 1 Treatment details.

Treatment symbol	Treatment details
T ₁	100% RDN applied conventionally (fertilizers) for maize, berseem, and cowpea
T ₂	100% RDN supplied via FYM (20 t ha ⁻¹) during maize cultivation; no nutrient application in berseem and cowpea
T ₃	50% of the recommended dose of nitrogen (RDN) was applied through FYM (10 t ha ⁻¹), along with plant PGPR and a 3% foliar spray of Panchagavya during maize. The same PGPR and foliar Panchagavya spray were continued in berseem and cowpea
T ₄	75% RDN was provided using FYM (15 t ha ⁻¹) along with PGPR during the maize phase; only PGPR applied during berseem and cowpea
T ₅	100% RDN via FYM (20 t ha ⁻¹) combined with PGPR during maize; PGPR continued in the subsequent berseem and cowpea
T ₆	75% RDN through FYM (15 t ha ⁻¹) supplemented with PGPR and 3% foliar Panchagavya spray during maize, followed by PGPR and foliar spray in berseem and cowpea
T ₇	100% RDN delivered via FYM (20 t ha ⁻¹) along with PGPR and foliar application of 3% Panchagavya for all three crops rotation

design (RCBD) with seven distinct treatment combinations. The treatment details are given in Table 1:

In treatment T₁: 100 kg N: 60 kg P₂O₅: 40 kg K₂O, 20 kg N:60 kg P₂O₅:40 kg K₂O and 20 kg N:60 kg P₂O₅ were applied as recommended fertilizer doses for maize, berseem, and cowpea crops, respectively. For treatment T₁, nitrogen (N) in maize was applied in two equal splits - half at sowing and the other half 30 DAS. In contrast, berseem and cowpea received the full N dose at sowing. The P and K were also applied as basal doses for all three crops. According to the treatment details, FYM quantity was applied as a basal input in treatments T₂ through T₇, calculated based on its N content. Seeds were treated with PGPR in accordance with the respective treatments. Panchagavya, used as a foliar spray at a 3% concentration, was applied at 30, 40, and 50 DAS.

The average nutrient composition of FYM over the 3 years was 11.5% oxidizable organic carbon, 21.37% total carbon, 0.68% N, 0.45% P, and 0.90% K. The average nutrient composition of the *Panchagavya* was analyzed and found to contain total nitrogen (0.64%), total phosphorus (0.10%), and total potassium (0.47%), along with micronutrients such as zinc (1.05 mg kg⁻¹), iron (8.75 mg kg⁻¹), copper (0.61 mg kg⁻¹), and manganese (1.50 mg kg⁻¹). Further, it carries average total bacterial population 39.4 × 10⁵ cfu ml⁻¹, total fungi 26.2 × 10³ cfu ml⁻¹, total actinomycetes 19.9 × 10² cfu ml⁻¹, azotobacter 7.2 × 10² cfu ml⁻¹, and P solubilizers 8.1 × 10² cfu ml⁻¹.

The varieties used in the experiment were J-1006 for fodder maize, Mascavi for berseem, and C-152 for cowpea, with seed rates of 40 kg ha⁻¹ for maize, 25 kg ha⁻¹ for berseem, and 40 kg ha⁻¹ for cowpea. The spacing adopted for maize was 30 cm row to row, while berseem was broadcast, and cowpea was planted at a spacing of 30 cm × 10 cm. Each crop was grown sequentially in the same field within a year (Supplementary Table S1). The crops were sown according to standard agronomic recommendations for the region and their respective seasonal requirements. Maize was sown during the second fortnight of June and harvested approximately 65 days after sowing (DAS). Berseem was sown in the first fortnight of October, with the first harvest taken at 65 DAS, followed by two subsequent cuts at intervals of 35 days each, resulting in a total of three cuts. Cowpea was sown during the first fortnight of April and harvested at 65 DAS. A single hand weeding was conducted in the maize crop 20 days after sowing, while no weeding was performed in berseem and cowpea. To control insect pests in the fodder maize, Azadirachtin (1,500 ppm) was applied at a concentration of 4 mL L⁻¹ of water. No insect damage was observed in the berseem and cowpea crops.

Yield assessment

Fodder crops including maize, berseem, and cowpea were carefully harvested by hand from each designated plot to ensure accuracy in yield estimation. Immediately after harvesting, the fresh biomass from each plot was weighed using a digital balance, and the fresh yield was expressed in kilograms per plot. These values were subsequently extrapolated to express the green fodder yield (GFY) in tons per hectare using standard conversion methods based on plot size. To determine the dry fodder yield, representative subsamples of the freshly harvested fodder were collected from each plot. These samples were placed in a hot air oven maintained at a constant temperature of 60 °C and dried for a period of 48 h to achieve a consistent moisture-free weight. After drying, the dry fodder yield (DFY) was recorded and also converted into tons per hectare.

Nutrient concentration and uptake in crops

The dried samples of maize, berseem and cowpea were then finely ground using a Wiley mill to ensure uniform particle size. The ground material was passed through a 1 mm mesh sieve and stored in airtight plastic bags to preserve sample integrity for subsequent laboratory analyses. Total nitrogen N was estimated using the Kjeldahl digestion method (Jackson, 1973). Concentration of P and K were determined after wet digestion using di-acid (HNO₃: HClO₄) mixture, with phosphorus measured through UV-Visible spectrophotometry and potassium using flame photometry (Piper, 1966). For micronutrients zinc (Zn) and iron (Fe), the samples were digested similarly, and concentrations were analyzed using Atomic Absorption Spectroscopy (AAS) (Lindsay and Norvell, 1978). The uptake of N, P, and K (kg ha⁻¹) was determined by multiplying the respective nutrient concentrations, expressed as percentages, by the corresponding dry matter yield (kg ha⁻¹) of fodder, and subsequently dividing the result by 100.

The equation used was as follows:

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \left[\frac{\text{Nutrient concentration (\%)} \times \text{Dry matter yield (kg ha}^{-1}\text{)}}{100} \right]$$

This calculation followed the standardized methodology recommended by Tandon (1993).

Soil available nutrient after harvest of each crop during third year of the experiment

Soil nutrient accumulation under each treatment was assessed through sampling conducted after the harvest of maize, berseem, and cowpea in each cropping cycle. Composite soil samples were collected from the 0–15 cm soil layer of each plot, air-dried, and sieved prior to analysis. Available nitrogen was determined using the alkaline permanganate method (Subbaiah and Asija, 1956), available phosphorus by the 0.5 M sodium bicarbonate method (Olsen et al., 1954), and available potassium by the ammonium acetate extraction method (Jackson, 1973).

Statistical evaluation

The experimental data obtained from the field trials were subjected to statistical evaluation through analysis of variance (ANOVA) to determine significant differences among treatment means. This statistical approach was carried out following the methodology outlined by Gomez and Gomez (1984), maintaining a 5% probability level ($p \leq 0.05$) as the threshold for statistical significance. As the experiments spanned multiple years, data were analyzed separately for each year to account for environmental variability, and treatment effects are presented on a year-wise basis. Post-hoc comparisons of treatment means were conducted using the Least Significant Difference (LSD) test at $p \leq 0.05$, chosen for its sensitivity in an RCBD with seven treatments and three replications. Although no formal statistical tests of residual normality or variance homogeneity were performed, the RCBD design with replications and exploratory data evaluation suggested no major assumption violations. Differences between treatment means are also graphically represented with standard deviation error bars. For multivariate analysis, PCA was carried out on standardized variables, with component retention based on eigenvalues >1 and scree plot inspection. Graphs were prepared using GraphPad Prism (v8.0), OriginPro, and JASP (version 0.95.1.0).

Results

Growth attributes

The growth performance of fodder maize was significantly influenced by organic nutrient management over the three-year period (2018–2020). Treatment T_7 consistently enhanced growth attributes, including plant height, leaf length, and leaf width, showing 20–22% increases over T_3 , and performed comparably to T_5 and T_6 . Treatment T_1 produced the tallest plants and the highest leaf number overall, significantly exceeding other treatments. Across the study period, T_7 maintained superior growth trends in terms of leaf dimensions and overall plant vigor, highlighting its effectiveness in promoting robust vegetative growth compared to conventional and less effective treatments (Supplementary Table S2).

Berseem growth was markedly improved by T_7 , especially during the second and third years. Treatment T_7 produced the highest plant height and leaf numbers, with 23–33% increases over T_2 and T_3 , and

significantly enhanced nodulation, including a 59–111% increase in nodule number over T_1 . Nodule dry weight was also maximized under T_7 , outperforming all other treatments. These results indicate that T_7 not only promotes vegetative growth but also supports symbiotic nitrogen fixation, demonstrating its superior overall effect on berseem productivity (Supplementary Table S3).

Among organic nutrient management strategies, T_7 consistently improved cowpea growth over the 3 years (2019–2021). Plant height and leaf number under T_7 were statistically similar to T_1 , while leaf dimensions showed 25–34% increases over T_3 . Although T_6 occasionally recorded slightly higher leaf length, it was generally comparable to T_5 – T_7 . Treatment T_1 produced the widest leaves, yet T_7 maintained balanced growth across all vegetative parameters, emphasizing its reliability in enhancing cowpea growth under organic nutrient management systems (Supplementary Table S4).

Yield

Fodder maize performance under different organic nutrient management strategies showed that treatment T_7 consistently produced the highest green and dry fodder yields across the 3 years. On average, T_7 increased GFY and DFY by 12–18% compared to the lowest-yielding treatment, T_3 . While T_7 often performed comparably with treatments T_2 , T_4 , T_5 , and T_6 , it significantly outperformed T_3 , highlighting the superior efficiency of the integrated organic nutrient approach in enhancing biomass production. Notably, the inorganic fertilizer treatment (T_1) matched T_7 in 2018 but showed slightly lower yields in subsequent years, underscoring the potential of well-managed organic nutrient strategies to sustain fodder productivity over multiple seasons (Figures 1A,B).

Among berseem treatments, T_7 consistently achieved the highest GFY and DFY over 3 years, averaging a 6–8% increase over T_1 and T_6 . In contrast, T_3 produced the lowest yields, indicating limited effectiveness of its nutrient management regime. Statistical analysis revealed T_7 to be comparable with T_1 and T_6 , suggesting that optimized organic strategies can match or exceed conventional fertilization. These results emphasize T_7 's capacity to enhance fodder accumulation efficiently, particularly under organic systems, while minimizing reliance on synthetic inputs (Figures 1C,D).

Cowpea yields responded similarly, with T_7 delivering the highest GFY and DFY over the study period. On average, T_7 improved GFY by 10–15% relative to the lowest-yielding treatment, T_4 . Treatments T_1 , T_5 , and T_6 also performed well, remaining statistically comparable to T_7 . The lowest biomass consistently occurred under T_4 , highlighting the importance of adequate organic nutrient management for cowpea productivity. These trends confirm T_7 's broad effectiveness in improving forage yields across different leguminous and cereal crops, supporting its recommendation as the most efficient organic nutrient management practice (Figures 1E,F).

Nutrient concentration

Organic nutrient management significantly influenced N, P, K, Zn, and Fe concentrations in fodder maize over the three-year study (Figures 2A–C, 3A,B). Treatment T_7 consistently outperformed other treatments, providing sustained improvements across all nutrients.

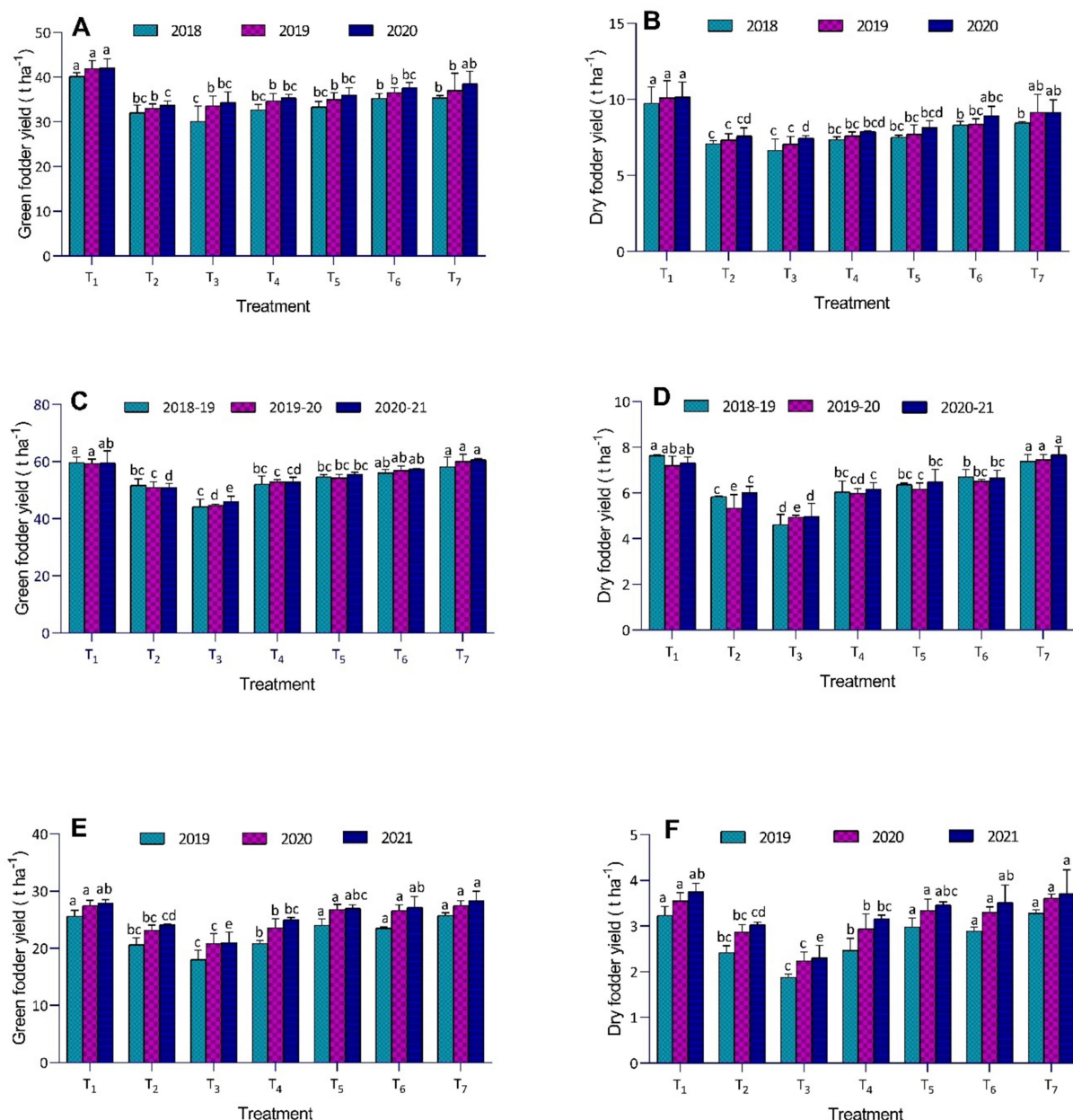


FIGURE 1
Effect of organic nutrient management on yield performance: maize green fodder yield (A), maize dry fodder yield (B), berseem green fodder yield (C), berseem dry fodder yield (D), cowpea green fodder yield (E), and cowpea dry fodder yield (F). The data represents the mean values across treatments (T₁–T₇) with error bars indicating standard deviation. Statistical significance was assessed using one way ANOVA, with differences considered significant at $p \leq 0.05$. Different lowercase letters indicate significant differences among different treatments based on LSD test.

Notably, T₇ recorded the highest N concentration in the second and third years (1.42 and 1.45%), surpassing T₃, while P (0.288–0.317%) and K, Zn, and Fe increased markedly, with K showing 54.7–68.8%, Zn 27.0–70.3%, and Fe 26.3–30.4% increases over T₃. Treatment T₁ exhibited a higher N concentration in the first year (1.42%) but its effect was less consistent over time. Treatments T₅ and T₆ were statistically similar, while T₃ consistently had the lowest nutrient concentrations. Overall, Treatment T₇ provided the most consistent and substantial improvement in fodder maize nutrient content.

Nutrient concentrations in berseem were significantly enhanced under different organic nutrient management practices

(Figures 2D–F, 3C,D), with T₇ providing the most consistent improvements. Across 3 years, T₇ achieved higher N content (3.36–3.71%), P (0.249–0.269%), and K (3.55–3.99%), while Zn and Fe concentrations increased substantially (Zn: 38.1–44.0 mg kg⁻¹; Fe: 473.3–542.0 mg kg⁻¹). T₁ exhibited comparable N and P levels in the second and third years but generally remained lower than T₇. Treatments T₅ and T₆ were statistically similar, whereas T₂ and T₄ provided moderate improvements over T₃, which consistently recorded the lowest nutrient levels. These results indicate that T₇ consistently maximized nutrient accumulation in berseem, demonstrating its effectiveness for improving forage quality.

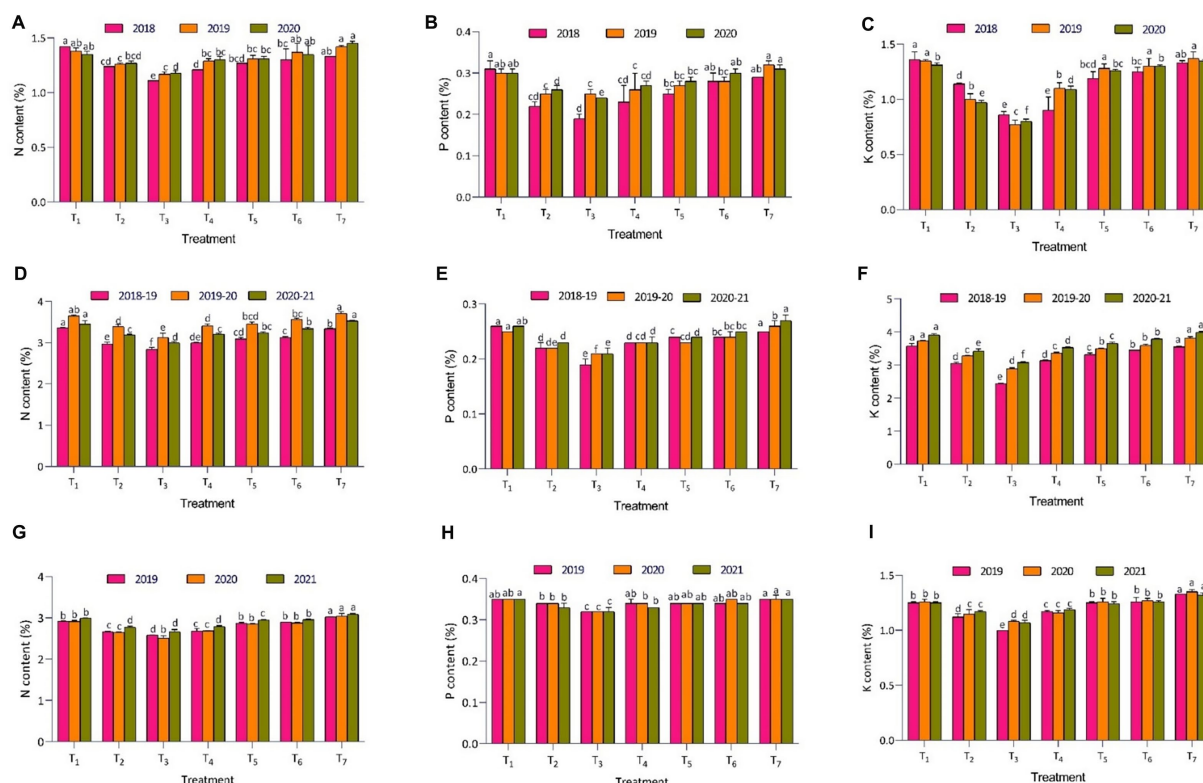


FIGURE 2

Effect of organic nutrient management on nutrient concentration: maize N content (A), maize P content (B), maize K content (C), berseem N content (D), berseem P content (E), berseem K content (F), cowpea N content (G), cowpea P content (H), and cowpea K content (I). The data represents the mean values across treatments (T₁–T₇) with error bars indicating standard deviation. Statistical significance was assessed using one way ANOVA, with differences considered significant at $p \leq 0.05$. Different lowercase letters indicate significant differences among different treatments based on LSD test.

Significant differences in nutrient concentrations were observed in vegetable cowpea under various organic nutrient management strategies (Figures 2G–I, 3E,F). Treatment T₇ consistently led to the highest N (3.02–3.09%), P (stable at 0.353%), and K (1.32–1.35%) levels, with corresponding increases over T₃ of 9.3–11.4% for P and marked improvements in Zn (36.7–38.2 mg kg⁻¹) and Fe (432.7–471.0 mg kg⁻¹). Treatment T₁ provided moderate nutrient enhancements, similar to T₅ and T₆, while T₂ and T₄ were statistically comparable and superior to T₃. Overall, Treatment T₇ demonstrated the most pronounced and consistent improvements in vegetable cowpea nutrient content, emphasizing its effectiveness among the tested organic nutrient management strategies.

Nutrient uptake

The application of different organic nutrient management strategies significantly enhanced nutrient uptake in fodder maize across the three-year maize–berseem–cowpea cropping system. Among these, treatment T₇ consistently demonstrated superior nutrient acquisition compared to most other treatments. Although treatment T₁, which involved 100% recommended dose of inorganic fertilizers, recorded the highest total nitrogen uptake (138.7, 138.2, and 137.6 kg ha⁻¹ in the first, second, and third years, respectively), its performance was statistically comparable to T₇. Furthermore, T₇ also exhibited comparable P and K uptake to T₁. In contrast, treatments

such as T₅ and T₆, though statistically at par with each other, showed moderate increases in P uptake 48.9, 17.1, and 29.9 and K uptake 57.4, 80.0, and 71.9 kg ha⁻¹ over T₃ across the 3 years (Table 2).

Treatment T₇ consistently recorded a significantly higher uptake of nitrogen (257.2, 262.6, and 259.9 kg ha⁻¹), phosphorus (18.3, 19.3, and 20.6 kg ha⁻¹), and potassium (262.7, 285.1, and 306.6 kg ha⁻¹) in berseem over three consecutive years, outperforming all treatments except T₁ ($p \leq 0.05$). In comparison, treatments T₅ and T₆ showed statistically similar performance to each other. Likewise, treatments T₂ and T₄ demonstrated statistical parity in nutrient uptake but remained inferior to T₇. Although T₆ achieved comparable nutrient uptake values, particularly for N (Table 3).

Marked differences in N, P, and K uptake by cowpea were observed across treatments, with treatment T₇ consistently outperforming most others over the three-year study period. Specifically, T₇ recorded the highest N uptake values (98.9, 109.8, and 114.7 kg ha⁻¹), significantly surpassing treatments T₂ to T₆ ($p \leq 0.05$), while remaining statistically comparable to T₁. Similarly, P uptake under T₇ was markedly improved, registering 11.59, 12.74, and 13.09 kg ha⁻¹ across the 3 years, which represented a substantial increase of 90.6, 77.9, and 79.3% over T₃. This enhanced performance placed T₇ on par with T₁, T₅, and T₆ in the latter 2 years. The K uptake under T₇ recorded significantly highest (43.48, 48.85, and 49.13 kg ha⁻¹), exceeding that of T₃. While T₁ showed comparable results to T₅ and T₆ in terms of K uptake (Table 4).

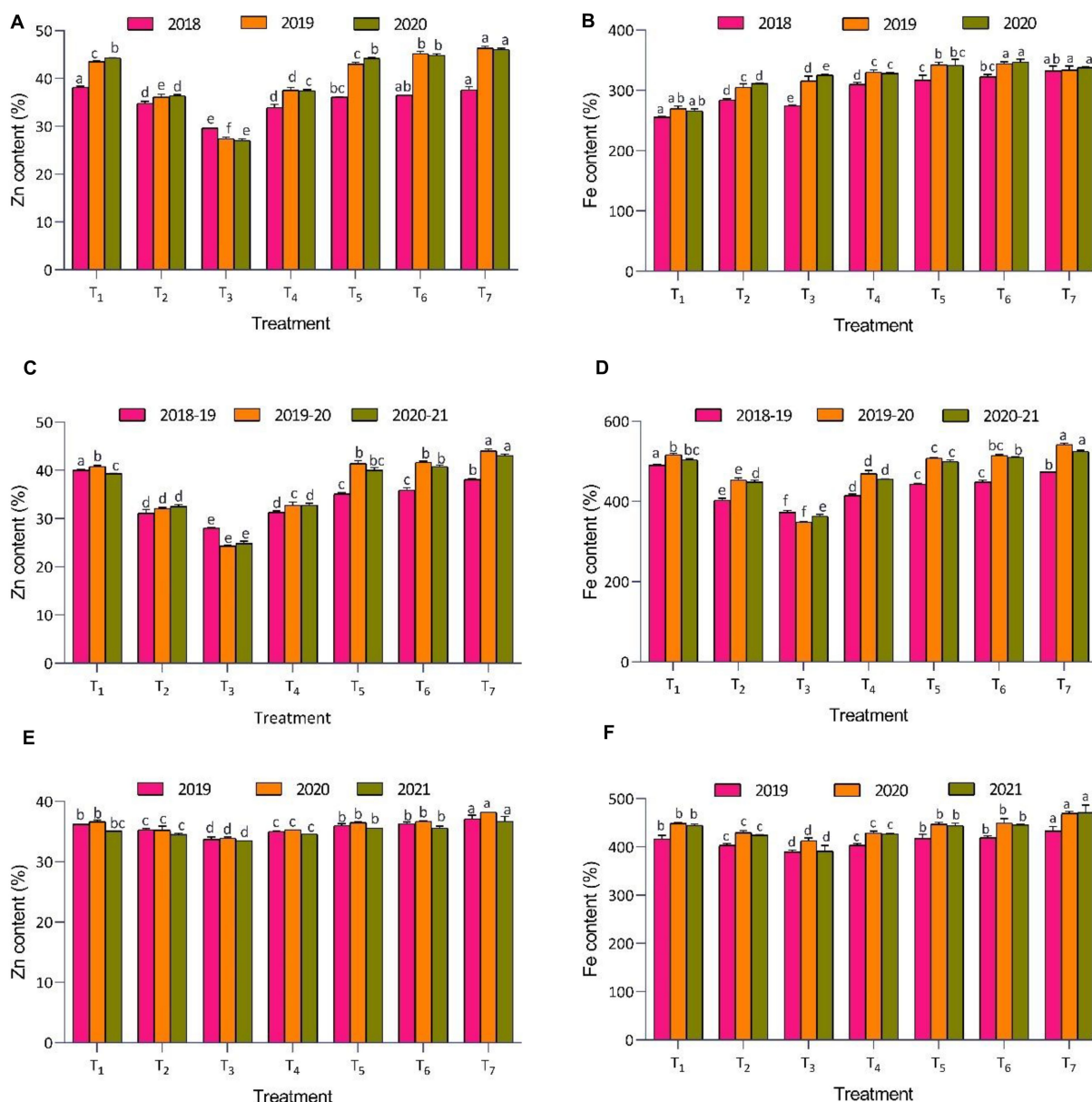


FIGURE 3

Effect of organic nutrient management on nutrient concentration: maize Zn content (A), maize Fe content (B), berseem Zn content (C), berseem Fe content (D), cowpea Zn content (E), cowpea Fe content (F). The data represents the mean values across treatments (T₁–T₇) with error bars indicating standard deviation. Statistical significance was assessed using one way ANOVA, with differences considered significant at $p \leq 0.05$. Different lowercase letters indicate significant differences among different treatments based on LSD test.

Sequential cumulative changes in soil nutrient availability under fodder maize-berseem-cowpea cropping system

Soil N availability showed a steady and cumulative increase over the three-year maize–berseem–cowpea rotation, with marked differences among nutrient management treatments (Figure 4A). Treatment T₇ consistently exhibited the highest N levels, whereas T₃ remained the lowest. Across rotations, T₇ improved soil N by 11.3–20.2% relative to T₃ and 11.4–13.9% relative to T₁. Intermediate treatments (T₂, T₄, T₅) showed moderate increases, particularly in later years. These trends indicate that integrated

nutrient management, combining organic and inorganic sources, effectively sustains and enhances soil N availability over sequential cropping cycles.

Soil P availability also progressively increased under the cropping system, with T₇ consistently outperforming all other treatments (Figure 4B). Compared to T₃, T₇ increased soil P by 19.0–27.4%, and by 13.1–30.3% relative to T₁. T₅ and T₆ showed notable improvements, reflecting the benefits of balanced nutrient application, while T₃ consistently lagged behind. The cumulative effect of integrated nutrient management was particularly evident after leguminous crops (berseem and cowpea), highlighting enhanced nutrient cycling and retention in the soil.

TABLE 2 Effect of organic nutrient management on nutrient uptake (N, P, K) in maize crop.

Treatment	N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			K uptake (kg ha ⁻¹)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
T ₁	138.7 ^a	138.2 ^a	137.6 ^a	30.3 ^a	30.0 ^a	30.6 ^a	133.3 ^a	134.9 ^a	133.3 ^a
T ₂	88.4 ^{cd}	92.6 ^d	96.6 ^c	15.6 ^{cd}	18.2 ^{cd}	19.7 ^{cd}	81.0 ^{de}	73.4 ^{ef}	73.4 ^{de}
T ₃	74.0 ^d	82.6 ^d	88.1 ^c	12.5 ^d	17.5 ^d	17.7 ^d	57.1 ^f	54.7 ^f	59.5 ^e
T ₄	89.2 ^{cd}	98.5 ^{cd}	102.6 ^{bc}	16.9 ^{cd}	19.6 ^{cd}	21.1 ^{cd}	66.5 ^{ef}	83.8 ^{de}	85.8 ^{cd}
T ₅	95.6 ^{bc}	101.3 ^{cd}	107.0 ^{bc}	18.6 ^c	20.5 ^{cd}	23.0 ^{bc}	89.9 ^{cd}	98.5 ^{cd}	102.3 ^{bc}
T ₆	108.6 ^b	114.3 ^{bc}	120.0 ^{ab}	23.3 ^b	23.1 ^{bc}	26.4 ^{ab}	104.4 ^{bc}	108.4 ^{bc}	115.7 ^{ab}
T ₇	112.3 ^b	130.2 ^{ab}	132.5 ^a	24.3 ^b	29.1 ^a	28.6 ^a	112.8 ^{ab}	125.4 ^{ab}	123.5 ^a
LSD ($p \leq 0.05$)	16.1	19.6	18.0	4.5	5.3	4.3	21.2	22.9	18.7

Different lowercase letters indicate significant differences among different treatments based on LSD test.

TABLE 3 Effect of organic nutrient management on nutrient uptake (N, P, K) in berseem crop.

Treatment	N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			K uptake (kg ha ⁻¹)		
	2018–19	2019–20	2020–21	2018–19	2019–20	2020–21	2018–19	2019–20	2020–21
T ₁	257.2 ^a	262.6 ^a	259.9 ^a	20.1 ^a	17.9 ^a	18.8 ^{ab}	274.1 ^a	269.1 ^a	286.1 ^a
T ₂	173.3 ^d	181.2 ^{de}	177.2 ^d	12.8 ^e	12.0 ^d	13.7 ^d	178.2 ^c	175.4 ^d	205.7 ^d
T ₃	131.4 ^e	154.6 ^f	143.0 ^e	8.9 ^f	10.2 ^e	10.4 ^e	113.1 ^d	142.4 ^e	153.0 ^e
T ₄	180.7 ^{cd}	203.8 ^{cd}	192.3 ^c	13.8 ^{de}	13.8 ^c	14.1 ^d	189.4 ^c	201.4 ^{cd}	217.1 ^{cd}
T ₅	196.5 ^{bc}	212.8 ^{bc}	204.6 ^c	15.2 ^{cd}	14.5 ^{bc}	15.7 ^{cd}	211.2 ^b	215.5 ^{bc}	237.2 ^{bc}
T ₆	208.9 ^b	232.1 ^b	220.5 ^b	16.2 ^c	15.8 ^b	17.0 ^{bc}	231.3 ^b	234.3 ^b	252.2 ^b
T ₇	246.3 ^a	276.7 ^a	261.5 ^a	18.3 ^b	19.3 ^a	20.6 ^a	262.7 ^a	285.1 ^a	306.6 ^a
LSD ($p \leq 0.05$)	21.8	24.2	14.6	1.6	1.7	2.4	21.2	26.5	31.0

Different lowercase letters indicate significant differences among different treatments based on LSD test.

TABLE 4 Effect of organic nutrient management on nutrient uptake (N, P, K) in cowpea crop.

Treatment	N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			K uptake (kg ha ⁻¹)		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
T ₁	94.2 ^{ab}	103.5 ^{ab}	112.2 ^a	11.17 ^{ab}	12.26 ^a	12.94 ^a	40.38 ^{ab}	44.79 ^{ab}	46.82 ^a
T ₂	64.5 ^c	76.0 ^c	84.2 ^b	8.14 ^d	9.62 ^c	9.99 ^b	27.09 ^c	33.10 ^c	35.33 ^{cd}
T ₃	48.5 ^d	56.3 ^d	61.6 ^c	6.08 ^e	7.16 ^d	7.30 ^c	18.85 ^d	24.23 ^d	24.64 ^c
T ₄	66.2 ^c	79.0 ^c	88.1 ^b	8.35 ^d	9.85 ^{bc}	10.51 ^b	28.98 ^c	34.21 ^c	37.56 ^{bcd}
T ₅	85.5 ^b	95.5 ^b	102.2 ^{ab}	10.22 ^{bc}	11.42 ^{ab}	11.91 ^{ab}	37.30 ^b	41.97 ^b	43.00 ^{abc}
T ₆	83.8 ^b	95.1 ^b	104.4 ^{ab}	9.92 ^c	11.42 ^{ab}	12.11 ^{ab}	36.52 ^b	41.91 ^b	44.46 ^{ab}
T ₇	98.9 ^a	109.8 ^a	114.7 ^a	11.59 ^a	12.74 ^a	13.09 ^a	43.48 ^a	48.85 ^a	49.13 ^a
LSD ($p \leq 0.05$)	11.0	13.3	19.8	1.1	1.6	2.2	4.5	6.1	8.3

Different lowercase letters indicate significant differences among different treatments based on LSD test.

Soil K availability followed a similar pattern, with T₇ achieving the highest levels across all crops and years (Figure 4C). K availability under T₇ exceeded T₃ by 17.3–18.5% and T₁ by 17.7–21.9%, while intermediate treatments demonstrated moderate increases over time. The cumulative buildup of K under integrated management indicates a sustained nutrient supply capable of supporting intensive cropping systems.

Overall, the maize–berseem–cowpea system under T₇ displayed consistent superiority in enhancing soil fertility, with cumulative improvements in N, P, and K over three rotations. Treatments

integrating both organic and inorganic inputs (T₆, T₅) also contributed positively but were less effective than T₇. The sequential cropping of legumes and cereals amplified nutrient availability, emphasizing the importance of combined nutrient strategies in sustaining long-term soil health and crop productivity. These results underscore the value of integrated nutrient management for maintaining high nutrient availability and optimizing soil fertility in intensive crop rotations, with figures providing detailed numerical trends.

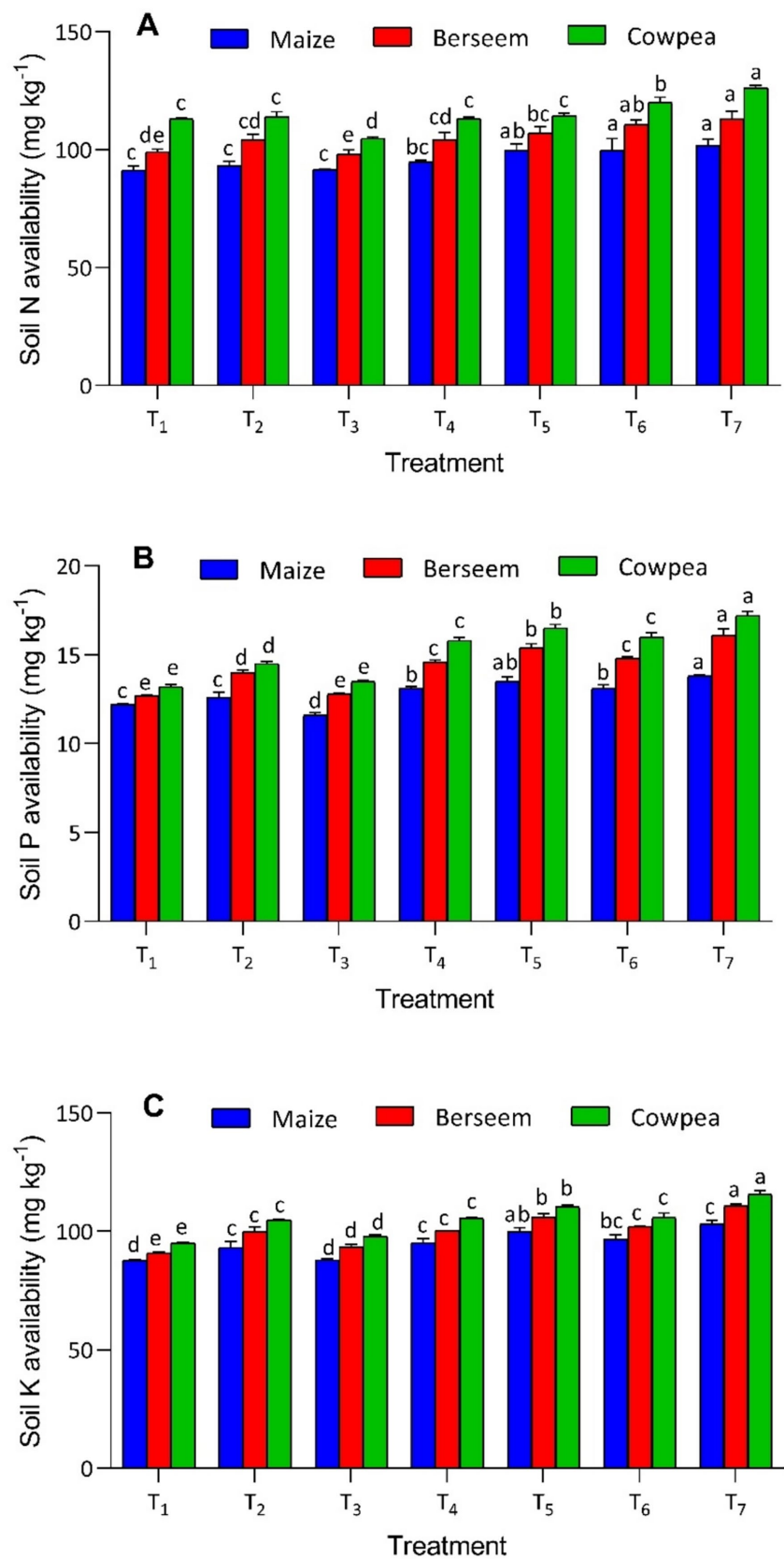


FIGURE 4
 Effect of organic nutrient management on post-harvest soil nutrient availability during the third year (mean of three crop seasons): Soil N availability (A), Soil P availability (B), and Soil K availability (C). The data represents the mean values across treatments (T₁–T₇) with error bars indicating standard deviation. Statistical significance was assessed using one way ANOVA, with differences considered significant at $p \leq 0.05$. Different lowercase letters indicate significant differences among different treatments based on LSD test.

Multivariate analysis of growth, yield, and nutrient dynamics

In maize (Figure 5A), PCA explains 99.53% of variation through PC1 and 0.41% by PC2. Treatment ovals show Cluster I (T_1 , T_6 , T_7) associated with Fe% and nutrient uptake, while Cluster II (T_2 , T_3 , T_4 , T_5) strongly aligns with available N and K. Parameter rectangles indicate Cluster I (Fe%), Cluster II (available N, K, and plant height), Cluster III (nutrient concentrations and GFY), and Cluster IV (P uptake, Zn%). The correlation heatmap supported these results, showing high positive correlations between GFY and N uptake (0.962), P uptake (0.959), and leaf length (0.953), indicating nutrient uptake and foliar traits as key determinants of green biomass yield (Supplementary Figure S2).

The PCA biplot for berseem (Figure 5B) explains 99.20% variation through PC1 and 0.70% by PC2. Treatments are grouped into ovals: Cluster I (T_2 , T_3 , T_4 , T_5) relates to available N and K, Cluster II (T_1 , T_6 , T_7) aligns with nutrient uptake (N and K). Parameters in rectangles form distinct groups: Cluster I (available N, K), Cluster II (N and K uptake), Cluster III (N, P, K, Zn concentrations and uptake), and Cluster IV (plant height and nodules). The correlation heatmap showed strong positive correlations between GFY and leaf length (0.981), leaf width (0.865), N uptake (0.998), and P uptake (0.998), highlighting the importance of internal nutrient assimilation and leaf morphological traits in yield formation (Supplementary Figure S3).

In cowpea (Figure 5C), PCA biplot shows PC1 contributing 99.87% and PC2 0.11%. Treatment clustering in ovals reveals Cluster I (T_2 , T_3 , T_4) closely associated with available K, while Cluster II (T_1 , T_5 , T_6 , T_7) is linked with available N and uptake traits. Parameter clustering in rectangles shows Cluster I (available K, Fe%), Cluster II (available N and N uptake), Cluster III (plant height, leaf number, K uptake), and Cluster IV (nutrient concentration and GFY). The correlation matrix further confirmed strong positive correlations between GFY and leaf length (0.964), leaf width (0.856), and N uptake (0.989), indicating that nutrient uptake and vegetative growth traits significantly drive productivity. Soil nutrient availability showed moderate associations, suggesting a supporting but not dominant role (Supplementary Figure S4).

Discussion

The superior performance of treatment T_7 , which combined 100% RDN through FYM, PGPR, and foliar spray of Panchagavya, highlights the effectiveness of integrated organic nutrient management in enhancing vegetative growth, yield, and nutrient uptake. Compared to T_5 and T_6 , T_7 consistently produced taller plants, larger leaves, and higher biomass, particularly in legumes such as berseem and cowpea. The contribution of FYM lies in its ability to improve soil physical, chemical, and biological properties, ensuring sustained nutrient release and favorable root growth, as also reported by Liu et al. (2024) and Dhaliwal et al. (2023). PGPR further strengthened nutrient availability by fixing atmospheric nitrogen, solubilizing phosphorus, and stimulating rhizospheric health, consistent with Hasan and Ram (2015), who demonstrated improved nodulation and growth in legumes with PGPR–FYM integration. Panchagavya acted as a

biostimulant, supplying growth hormones, enzymes, and beneficial microbes that enhanced photosynthesis and metabolic activity, which was especially beneficial in legume crops responsive to hormonal stimulation. The integration of these components in T_7 produced synergistic effects greater than their individual contributions, with FYM ensuring steady nutrient supply, PGPR enhancing nutrient cycling, and Panchagavya boosting physiological efficiency. This synergy not only improved nutrient use efficiency and soil health but also sustained higher productivity across the cropping system, aligning with reports by Rawal et al. (2023).

on integrated organic management. In contrast, the sole application of chemical fertilizers (100% RDF) accelerated early maize growth due to rapid nutrient release but was less effective in legumes, reaffirming the importance of biologically enriched approaches.

The results of this study highlight the superiority of treatment T_7 , which integrated FYM, PGPR, and Panchagavya, in enhancing both green and dry fodder yields across the maize–berseem–cowpea rotation. The consistent outperformance of T_7 compared to the lowest-yielding treatment (T_3) underscores the value of combining multiple organic inputs to improve nutrient supply, uptake, and plant growth. The contribution of FYM in this system is critical, as it enriches soil organic matter, improves structure, and stimulates microbial activity, thereby ensuring sustained nutrient mineralization and availability that supports vigorous crop growth (Kumar et al., 2021). PGPR further reinforced this effect by accelerating decomposition, solubilizing phosphorus, and producing growth-promoting substances that enhanced root proliferation and nutrient uptake (Choudhary et al., 2024; Shilpa et al., 2024). Panchagavya, rich in beneficial microbes, micronutrients, and growth regulators, added another dimension by enhancing photosynthetic efficiency, stimulating plant metabolism, and improving yield attributes (Kumar et al., 2023). The combined effect of these components produced a synergistic response: FYM provided a substrate that favored PGPR activity, Panchagavya stimulated microbial and plant metabolic processes, and together they reinforced soil fertility and crop performance. Such synergy has been documented in earlier studies, where integrated use of organic manures, microbial inoculants, and biostimulants produced greater improvements in productivity than their individual application, and this study confirms those findings in a maize–berseem–cowpea system.

Among the nutrient management treatments, T_7 consistently outperformed others by sustaining the highest nutrient concentrations in fodder maize, berseem, and cowpea, particularly during the later years, highlighting the effectiveness of integrating FYM, PGPR, and Panchagavya. The contribution of FYM lies in its steady release of macro- and micro-nutrients, improvement of soil organic matter, and enhancement of soil structure, which supported long-term fertility and nutrient uptake (Garg et al., 2024). PGPR further strengthened this effect by solubilizing phosphorus and potassium, fixing atmospheric nitrogen, and stimulating root proliferation and nodulation in legumes, thereby improving nutrient assimilation (Kumar et al., 2025b). Panchagavya complemented these inputs by supplying plant growth regulators and stimulating rhizospheric microbial activity, which enhanced chlorophyll content, photosynthesis, and nutrient translocation (Kalsan et al., 2024). The synergistic interaction among FYM, PGPR, and Panchagavya created a positive feedback loop: FYM improved soil conditions that supported PGPR activity, while Panchagavya promoted root growth and microbial proliferation,

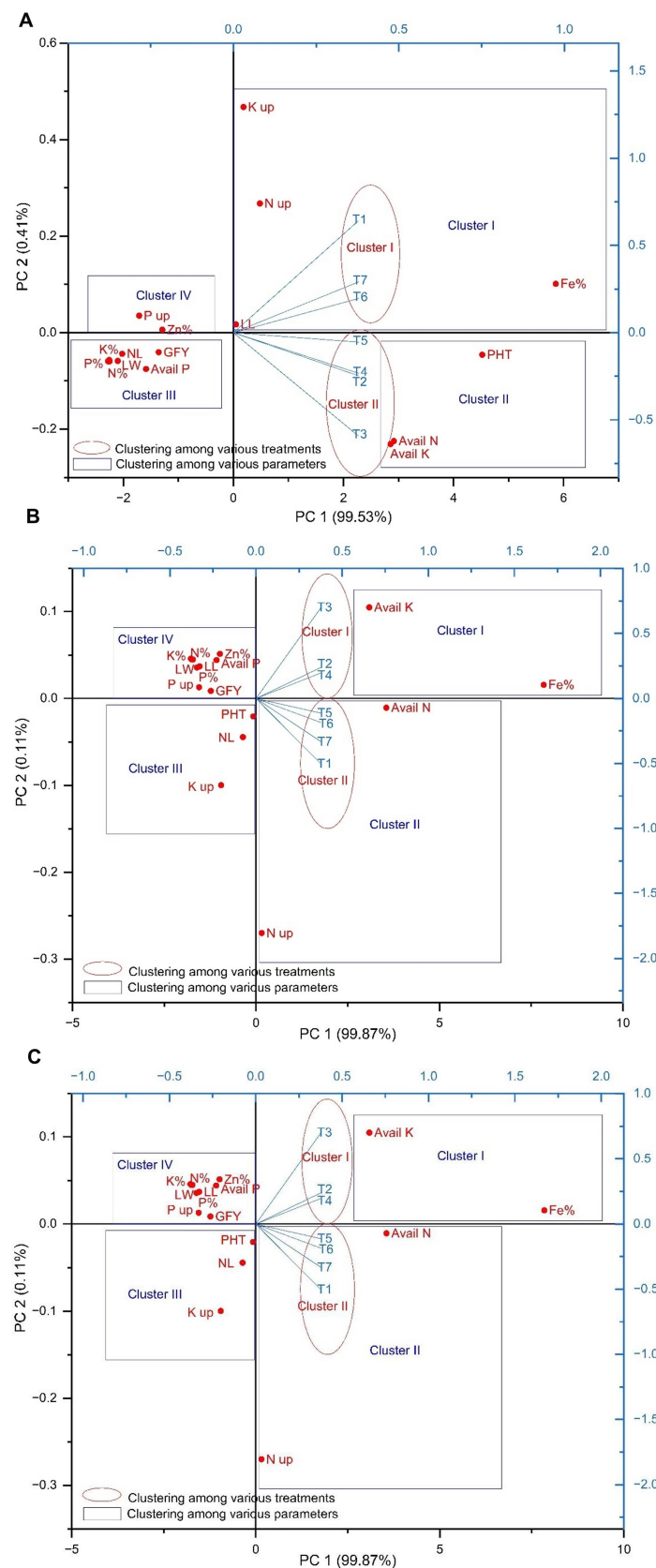


FIGURE 5

(A) Effect of organic nutrient management on growth, yield, and nutrient dynamics in maize: a multivariate analysis. (B) Effect of organic nutrient management on growth, yield, and nutrient dynamics in berseem: a multivariate analysis. (C) Effect of organic nutrient management on growth, yield, and nutrient dynamics in cowpea: a multivariate analysis. PHT, plant height; LL, leaf length; NL, Number of leaves; LW, leaf width; GFY, Green fodder yield; N%, N content; P%, P content; K%, K content; Zn%, Zinc content; Fe%, Iron content; Avail N, Available N; Avail P, Available P; Avail K, Available K; N up, N uptake; P up, P uptake; K up, K uptake.

collectively maximizing nutrient availability and uptake. This integration explains the superior and consistent performance of T_7 compared with T_1 , which showed only short-term nutrient availability, and T_3 , which remained nutrient-deficient due to insufficient N input. Similar synergistic benefits of combining organic amendments with microbial inoculants have been reported in other intensive systems (Kushwah et al., 2024; Kumar et al., 2025a), underscoring the long-term advantage of integrated organic nutrient management for sustaining soil fertility and crop productivity.

Treatment T_7 consistently recorded the highest nutrient uptake in berseem and cowpea, confirming its superiority among the nutrient management practices evaluated. This enhanced performance was attributed to the combined contributions of its components FYM, PGPR, and Panchagavya which together improved nutrient availability, uptake, and soil health. FYM played a critical role by supplying nutrients gradually while improving soil structure, organic matter content, and microbial activity, thereby sustaining nutrient release over time. PGPR further enhanced nutrient acquisition by stimulating root growth, solubilizing phosphorus, and facilitating biological nitrogen fixation, particularly in legumes, which benefited from improved nodulation and rhizosphere enzymatic activity (Gokulakannan and Veeral, 2022; Kalson et al., 2024; Kumar et al., 2025a). Panchagavya acted as a potent bio-stimulant, stimulating microbial proliferation and plant metabolism, which enhanced nutrient absorption and efficiency (Gokulakannan and Veeral, 2022; Kalson et al., 2024; Kumar et al., 2025a). The synergistic integration of these three components in T_7 created favorable soil–plant–microbe interactions, where FYM served as a substrate for microbial colonization, PGPR supported solubilization and fixation, and Panchagavya enhanced metabolic activity, together leading to superior nutrient cycling and uptake. This synergy explains why T_7 outperformed other integrated organic treatments (T_5 , T_6) and even the 100% RDF treatment (T_1), which showed high uptake in maize due to immediate nutrient availability but lacked sustained release and soil biological benefits (Kumar et al., 2018b; Bhakar et al., 2021). In contrast, T_3 showed the lowest uptake due to inadequate nitrogen input through 50% RDN via FYM, which was insufficient to maintain optimum nutrient absorption. These results collectively demonstrate that the integrated approach in T_7 ensures superior nutrient uptake, particularly in legumes, while also improving long-term soil fertility.

Treatment T_7 , which integrated 100% RDN through FYM, PGPR, and foliar application of Panchagavya, consistently recorded the highest residual nitrogen levels across the maize–berseem–cowpea cropping system, confirming its superiority over partial organic inputs (T_5 , T_6) and sole chemical fertilization (T_1). The contribution of FYM lies in its ability to provide a steady release of nitrogen along with organic matter that sustains microbial activity and nutrient cycling (Kumar et al., 2018a; Abrol et al., 2024). PGPR further enhances soil N availability by promoting biological nitrogen fixation and improving rhizospheric health, while Panchagavya stimulates root proliferation, microbial activity, and nutrient uptake due to its hormonal and enzymatic constituents. Similar results highlighting the role of integrated approaches in improving soil fertility and crop performance have been reported by Onte et al. (2025). In contrast, T_1 initially showed higher N after maize but declined in subsequent crops, lacking

the biological support and organic matter required for sustained nutrient cycling (Valenzuela, 2023). The combined application of FYM, PGPR, and Panchagavya in T_7 produced synergistic effects, where organic matter inputs supported microbial activity, PGPR enhanced nutrient transformation, and Panchagavya stimulated both root and microbial growth, thereby explaining its consistent superiority in maintaining soil nitrogen availability across sequential crop rotations.

Treatment T_7 , which combined 100% RDN through FYM, PGPR, and foliar Panchagavya, consistently outperformed all other nutrient management treatments in terms of soil nutrient availability, vegetative growth, and yield across the maize–berseem–cowpea cropping system. The superior performance of T_7 is attributable to the cumulative and synergistic effects of its components. FYM improved soil structure, phosphorus retention, and microbial habitat, providing a sustained nutrient supply (Kumar et al., 2021). PGPR enhanced nutrient availability by solubilizing phosphorus and supporting nitrogen uptake, while also stimulating root growth and enzyme activity (Turan et al., 2012). Foliar application of Panchagavya further promoted microbial activity and enzymatic processes that support nutrient cycling and plant vigor (Sujith and Devakumar, 2017). Together, these components interacted synergistically, improving nutrient use efficiency and cumulative soil fertility, which ultimately translated into higher crop performance. On average, T_7 increased soil P availability by 16.1–24.6% over T_3 and 6.5–21.0% over T_1 , underscoring the long-term benefit of integrated organic nutrient management. These results highlight that combining FYM, PGPR, and Panchagavya is more effective than individual applications in sustaining soil fertility and enhancing crop productivity.

The superior performance of treatment T_7 in enhancing vegetative growth, yield, and soil nutrient availability across the maize–berseem–cowpea cropping system can be attributed to the combined and synergistic effects of FYM, PGPR, and foliar-applied Panchagavya. FYM acted as a slow-releasing source of nutrients, particularly potassium, while improving soil structure and cation exchange capacity, which reduced nutrient losses and supported sustained availability (Kumar et al., 2021). PGPR, especially potassium-solubilizing strains, mobilized otherwise unavailable nutrients into plant-accessible forms and enhanced microbial activity in the rhizosphere, promoting nutrient cycling and uptake (Verma et al., 2017). Panchagavya, rich in organic acids, micronutrients, and microbial metabolites, stimulated root growth and microbial proliferation, indirectly facilitating nutrient solubilization and absorption (Srinivasan and Aithal, 2025). The integration of these components created synergistic interactions whereby FYM provided a nutrient reservoir, PGPR enhanced mobilization, and Panchagavya promoted root–microbe activity, collectively resulting in higher nutrient use efficiency and sustained soil fertility. This cumulative effect led to consistently higher N, P, and K availability under T_7 , highlighting the long-term benefits of integrated nutrient management in intensive cropping systems compared to single-component or low-input treatments.

The findings across maize, berseem, and cowpea underscore the pivotal role of internal nutrient uptake particularly nitrogen and

potassium in driving biomass accumulation and forage yield. In maize, treatments such as T_1 , T_6 and T_7 demonstrated superior nutrient assimilation, notably enhancing associated traits like iron concentration, indicative of improved physiological and metabolic functioning. Leaf morphological characteristics, including leaf length and number of leaves, exhibited strong positive associations with green forage yield, highlighting their contribution to enhanced photosynthetic capacity and growth. In berseem, nutrient-enriched treatments significantly elevated macronutrient and micronutrient uptake, with robust correlations observed between yield and foliar traits such as leaf length, width, and nutrient uptake, suggesting that efficient nutrient use and vegetative development are central to maximizing productivity. Similarly, cowpea responded positively to integrated organic nutrient management practices, with improved nutrient accumulation translating into higher green forage yield. Leaf traits emerged as reliable yield indicators, whereas soil nutrient availability played a more supportive role. Collectively, these results affirm the primacy of plant-internal nutrient dynamics and vegetative traits over external soil fertility factors in determining forage yield performance across species. Similarly, cowpea responded positively to integrated organic nutrient management practices, but multivariate analyses indicated slightly different correlations than maize and berseem, with yield being more strongly linked to leaf morphological traits and less directly to soil nutrient availability. Leaf traits emerged as reliable yield indicators, whereas soil nutrient availability played a more supportive role.

Collectively, these results affirm the primacy of plant-internal nutrient dynamics and vegetative traits over external soil fertility factors in determining forage yield performance across species. For farm managers and policymakers, the analysis indicates that optimizing internal nutrient uptake and maintaining healthy leaf development are key to maximizing forage yield, while soil amendments should be tailored to support overall plant growth rather than being the sole focus.

Conclusion

The findings of this study demonstrated that the integrated application of FYM, PGPR, and Panchagavya (T_7) significantly improved crop growth, fodder yield, nutrient concentration, and nutrient uptake in a maize -berseem -cowpea cropping system. Across three consecutive years, T_6 consistently outperformed other organic treatments and remained statistically comparable to inorganic fertilizer treatment (T_1) in most parameters, while providing additional benefits in terms of sustained soil nitrogen, phosphorus, and potassium availability. Compared to sole FYM or partial RDN treatments, the full integration of organic inputs in T_7 resulted in cumulative improvements across crops and seasons. These results confirm that integrated organic nutrient management can enhance productivity while maintaining soil fertility, offering a viable and sustainable alternative to chemical fertilizer-based practices in intensive fodder systems. The study supports the adoption of such integrated strategies to ensure long-term agricultural sustainability, particularly in systems demanding year-round green fodder supply.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

SO: Data curation, Investigation, Writing – original draft. VF: Data curation, Writing – original draft. DD: Methodology, Writing – original draft. GK: Data curation, Methodology, Writing – original draft. PR: Formal analysis, Visualization, Writing – original draft. KB: Formal analysis, Visualization, Writing – original draft. TV: Data curation, Visualization, Writing – original draft. RY: Formal analysis, Visualization, Writing – original draft. HS: Data curation, Formal analysis, Writing – original draft. PPr: Conceptualization, Data curation, Methodology, Writing – review & editing. MS: Investigation, Supervision, Writing – review & editing. DK: Conceptualization, Methodology, Visualization, Writing – review & editing. YB: Conceptualization, Writing – review & editing. SuK: Software, Visualization, Writing – review & editing. KG: Visualization, Writing – original draft. HG: Software, Visualization, Writing – review & editing. AS: Visualization, Writing – review & editing. PPY: Writing – review & editing. MK: Conceptualization, Methodology, Writing – review & editing. RC: Conceptualization, Resources, Writing – review & editing. SM: Conceptualization, Resources, Writing – review & editing. SaK: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

Authors are thankful to Indian Council of Agriculture Research (ICAR) and ICAR - National Dairy Research Institute, Karnal, Haryana for providing the financial facilities to conduct the present study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated

organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1678536/full#supplementary-material>

References

- Abrol, V., Sharma, P., Chary, G. R., Srinivasarao, C., Maruthi Sankar, G. R., Singh, B., et al. (2024). Integrated organic and mineral fertilizer strategies for achieving sustainable maize yield and soil quality in dry sub-humid inceptisols. *Sci. Rep.* 14:27227. doi: 10.1038/s41598-024-74727-4
- Bhakar, A., Singh, M., Kumar, S., Kumar, D., Meena, B., Meena, V., et al. (2021). Enhancing root traits and quality of sorghum and guar through mixed cropping and nutrient management. *Indian J. Agric. Sci.* 91, 99–104. doi: 10.56093/ijas.v91i1.110935
- Choudhary, M., Garg, K., Reddy, M. B., Meena, B. L., Mondal, B., Tuti, M. D., et al. (2024). Unlocking growth potential: synergistic potassium fertilization for enhanced yield, nutrient uptake, and energy fractions in Chinese cabbage. *Heliyon* 10:e28765. doi: 10.1016/j.heliyon.2024.e28765
- Dhaliwal, S. S., Sharma, V., Shukla, A. K., Gupta, R. K., Verma, V., Kaur, M., et al. (2023). Residual effect of organic and inorganic fertilizers on growth, yield and nutrient uptake in wheat under a basmati rice–wheat cropping system in North-Western India. *Agriculture* 13:556. doi: 10.3390/agriculture13030556
- Garg, K., Dhar, S., Sharma, V. K., Azman, E. A., Meena, R. P., Hashim, M., et al. (2024). Optimizing agricultural sustainability: enriched organic formulations for growth, yield, and soil quality in a multi-crop system. *Front. Plant Sci.* 15, 15–2024. doi: 10.3389/fpls.2024.1398083
- Gokulakannan, K., and Veeral, D. K. (2022). Effect of integrated nutrient management practices on physiological and yield traits of maize (*Zea mays* L.)+ cowpea (*Vigna unguiculata* L.) intercropping system in northwestern agro climatic zones of Tamil Nadu. *Indian J. Appl. Pure Biol.* 37, 684–689.
- Golakiya, P., Kaswala, A., Dubey, P., Sisodiyaan, R., and Neethu, T. (2019). Panchagavya-cow-based bio-enhancers and botanicals for organic farming. *Int. J. Chem. Stud.* 7, 2741–2746.
- Gollin, D., Hansen, C. W., and Wingender, A. M. (2021). Two blades of grass: the impact of the green revolution. *J. Polit. Econ.* 129, 2344–2384. doi: 10.1086/714444
- Gomez, K. A., and Gomez, A. A. (1984). Statistical procedures for agricultural research. New York, USA: John Wiley & Sons.
- Hasan, B. K., and Ram, M. R. (2015). Evaluation of PGPR and organic manure applications on soil fertility, growth, nodulation and yield of black gram (*Vigna mungo* L. Hepper). *Int. J. Agric. Sci. Res.* 5, 183–192.
- Jackson, M. L. (1973). Soil chemical analysis. New Delhi, India: Pentice hall of India Pvt Ltd, 151–154.
- Kalson, A., Qazizadah, N. A., Pv, P., Khaiper, M., and Qane, K. (2024). Effect of organic manures and biofertilizers on yield attributes, yield and economics of mung bean (*Vigna radiata*). *J. Adv. Biol. Biotechnol.* 27, 370–378. doi: 10.9734/jabb/2024/v27i111622
- Kansanga, M., Andersen, P., Kpienbaareh, D., Mason-Renton, S., Atuoye, K., Sano, Y., et al. (2019). Traditional agriculture in transition: examining the impacts of agricultural modernization on smallholder farming in Ghana under the new green revolution. *Int. J. Sustain. Dev. World Ecol.* 26, 11–24. doi: 10.1080/13504509.2018.1491429
- Kumar, S., Dhar, S., Barthakur, S., Chandrakala, M., Kochewad, S., Meena, L., et al. (2018a). Effect of integrated potassium management on soil biological properties and yields of corn under corn–wheat cropping system. *Int. J. Curr. Microbiol. Appl. Sci.* 7, 1855–1866. doi: 10.20546/ijcmas.2018.712.217
- Kumar, S., Dhar, S., Barthakur, S., Kumar, S., Mondal, B., Kumar, D., et al. (2018b). Integrated k management exhibit a key role in potassium uptake transporter (ZmKUP) expression to improve growth and yield of corn. *Int. J. Curr. Microbiol. Appl. Sci.* 7, 1867–1887. doi: 10.20546/ijcmas.2018.712.218
- Kumar, S., Dhar, S., Barthakur, S., Rajawat, M. V. S., Kochewad, S., Kumar, S., et al. (2021). Farmyard manure as k-fertilizer modulates soil biological activities and yield of wheat using the integrated fertilization approach. *Front. Environ. Sci.* 9:764489. doi: 10.3389/fenvs.2021.764489
- Kumar, S., Onte, S., Boregowda, Y. S., Angadi, A. P., Pyati, P. S., Naveena, K., et al. (2025a). Organic farming for a sustainable future: soil and yield improvement through integrated nitrogen management. *Front. Sustain. Food Syst.* 9:1564945. doi: 10.3389/fsufs.2025.1564945
- Kumar, D., Singh, M., Kumar Meena, R., Kumar, S., Meena, B. L., Yadav, M. R., et al. (2023). Productivity and profitability improvement of fodder maize under combined application of indigenously prepared Panchagavya with organic and inorganic sources of nutrient. *J. Plant Nutr.* 46, 3519–3534. doi: 10.1080/01904167.2023.2206433
- Kumar, S., Singh, M., Kumar, S., and Rajeev (2025b). Changes in root nodules dynamics under mixed cropping with varying nutrient management of berseem crop and succeeding fodder cowpea. *J. Plant Nutr.* 48, 617–638. doi: 10.1080/01904167.2024.2410818
- Kushwah, M., Lal Meena, B., Choudhary, M., Karunakaran, V., Kanwat, M., Rajawat, M. V. S., et al. (2024). Enhancing yield, mineral composition, and energy fractions through intercropping and nutrient management in oats and berseem. *J. Saudi Soc. Agric. Sci.* 23, 508–520. doi: 10.1016/j.jssas.2024.06.001
- Lindsay, W. L., and Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* 42, 421–428. doi: 10.2136/sssaj1978.03615995004200030009x
- Liu, Y., Lan, X., Hou, H., Ji, J., Liu, X., and Lv, Z. (2024). Multifaceted ability of organic fertilizers to improve crop productivity and abiotic stress tolerance: review and perspectives. *Agronomy* 14:1141. doi: 10.3390/agronomy14061141
- Olsen, S., Cole, C., Watanabe, F., and Dean, L. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington D.C, USA: US Department of Agriculture.
- Onte, S., Kumar, D., Kochewad, S., Kumar, S., Dhar, S., Kumar, S., et al. (2025). Enhancing soil health, fodder energy fractions, and fodder yield in maize–berseem cropping sequence through integrated organic nitrogen fertilization. *Land Degrad. Dev.* 36, 4605–4625. doi: 10.1002/ldr.5657
- Piper, C. (1966). Soil and plant analysis. Bombay: Hans Publisher, 368–374.
- Rawal, N., Khatri, N., Khadka, D., and Paneru, P. (2023). Fertilizer management and incorporation of legumes on performance of maize (*Zea mays* L.) in western hills of Nepal. *J. Agric. Food Res.* 14:100690. doi: 10.1016/j.jafr.2023.100690
- Shah, A., Nazari, M., Antar, M., Msimbira, L. A., Naamala, J., Lyu, D., et al. (2021). PGPR in agriculture: a sustainable approach to increasing climate change resilience. *Front. Sustain. Food Syst.* 5:667546. doi: 10.3389/fsufs.2021.667546
- Shilpa, Sharma, A. K., Chauhan, M., and Bijalwan, P. (2024). Plant growth promoting rhizobacteria, organic manures, and chemical fertilizers: impact on crop productivity and soil health of capsicum (*Capsicum annuum* L.) in North Western Himalayan region. *J. Plant Nutr.* 47, 448–467. doi: 10.1080/01904167.2023.2280120
- Srinivasan, R., and Aithal, P. (2025). Organic alchemy: Panchagavya's role in green agriculture transformation. *Poornaprajna Int. J. Basic ABD Appl. Sci.* 2, 1–23.
- Subbaiah, B., and Asija, G. (1956). A rapid procedure for estimation of available nitrogen in soil. *Curr. Sci.* 25, 259–260.
- Sujith, G., and Devakumar, N. (2017). Nutrient status and microbial activity as influenced by *jeevamrutha* and *panchagavya* in cowpea [*Vigna unguiculata* (L.) Walp.] grown on Alfisols. *Crop. Res.* 52, 218–223. doi: 10.5958/2454-1761.2017.00020.1
- Tandon, H. L. S. (1993). Methods of analysis of soils, plants, waters and fertilisers. New Delhi: Fertiliser Development and Consultation Organisation.
- Turan, M., Gulluce, M., Von Wirén, N., and Sahin, F. (2012). Yield promotion and phosphorus solubilization by plant growth–promoting rhizobacteria in extensive wheat production in Turkey. *J. Plant Nutr. Soil Sci.* 175, 818–826. doi: 10.1002/jpln.201200054
- Valenzuela, H. (2023). Ecological management of the nitrogen cycle in organic farms. *Nitrogen* 4, 58–84. doi: 10.3390/nitrogen4010006
- Verma, P., Yadav, A. N., Khannam, K. S., Saxena, A. K., and Suman, A. (2017). “Potassium-solubilizing microbes: diversity, distribution, and role in plant growth promotion” in Microorganisms for green revolution: Volume I: Microbes for sustainable crop production. eds. D. G. Panpatte, Y. K. Jhala, R. V. Vyas and H. N. Shelat (Singapore: Springer Singapore), 125–149.