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Organic farming for a sustainable future: soil and yield improvement through integrated nitrogen management

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Efficient nitrogen management is crucial for sustaining soil health, optimizing yields, and ensuring the long-term viability of organic farming systems. A cereal-legume cropping system is widely recognized for improving nutrient cycling and ecosystem services. This study investigates the impact of these treatments on soil quality, energy fractions, and yield of fodder maize-berseem-cowpea under organic farming with a focus on enhancing ecosystem services and supporting agroecological principles. A three-year field experiment (2018–19 to 2020–21) was conducted with maize (M) - berseem (B) - cowpea (C) cropping system laid in a randomized complete block design (RCBD) with three replications and seven treatments. Drawing upon the theoretical framework of sustainable agriculture and integrated nutrient management, treatment T_7, (Farmyard manure (FYM) + Plant growth promoting rhizobacteria (PGPR) + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C), resulted in significant improvements in soil organic carbon (4.0–15.2%), soil organic matter content (3.8–14.7%), available nutrients (10.7–36.6%), microbial population (54.8–119.3%), and soil enzymatic activities (103.0–187.2%). Additionally, energy fractions and TDCP content showed positive trends. Yield penalties in maize declined from 11.9 to 8.09% over 3 years; berseem showed a 2.5% initial reduction but improved in subsequent years, while cowpea consistently exhibited slight yield gains. Compared to treatment T_1 (100% chemical fertilizers), treatment T_7 enhanced soil health and nutrient cycling with only a slight reduction in system productivity (4.3 to 7.0%), demonstrating the long-term benefits of organic inputs. This study highlights the importance of integrated nitrogen management in organic systems, reducing reliance on synthetic fertilizers while enhancing ecological sustainability. It offers a practical approach to improving soil resilience, boosting energy efficiency, and supporting sustainable development goals—providing valuable insights for policymakers and practitioners pursuing environmentally responsible agricultural practices.

KEYWORDS

energy fractions, fodder yield, nutrient availability, soil enzymatic activities, soil organic carbon

Introduction

Sustainable agricultural practices are indispensable for ensuring long-term food security and environmental health (Patel et al., 2020; Viana et al., 2022). Organic farming, characterized by reduced synthetic inputs and reliance on natural processes, exemplifies a cornerstone of sustainable agriculture (Lorenz and Lal, 2023). This approach supports agroecological transitions by enhancing biodiversity, improving nutrient cycling, and promoting ecosystem resilience. However, optimizing nitrogen management within organic systems remains a key challenge, influencing soil health and crop productivity.

Nitrogen (N) is pivotal for regulating crop growth, affecting root dynamics, leaf expansion, nutrient uptake, and biomass synthesis (Luo et al., 2020; Sun et al., 2020; Ahmad et al., 2023; Reddy et al., 2024). It is essential for amino acids, chlorophyll, nucleic acids, ATP, and phytohormones, vital components in carbon and nitrogen metabolism, photosynthesis, and protein production (Anas et al., 2020; Mengesha, 2021; Tariq et al., 2023). Effective nitrogen management is thus imperative in sustainable agriculture to enhance crop productivity while minimizing environmental footprints. However, conventional organic systems often struggle with nitrogen limitations, necessitating innovative approaches that integrate natural amendments to sustain soil fertility and crop yield.

Soil health, encompassing physicochemical and biological attributes, dictates food production dynamics for human and animal consumption (Lehmann et al., 2020; Naz et al., 2023). Physicochemical parameters such as soil organic carbon (SOC), soil organic matter (SOM), water holding capacity, aggregate stability, and nutrient availability critically influence soil health (Seifu et al., 2020; Vikram et al., 2023). Biological factors, including microbial population and enzymatic activity, interact intricately under optimal soil conditions, influencing their proliferation and functionality (Shah et al., 2022; Daunoras et al., 2024; Wei et al., 2024). Given the increasing environmental concerns associated with chemical fertilizers, there is a growing need to explore sustainable nitrogen management practices that enhance soil health while maintaining productivity.

With the growing concerns over the environmental impacts of the Green Revolution's intensive practices, sustainable approaches like organic farming are gaining traction. These systems promote reduced agrochemical dependency while enhancing natural soil fertility through organic inputs (e.g., FYM and biofertilizers). However, fodder crops such as maize, berseem, and cowpea remain understudied in the context of organic systems, particularly regarding their contribution to soil health and sustainability. Given the importance of these crops in livestock-based farming systems, optimizing their production through sustainable nitrogen management is essential.

Indo - Gangetic Plain in India are prominent agricultural region known for its intensive cropping systems and significant contribution to India's fodder production and dairy farming. However, continuous cultivation and heavy reliance on synthetic fertilizers have led to soil degradation, necessitating sustainable interventions. The region's agro-climatic conditions make it an ideal site to evaluate organic nitrogen management strategies in fodder-based cropping systems.

The synergistic integration of farmyard manure, PGPR and panchagavya, an indigenous liquid formulation, presents a promising strategy in organic farming to overcome nitrogen limitations during critical growth phases. PGPR establishes symbiotic relationships with plant roots, enhancing nutrient uptake through mechanisms such as increased root surface area, biological nitrogen fixation, phosphorus solubilization, and siderophore production (Jansson et al., 2023; Li et al., 2024). Additionally, panchagavya enhances soil microbial activity, promotes plant immunity, and improves nutrient assimilation efficiency, making it a crucial component of agroecological systems (Upadhyay et al., 2018; Onte et al., 2025). The combination of these amendments is expected to enhance soil health, improve crop yield, and promote sustainability by reducing reliance on chemical fertilizers.

This study was conducted to assess the effectiveness of integrated nitrogen management using FYM, PGPR, and panchagavya in a maize-berseem-cowpea cropping system under organic farming conditions in Karnal, Haryana. The study aims to provide insights into sustainable intensification strategies that align with global sustainability goals by fostering resilient agricultural systems, improving nutrient cycling, and reducing environmental footprints.

Materials and methods

Experimental details

The experiment was carried out at the experimental research farm, Agronomy Section, ICAR-National Dairy Research Institute, Karnal, Haryana, consecutively from 2018 to 2021 during the rainy, winter and summer seasons. The soil of the experimental field (0–15 cm) was clay loam in texture with EC (0.23 dS m^{-1}), pH (7.52), medium in SOC (0.601%) and medium in available potassium (190.2 kg ha^{-1}), low in available N (188.4 kg ha^{-1}) and high in available phosphorus (28.5 kg ha^{-1}) with SOM content (1.03 ± 0.01%). The field experiment consisting of maize (M), berseem (B) and cowpea (C) cropping system was laid down in randomized complete block design (RCBD) *viz.,* T_1: Control (100% RDF (M) - 100% RDF (B) - 100% RDF (C)); T_2: 100% RDN through FYM (M) - No application (B) - No application (C); T_3: 50% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C); T_4: 75% RDN through FYM + PGPR

(M) - PGPR (B) - PGPR (C); T_5: 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C); T_6: 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C); and T_7: 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C). In treatment T_1 (control) 100 kg N: 60 kg P_2O_5: 40 kg K_2O, 20 kg N: 60 kg P_2O_5: 40 kg K_2O and 20 kg N: 60 kg P_2O_5: 40 kg K_2O were applied as recommended fertilizer doses for maize, berseem, and cowpea crops, respectively. The N in the control treatment was applied in two splits (50 kg N as basal and 30 days after sowing (DAS)) in maize, while in berseem and cowpea, N was applied as basal dose only. Phosphorus (P) and potassium (K) were applied as basal applications for maize, berseem and cowpea crops. A PGPR formulation "NPK liquid biofertilizer" was obtained from the Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi for seed inoculation in the present study. This formulation consists of three different microbial strains namely *Azotobacter chroococcum* (N_2 fixing bacteria), *Pseudomonas straita* (P-solubilizing bacteria), and *Bacillus decolorationis* (K-solubilizing bacteria). Each bacterial strain contains 10^9 or greater CFU mL^{-1} in the formulation. FYM was applied as basal dose at sowing in treatments T_2 to T_7 based on the N content as per the schedule, and seeds were treated with PGPR solution as per treatment details. The foliar spray of panchagavya was applied at the rate of 3% (liquid formulation) at 30, 40, and 50 DAS. During the three-year experimentation period, the mean concentration values in the applied FYM were as follows: oxidizable organic carbon (11.49%), total carbon (21.37%), total nitrogen (0.68%), total phosphorus (0.45%), and total potassium (0.90%). The mean total N, P, and K nutrient concentration values of the panchagavya foliar spray were 0.65, 0.10, and 0.47%, respectively. For the fodder maize, berseem and cowpea crops, varieties J-1006, Mascavi and C-152 were employed for the experiment and sown at the seed rates of 40, 25 and 40 kg ha^{-1}, respectively.

Estimation of soil physicochemical properties

Following the annual harvest of the maize-berseem-cowpea cropping system, soil samples were systematically collected. These samples underwent processing and subsequent analysis for SOC utilizing the wet digestion method as outlined by Walkley and Black (1934). Bulk Density (BD) of the soil was determined by employing the core sampler method per the methodology described by Grossman and Reinsch (2002). Available N content was assessed using the Alkaline permanganate method, following the protocol established by Subbaiah and Asija (1956). Similarly, available P was measured utilizing the 0.5 M sodium bicarbonate method outlined by Olsen et al. (1954), while available K content was determined through the ammonium acetate extraction method as per Jackson (1973). The SOM content in the soil sample was computed by multiplying the SOC value by a factor of 1.72.

Estimation of soil biological properties

The examination of soil biological properties encompasses both soil microbial counts and soil enzymatic activities. To assess these properties, soil samples were collected from the rhizospheric soil adhering to the plant roots. Soil microbial counts were determined using serial dilution techniques followed by plating on specific agar media. Total bacterial population count (TBPC), P solubilizing bacteria count (PSBPC), K solubilizing bacteria count (KSBPC), actinomycetes population count (APC), and fungi population count (FPC) were quantified using nutrient agar, Pikovskaya agar, Aleksandrov agar, Kenknight and Munaiers's agar, and Potato dextrose agar. For enzymatic activity assessment, established protocols were followed for to dehydrogenase activity (DHA) by Klein et al. (1971), acid phosphatase activity (Apase) by Tabatabai and Bremner (1969), alkaline phosphatase activity (Alpase) by Tabatabai and Bremner (1969), and β-glucosidase activity (BG) by Eivazi and Tabatabai (1988).

Estimation of energy fractions and total digestible crude protein content in cereal - legumes based cropping system

The different energy fractions in the fodder maize, berseem and cowpea crops were estimated using various equations. The digestible energy (DE) was estimated by Equations 1 and 2 as given by Fonnesbeck et al. (1984) for fodder maize, berseem and cowpea, and the total digestible energy (TDE) of the cropping system was calculated by Equation 3. To estimate the digestible feed energy (DFE) of individual crops, Equation 4 was employed (Bull, 1981), and the total digestible feed energy (TDFE) of the cropping system was estimated by Equation 5. The metabolizable energy (ME) was estimated by Equation 6, given by Gonzalez (1982), and the net energy (NE) in fodder maize, berseem, and cowpea crops was estimated by Equation 8, given by Riviere (1977). At the same time, the total metabolizable energy (TME) and total net energy (TNE) were estimated for the fodder maize-berseem-cowpea cropping system using Equations 7, 9.

$$\mathrm{DE}\left(\mathrm{Mcal\ kg^{-1}}\right)=0.27+\left[0.0428X\ \mathrm{DMD}\left(\%\right)\right] \tag{1}$$

$$\mathrm{DE}\left(\mathrm{MJ\ kg^{-1}}\right)=\mathrm{DE}\left(\mathrm{Mcal\ kg^{-1}}\right)X\ 4.184 \tag{2}$$

$$\mathrm{TDE}\left(\mathrm{MJ\ kg^{-1}}\right)=\mathrm{DE}\left(\mathrm{Maize}\right)+\mathrm{DE}\left(\mathrm{Berseem}\right)+\mathrm{DE}\left(\mathrm{Cowpea}\right) \tag{3}$$

$$\mathrm{DFE}\left(\mathrm{MJ\ kg^{-1}}\right)=\left[\frac{4.4\ \mathrm{xTDN}\left(\%\right)}{100}\right]X\,4.184 \tag{4}$$

$$\begin{aligned}\mathrm{TDFE}\left(\mathrm{MJ\ kg^{-1}}\right)&=\mathrm{DFE}\left(\mathrm{Maize}\right)\\&+\mathrm{DFE}\left(\mathrm{Berseem}\right)+\mathrm{DFE}\left(\mathrm{Cowpea}\right)\end{aligned} \tag{5}$$

$$\mathrm{ME}\left(\mathrm{MJ\ kg^{-1}}\right)=\mathrm{DE}\left(\mathrm{MJ\ kg^{-1}}\right)\mathrm{x}\ 0.821 \tag{6}$$

$$\text{TME}\left(\text{MJ kg}^{-1}\right) = \text{ME}\left(\text{Maize}\right) + \text{ME}\left(\text{Berseem}\right) + \text{ME}\left(\text{Cowpea}\right) \tag{7}$$

$$\text{NE}\left(\text{MJ kg}^{-1}\right) = \left[\frac{\left(\text{TDN}\left(\%\right) X\, 3.65\right) - 100}{188.3}\right] X\, 6.9 \tag{8}$$

$$\text{TNE}\left(\text{MJ kg}^{-1}\right) = \text{NE}\left(\text{Maize}\right) + \text{NE}\left(\text{Berseem}\right) + \text{NE}\left(\text{Cowpea}\right) \tag{9}$$

The representative samples of fodder maize, berseem and cowpea were taken from each experimental plot and dried in a hot air oven at 60°C for 48 h. These samples were then crushed in a Wiley mill. After crushing the samples were sieved through a 1 mm mesh then crude protein content was estimated using the procedure described by AOAC (2005), and digestible crude protein (DCP) content was determined using Equation 10 provided by Demarquilly (1970) for the individual crop, and finally, the total digestible crude protein (TDCP) content of maize-berseem-cowpea cropping system was estimated by using Equation 11.

$$\text{DCP}\left(\%\right) = \left(0.929 \text{ X CP\%}\right) - 3.52 \tag{10}$$

$$\text{TDCP}\left(\%\right) = \text{DCP}\left(\text{Maize}\right) + \text{DCP}\left(\text{Berseem}\right) + \text{DCP}\left(\text{Cowpea}\right) \tag{11}$$

Estimation of yield and total system productivity of fodder maize-berseem-cowpea cropping system

The crop was harvested manually at 65 DAS from an area of 71.25 m^2, leaving the border rows to avoid the border effects. The green fodder yield was estimated by converting the yield obtained on kg plot^{-1} to ton ha^{-1}. Berseem crop was harvested thrice from an area of 71.25 m^2. The harvested green fodder yield of berseem was converted to ton ha^{-1} from kg ha^{-1}. Similarly, the cowpea crop was harvested from 71.25 m^2 area and yield was converted to ton ha^{-1} from kg ha^{-1}. Total system productivity was calculated using the support price for fodder in 2018–19, 2019–20, and 2020–21, along with the prevailing input costs, and expressed as cowpea equivalent yield (CEY).

Statistical analysis

The acquired data from the field experiment were statistically analyzed using analysis of variance (ANOVA) as described by Gomez and Gomez (1984) on a year-wise basis (2018–19, 2019–20, and 2020–21). When ANOVA indicated significant treatment effects at $p \leq 0.05$, Least Significant Difference (LSD) values were calculated, and a *post hoc* comparison of treatment means was performed accordingly. Although formal assumption testing (e.g., Shapiro–Wilk for normality or Levene's test for homogeneity of variances) was not conducted, the experimental data conformed to the expected assumptions for ANOVA based on randomized block design with replications. The bar graph and heat map were plotted by employing the GraphPad Prism version 8.0 for Windows, whereas Origin software version 9.0 was utilized for preparing the biplot and scatter plot matrix.

Results

Soil microbial properties

Total bacterial population count, P solubilizers count and K solubilizing bacterial count

The total bacterial population count (TBPC) was highest in treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M)-PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (63.0 ± 0.00, 71.3 ± 0.94, 74.0 ± 1.63), followed by T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B)-PGPR + 3% foliar spray of panchagavya (C) (60.7 ± 2.49, 68.3 ± 2.05, 70.3 ± 1.25) and T_5 applied with 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C) (61.3 ± 2.05, 69.0 ± 1.63, 72.2 ± 2.05), significantly surpassing T_1 applied with Control 100% RDF (M) - 100% RDF (B) - 100% RDF (C) (40.7 ± 2.05, 42.0 ± 1.63, 42.0 ± 2.45) during 2018–19, 2019–20, and 2020–21 (Figure 1A). Treatments T_4, T_2, and T_3 were also significantly superior to T_1. Treatment T_7 resulted in the increase of TBPC 54.8, 69.76, and 76.2% over T_1 in 2018–19, 2019–20, and 2020–21, respectively. Similarly, P solubilizing bacteria counts peaked in T_7 (58.3 ± 0.94, 60.7 ± 1.70, 60.7 ± 1.70), followed by T_6 (55.3 ± 1.25, 57.3 ± 2.05, 58.3 ± 0.47) and T_5 (56.7 ± 1.70, 58.7 ± 0.47, 59.7 ± 2.87), all significantly better than T_1 (31.0 ± 3.27, 31.7 ± 2.49, 31.7 ± 2.49) (Figure 1B). Treatment T_7 boosted P solubilizing bacteria counts by 88.1, 91.5, and 93.4% over T_1 in 2018–19, 2019–20, and 2020–21, respectively. The K solubilizing bacteria count was highest in T_7 (48.7 ± 2.05, 43.7 ± 1.70, 45.0 ± 2.94), followed by T_5 (47.3 ± 0.47, 43.0 ± 0.82, 43.7 ± 0.47) and T_6 (46.3 ± 0.94, 42.3 ± 0.47, 43.0 ± 0.82), all significantly outperforming T_1 (27.3 ± 0.47, 24.7 ± 1.25, 24.0 ± 0.82) (Figure 1C). Treatment T_7 showed increases of 78.4, 76.8, and 87.5% in K solubilizing bacterial counts over T_1 in 2018–19, 2019–20, and 2020–21, respectively. Treatment T_7 significantly boosted total bacterial, P and K solubilizing bacteria, and actinomycetes populations over three years, demonstrating its effectiveness in enhancing soil microbial activity.

Actinomycetes and fungi count

The actinomycetes population was highest in treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (64.0 ± 1.63, 62.9 ± 0.27, and 68.0 ± 1.63) followed by T_5 (62.7 ± 1.25, 60.2 ± 1.34, and 66.3 ± 2.05) and T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (61.0 ± 0.82, 59.7 ± 0.44, and 64.7 ± 2.05), significantly outperforming treatment T_1 applied with Control 100% RDF (M) - 100% RDF (B) - 100% RDF (C) (36.0 ± 2.16, 37.8 ± 2.35, and 31.0 ± 2.94) during 2018–19, 2019–20, and 2020–21, respectively. Treatments T_4, T_2, and T_3 also showed significantly higher

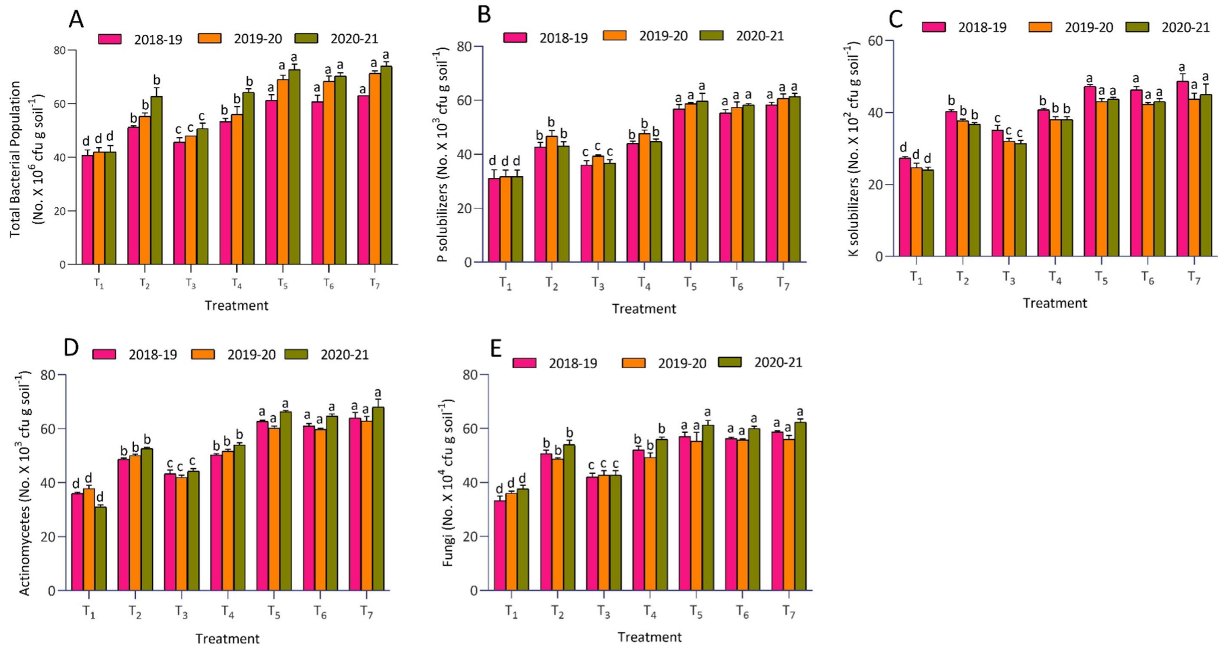

FIGURE 1
Effect of integrated nitrogen fertilization on post-harvest soil microbial populations of soil in fodder maize-berseem-cowpea cropping system: total bacterial population count **(A)**, P solubilizing bacteria population count **(B)**, K solubilizing bacteria population count **(C)**, actinomycetes population count **(D)**, and fungi population count **(E)** under organic farming. The data represents the mean values across treatments (T_1-T_7) 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.

counts than T_1 in all years, with the lowest actinomycetes counts consistently in T_1. Treatment T_7 resulted in increases of 77.8, 66.4, and 119.3% over T_1 during 2018–19, 2019–20, and 2020–21, respectively (Figure 1D). Similarly, for fungi population count (FPC), treatment T_7 recorded the highest values (58.7 ± 0.47, 56.0 ± 1.41, and 62.3 ± 1.25) followed by T_5 (57.0 ± 1.63, 55.3 ± 3.30, and 61.3 ± 1.70) and T_6 (56.3 ± 0.47, 55.7 ± 0.47, and 60.0 ± 0.82), all significantly higher than T_1 (33.3 ± 1.70, 36.0 ± 0.82, and 37.7 ± 1.25). Treatments T_4 (52.0 ± 1.41, 49.3 ± 1.70, and 56.0 ± 0.82), T_2 (50.7 ± 1.25, 48.7 ± 0.47, and 54.0 ± 1.63), and T_3 (42.0 ± 1.41, 42.7 ± 1.73, and 42.7 ± 1.70) also significantly exceeded T_1 in FPC across all years. Treatment T_1 recorded the lowest FPC values, whereas T_7 exhibited increases of 76.3, 55.6, and 65.2% over T1 in 2018–19, 2019–20, and 2020–21, respectively (Figure 1E). Treatment T_7 significantly enhanced actinomycetes and fungi populations, surpassing other treatments and T_1, showing potential for agricultural improvement.

Soil enzymatic activities

Dehydrogenase and β-glucosidase activity

In the study, treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) exhibited the highest dehydrogenase activity (DHA) with values of 123.8 ± 1.15, 139.8 ± 1.19, and 143.6 ± 4.06 μg TPF g soil^{-1} d^{-1}, followed by T_5 applied with 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C) and T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C), significantly surpassing treatment T_1 applied with Control 100% RDF (M) - 100% RDF (B) - 100% RDF (C) (55.9 ± 1.20, 50.9 ± 3.73, and 53.5 ± 2.04 μg TPF g soil^{-1} d^{-1}) across 2018–19, 2019–20, and 2020–21. Conversely, the lowest DHA activity was consistently recorded in T_1 throughout the study period. Treatment T_7 enhanced DHA activity by 121.5, 174.7, and 168.4% compared to T_1 in 2018–19, 2019–20, and 2020–21, respectively (Figure 2A). Similarly, β-glucosidase activity (BG) was highest in T_7 (3.40 ± 0.15, 4.13 ± 0.12, and 4.23 ± 0.12 μg PNP g soil^{-1} h^{-1}), followed by T_5 and T_6, significantly exceeding T_1 (1.30 ± 0.05, 1.51 ± 0.07, and 1.59 ± 0.01 μg PNP g soil^{-1} h^{-1}) from 2018 to 19 to 2020–21. Treatment T_1 consistently showed the lowest BG activity. Treatment T_7 enhanced BG activity by 161.5, 173.5, and 166.0% compared to T_1 in 2018–19, 2019–20, and 2020–21, respectively (Figure 2B). These results underscored the effectiveness of T_7 in enhancing soil enzymatic activities, suggesting its potential for improving soil health and nutrient cycling processes in agricultural systems.

Acid phosphatase and alkaline phosphatase activity

Acid phosphatase (Apase) activity exhibited its highest levels in treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) (26.4 ± 0.84, 29.0 ± 0.24, and 28.0 ± 0.21 μg PNP g soil^{-1} h^{-1}), followed

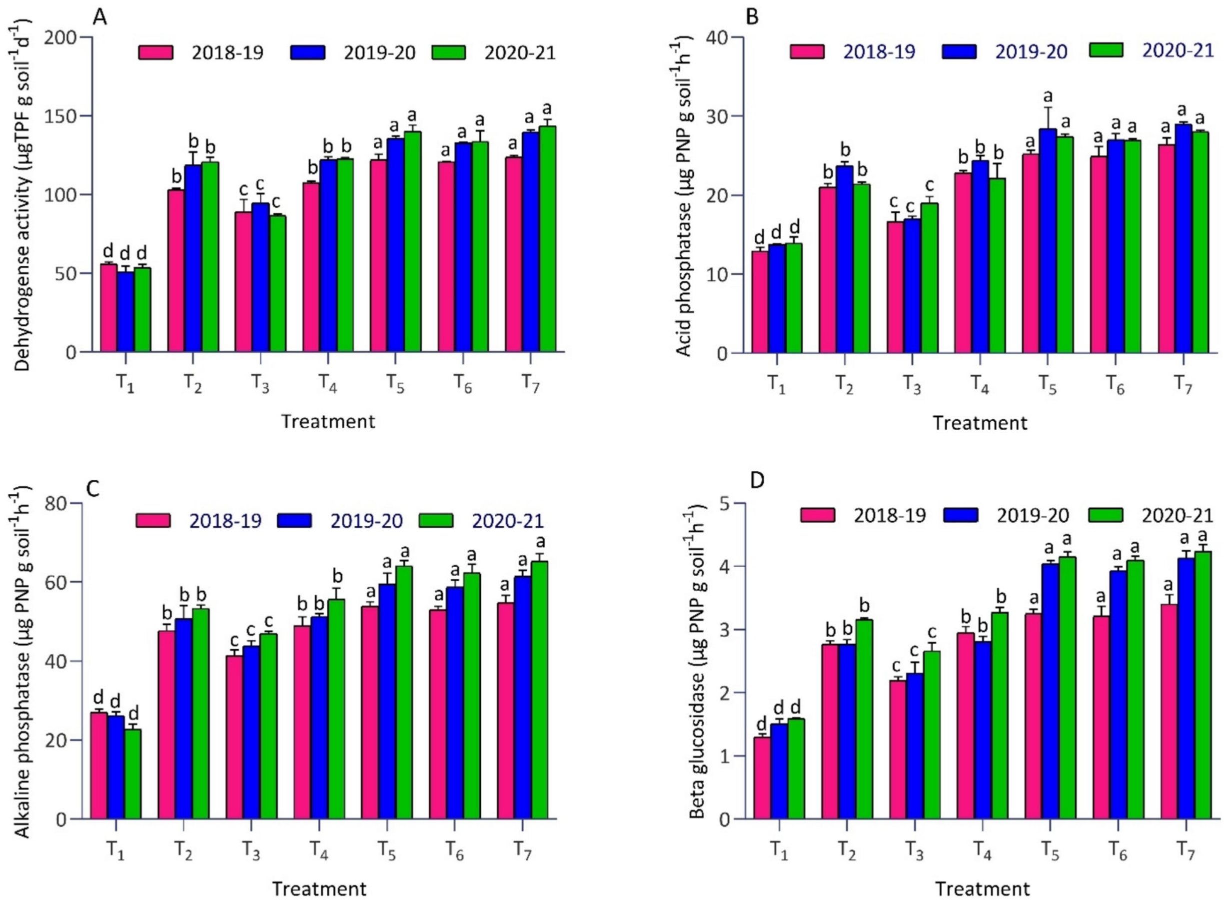

FIGURE 2
Effect of integrated nitrogen fertilization on post-harvest soil enzymatic activities in fodder maize-berseem-cowpea cropping system: dehydrogenase activity **(A)**, beta-glucosidase activity **(B)**, acid phosphatase activity **(C)**, and alkaline phosphatase activity **(D)** under organic farming. The data represents the mean values across treatments (T_1-T_7) 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.

by T_5 applied with 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C) (25.2 ± 0.53, 28.4 ± 2.72, and 27.4 ± 0.34 µg PNP g soil^{-1} h^{-1}) and T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) (24.9 ± 1.30, 27.0 ± 0.79, and 26.9 ± 0.25 µg PNP g soil^{-1} h^{-1}), significantly surpassing treatment T_1 applied with Control (100% RDF (M)- 100% RDF) (B)- 100% RDF (C) (12.9 ± 0.53, 13.7 ± 0.17, and 13.9 ± 0.82 µg PNP g soil^{-1} h^{-1}) throughout 2018–19, 2019–20, and 2020–21. Conversely, the lowest Apase activity was consistently observed in T_1 across all 3 years. Treatment T_7 notably increased Apase activity by 104.6, 111.7, and 101.4% compared to T_1 in 2018–19, 2019–20, and 2020–21, respectively, (Figure 2C). Similarly, alkaline phosphatase (AlPase) activity peaked in T_7 (54.8 ± 1.84, 61.4 ± 1.63, and 65.2 ± 1.99 µg PNP g soil^{-1} h^{-1}), followed by T_5 (53.9 ± 1.13, 59.4 ± 2.83, and 64.1 ± 1.35 µg PNP g soil^{-1} h^{-1}) and T_6 (53.0 ± 0.88, 58.7 ± 1.77, and 62.3 ± 2.17 µg PNP g soil^{-1} h^{-1}), significantly outperforming T_1 (27.0 ± 0.92, 26.2 ± 0.98, and 22.7 ± 1.41 µg PNP g soil^{-1} h^{-1}) across the study period. Treatment T_7 showed substantial increases in AlPase activity of 103.06, 135.4, and 187.2% over T_1 during 2018–19, 2019–20, and 2020–21, respectively, (Figure 2D). These findings underscore that T_7 significantly increased soil phosphatase activities, indicating its capacity to enhance nutrient availability in agricultural soils.

Soil physicochemical properties

Soil organic carbon, soil organic matter and bulk density

The SOC content was highest under treatments T_2 applied with 100% RDN through FYM (M) - No application (B) - No application (C) (0.624 ± 0.00, 0.651 ± 0.02, and 0.683 ± 0.00%), T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) (0.624 ± 0.01, 0.651 ± 0.01, and 0.683 ± 0.00%), and T_5 applied with applied with 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C) (0.624 ± 0.01, 0.651 ± 0.03, and 0.683 ± 0.00%), followed by treatments T_6, T_4, and T_3, during 2018–19, 2019–20, and 2020–21, respectively. Conversely, the lowest SOC content was observed in treatment T_1 applied with applied with Control 100% RDF (M) - 100% RDF (B) - 100% RDF (C) (0.600 ± 0.00, 0.597 ± 0.00, and 0.593 ± 0.00%) throughout these

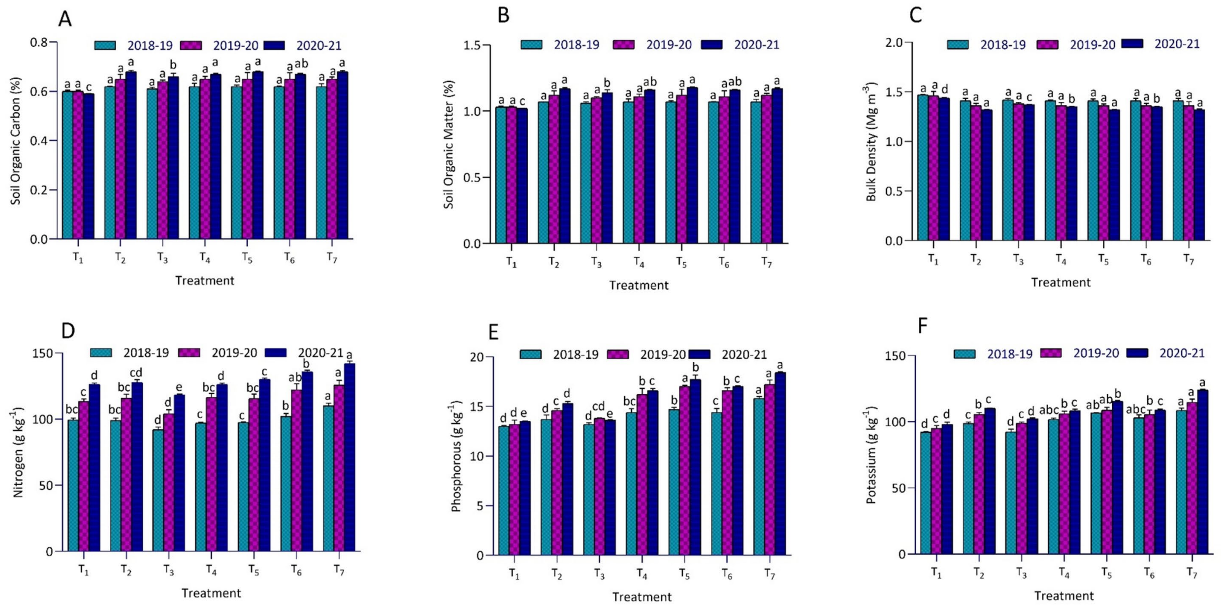

FIGURE 3
Effect of integrated nitrogen fertilization on post-harvest physiochemical soil properties in fodder maize-berseem-cowpea cropping system: soil organic carbon **(A)**, soil organic matter **(B)**, bulk density **(C)**, available nitrogen **(D)**, available phosphorus **(E)**, and available potassium **(F)** under organic farming. The data represents the mean values across treatments (T_1-T_7) 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.

years. In the first 2 years, no significant difference in SOC was noted among the treatments. However, by 2020–21, treatments T_2 to T_7, utilizing an integrated application of FYM, PGPR, and foliar spray of panchagavya, exhibited a notable SOC increase of 11.6 to 15.2% over T_1. Specifically, T_7 showed increases in SOC of 4.0, 9.0, and 15.2% over T_1 for 2018–19, 2019–20, and 2020–21, respectively (Figure 3A). Similarly, the highest SOM content was recorded under treatments T_7 (1.07 ± 0.02, 1.12 ± 0.01, and 1.17 ± 0.01%), T_5, and T_2 across the same period, with the lowest in T_1 (1.03 ± 0.01, 1.03 ± 0.01, and 1.02 ± 0.01%). During 2020–21, treatments T_2 to T_7 showed a significant increase in SOM content, ranging from 11.8 to 15.7% over T_1. Treatment T_7 demonstrated increase in SOM of 3.9, 8.7, and 14.7% over T_1 in 2018–19, 2019–20, and 2020–21, respectively (Figure 3B). For BD, no significant differences were observed during 2018–19 and 2019–20. The lowest BD values were under treatments T_7, T_6, T_5, T_4, and T_2, with the highest in T_1. By 2020–21, significant changes in BD were recorded, with treatments T_2 to T_7 showing declines of 4.1 to 6.8% over T_1. T_7 recorded BD decreases of 4.1, 6.8, and 8.3% over T_1 for 2018–19, 2019–20, and 2020–21, respectively (Figure 3C). Treatments T_2, T_7, and T_5 consistently exhibited highest SOC and SOM content, surpassing T_1, indicating significant soil improvement potential.

Nutrients availability

The highest available N content was observed under treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (110.1 ± 1.91, 125.2 ± 3.63, and 142 ± 1.87 g kg^{-1}) during 2018–19, 2019–20, and 2020–21, respectively. Treatment T_7 was closely followed by T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C), which had available N content values of 102.1 ± 2.19, 122.2 ± 4.63, and 142.2 ± 1.87 g kg^{-1} during 2018–19, 2019–20, and 2020–21, respectively. The lowest values of available N content (92.0 ± 2.00, 104.1 ± 2.94, and 118.3 ± 0.62 g kg^{-1}) were recorded under treatment T_1 applied with applied with applied with Control (100% RDF (M) - 100% RDF (B) - 100% RDF (C) during 2018–19, 2019–20, and 2020–21, respectively. Treatment T_7, showed a 10.8, 10.5, and 12.5% increase in available N over control treatment T_1 during 2018–19, 2019–20, and 2020–21, respectively (Figure 3D). Similarly, the highest available P content was noted in treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (15.8 ± 0.20, 17.2 ± 0.48, and 18.4 ± 0.10 g kg^{-1}) for the same periods, closely followed by T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (14.4 ± 0.40, 16.6 ± 0.29, and 17.0 ± 0.10 g kg^{-1}) and T_5. The lowest P content was in T_1 (13.0 ± 0.08, 13.2 ± 0.43, and 13.5 ± 0.03 g kg^{-1}). Treatment T_7 showed a 21.5, 30.3, and 36.3% increase in available P over T_1 for the respective years (Figure 3E). Furthermore, the highest available K content was observed in T_7 (108.5 ± 1.76, 114.7 ± 2.55, and 123.8 ± 0.80 g kg^{-1}) across the 3 years, closely followed by T_5 applied with applied with 100% RDN through FYM + PGPR (M) - PGPR (B) - PGPR (C) (106.7 ± 0.19, 108.7 ± 2.15, and 115.6 ± 0.43 g kg^{-1}). The lowest K values were recorded in T_1 (92.1 ± 2.08, 94.8 ± 2.32, and 98.1 ± 1.62 g kg^{-1}). Treatment T_7 demonstrated a 15.1, 17.3, and 26.2% increase in available K over T_1 during the corresponding years (Figure 3F). Treatment T_7 consistently exhibited the highest available N, P, and K content over 3 years, surpassing other treatments.

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Energy fractions in fodder maize-berseem-cowpea cropping system

Total digestible energy

The TDE was recorded at a maximum of 66.9 ± 0.19 MJ kg^{-1} in treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) and found at par with treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) (66.2 ± 0.23 MJ kg^{-1}) and significantly superior over the remaining treatments during the first year (2018–19) of experimentation. On the other hand, treatment T_7 recorded the highest TDE (66.6 ± 0.24 and 66.7 ± 0.09 MJ kg^{-1}) during 2019–20 and 2020–21, respectively and was found to be significantly superior over the remaining treatments. The treatment T_3 recorded the lowest values of TDE during all 3. In the present study, treatment T_7 resulted in a decrease of TDE to the tune of 1.04% over treatment T_1 applied with applied with applied with Control 100% RDF (M) - 100% RDF (B) - 100% RDF (C) during the first year of experimentation (2018–19), whereas treatment T_7 recorded an increase of TDE to the tune of 1.8 and 1.5% over treatment T_1 during the 2019–20 and 2020–21, respectively, (Figure 4A). Treatment T_7 consistently showed higher TDE than other treatments across all 3 years, indicating its potential for improved energy efficiency.

Total digestible feed energy

The TDFE was recorded at a maximum of 62.0 ± 0.32 MJ kg^{-1} in treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B)- 100% RDF (C) which was found significantly superior over the remaining treatments during the first year (2018–19) of experimentation. On the other hand, treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) recorded the highest TDFE (61.5 ± 0.41 and 61.7 ± 0.15 MJ kg^{-1}) during 2019–20 and 2020–21, respectively, and was significantly superior over the remaining treatments. The treatment T_3 recorded the lowest values of TDFE during all 3 years. In the present study, treatment T_7 recorded a decrease of TDFE to the tune of 1.8% over treatment T_1 during the first year of experimentation (2018–19), whereas treatment T_7 recorded an increase of TDFE to the tune of 3.4 and 3.0% over treatment T_1 during the 2019–20 and 2020–21, respectively, (Figure 4B). Treatment T_7

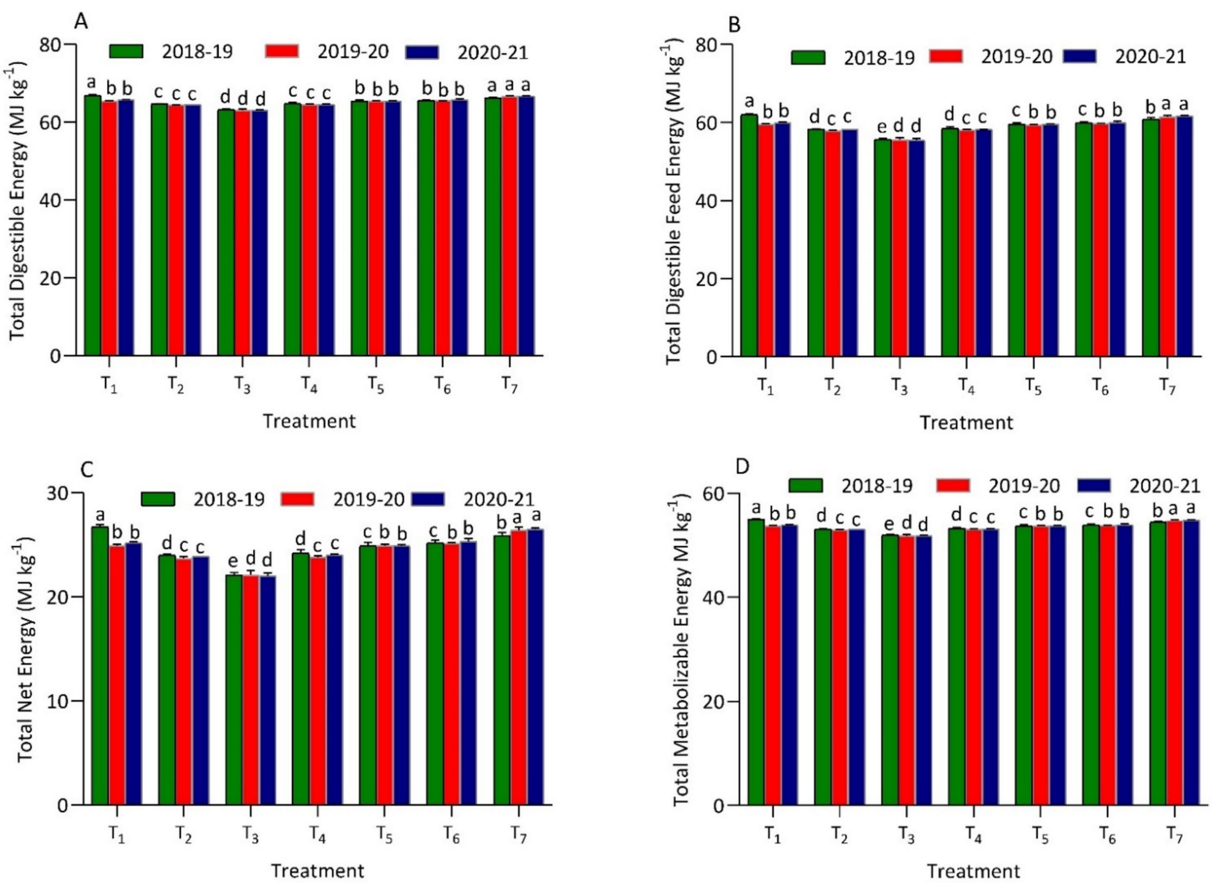

FIGURE 4
Effect of integrated nitrogen fertilization on energy fractions in a fodder maize-berseem-cowpea cropping system: total digestible energy **(A)**, total digestible feed energy **(B)**, total net energy **(C)**, and total metabolizable energy **(D)** under organic farming. The data represents the mean values across treatments (T_1-T_7) 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.

showed the highest TDFE in the second and third years, surpassing other treatments, while T_1 led in the first year.

Total net energy

The TNE was recorded at a maximum of 26.7 ± 0.24 MJ kg^{-1} in treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) which was found significantly superior over the remaining treatments during the first year (2018–19) of experimentation. Treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) was recorded as the highest TNE (26.4 ± 0.30 and 26.5 ± 0.11 MJ kg^{-1}) during 2019–20 and 2020–21, respectively and was found to be significantly superior over the remaining treatments. In the present study, treatment T_7 recorded a decrease of TNE to the tune of 3.0% over treatment T_1 during the first year of experimentation (2018–19), whereas treatment T_7 recorded an increase of TNE to the tune of 6.0 and 5.2% over treatment T_1 during the 2019–20 and 2020–21, respectively, (Figure 4C). Treatment T_7 showed varying TNE levels over the 3 years, peaking in 2019–20 and 2020–21, surpassing other treatments, indicating its effectiveness.

Total metabolizable energy

The TME was recorded maximum at a 54.9 ± 0.16 MJ kg^{-1} in treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) which was found significantly superior over the remaining treatments during the first year (2018–19) of experimentation. Treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) was recorded as the highest TME (54.7 ± 0.20 and 54.8 ± 0.07 MJ kg^{-1}) during 2019–20 and 2020–21, respectively and was found to be significantly superior over the remaining treatments. The treatment T_3 recorded the lowest values of TME during all 3 years. In the present study, treatment T_7 recorded a decrease of TME to the tune of 0.91% over treatment T_1 during the first year of experimentation (2018–19), whereas treatment T_7 recorded an increase of TME in the tune of 1.86 and 1.67% over treatment T_1 during the 2019–20 and 2020–21, respectively, (Figure 4D). Treatment T_7 consistently showed the highest TME values in the second and third years, surpassing other treatments significantly.

Yield and total digestible crude protein content in the maize-berseem-cowpea cropping system

Fodder maize

Green fodder yield of maize showed significant variation between the treatment applied with integrated application of FYM, PGPR and/or foliar spray of panchagavya and the recommended dose of fertilizer. Treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) recorded the highest and significantly superior yield (40.2 ± 0.83 and 41.9 ± 1.8 t ha^{-1}) during 2018 and 2019, respectively over all the other treatments. Treatment T_1 also recorded a maximum yield (42.0 ± 2.1 t ha^{-1}) and found at par treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (38.6 ± 2.7 t ha^{-1}) during the third year of experimentation (2020). The treatment T_3 recorded the lowest values of yield during all 3 years of experimentation. In the present study, treatment T_7 resulted in a decrease in green fodder yield to the tune of 11.9 and 11.7% compared to treatment T_1 in 2018 and 2019, respectively whereas a decrease in green fodder yield in treatment T_7 was recorded at 8.09% over treatment T_1 during the third (2020) year (Figure 5A). Treatment T_1 consistently yielded the highest green fodder maize, significantly outperforming other treatments over 3 years of experimentation.

Berseem

Green fodder yield of berseem showed significant variation between the treatment applied with integrated application of FYM, PGPR and/or foliar spray of panchagavya and the recommended dose of fertilizer. Treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) recorded the highest yield (59.7 ± 1.93 t ha^{-1}) followed by treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (58.2 ± 3.41 t ha^{-1}) and T_6 applied with 75% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (56.0 ± 1.25 t ha^{-1}) during 2018–19 and found significantly superior over all the other treatments. Treatment T_7 recorded maximum yield (60.0 ± 2.58 and 60.6 ± 0.50 t ha^{-1}) and found at par treatment T_1 (59.3 ± 1.59 and 59.6 ± 4.16 t ha^{-1}) and T_6 (56.9 ± 1.59 and 57.4 ± 0.20 t ha^{-1}) during second (2019–20) and third (2020–21) years of experimentation. The treatment T_3 recorded the lowest values of yield during all 3 years of experimentation. In the present study, treatment T_7 resulted in a decrease of green fodder yield to the tune of 2.5% compared to treatment T_1 during 2018–19, whereas an increase of 1.2 and 1.768% was recorded in green fodder yield over treatment T_1 during the second (2019–20) and third (2020–21) years of experimentation (Figure 5B).

Cowpea

Green fodder yield of cowpea showed significant variation between the treatment applied with integrated application of FYM, PGPR and/or foliar spray of panchagavya and the recommended dose of fertilizer. Treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) was recorded the highest yield (25.7 ± 0.51, 25.5 ± 0.80, and 28.3 ± 1.67 t ha^{-1}) followed by treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) (25.6 ± 1.06, 27.5 ± 0.87, and 27.9 ± 0.60 t ha^{-1}) and found at par with each other and found significantly superior over all the other treatments during 2018–19. The treatment T_3 recorded the lowest values of yield during all 3 years of experimentation. In the present study, treatment T_7 resulted in an increase of 0.40 to 1.43% in green fodder yield over treatment T_1 from the first year (2019–20) to the third year (2020–21) of experimentation (Figure 5C).

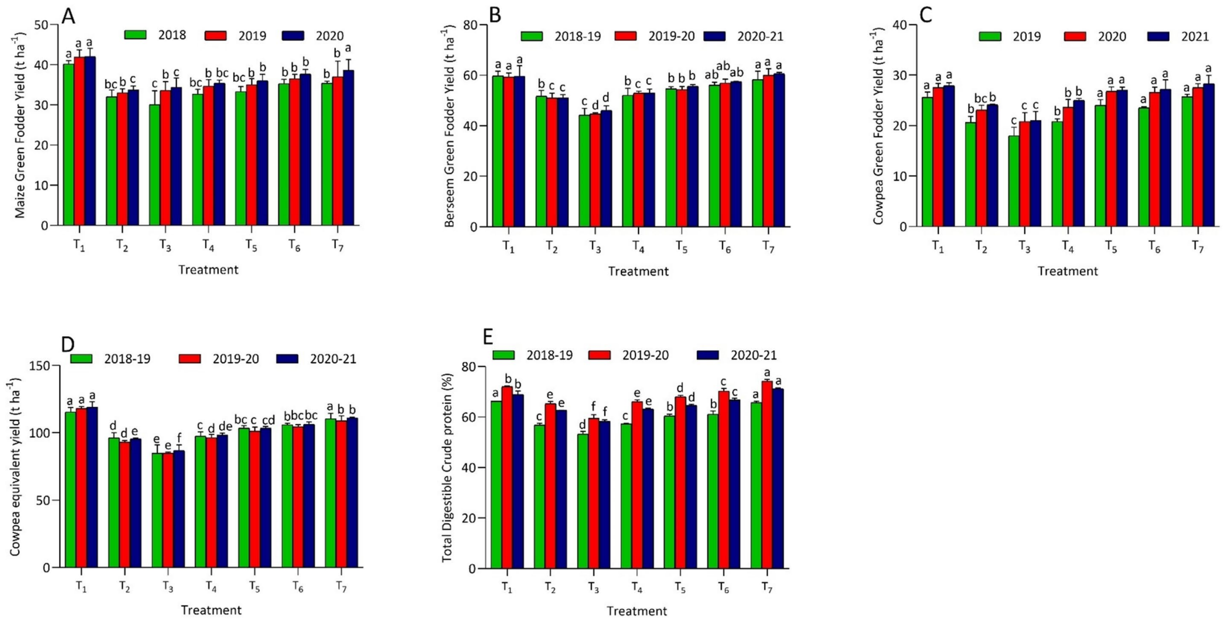

FIGURE 5
Effect of integrated nitrogen fertilization on yield and digestible crude protein content in a fodder maize-berseem-cowpea cropping system under organic farming: Maize green fodder yield **(A)**, Berseem green fodder yield **(B)**, Cowpea green fodder yield **(C)**, Cowpea equivalent yield **(D)**, and total digestible crude protein content **(E)**. The data represents the mean values across treatments (T_1-T_7) 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.

Cowpea equivalent yield

Cowpea equivalent yield showed significant variation between the treatment applied with the integrated application of FYM, PGPR and/or foliar spray of panchagavya and the recommended dose of fertilizer in the maize-berseem cropping sequence. Treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C) was recorded as the highest CEY (115.5 ± 3.3 t ha^{-1}) and found at par with T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (110.5 ± 4.1 t ha^{-1}) and found significantly superior in CEY over the remaining treatment during 2018–19. Again, treatment T_1 was recorded as the highest and significantly superior CEY (118.2 ± 1.3 and 119.5 ± 4.2 t ha^{-1}) during 2019–20 and 2020–21, respectively, over all the other treatments. On the other hand, treatment T_3 recorded the lowest values of CEY during all 3 years of experimentation. In the present study, treatment T_7 resulted in a decrease of CEY to the tune of 4.3, 7.9, and 7.0% compared to treatment T_1 during 2018–19, 2019–20, and 2020–21, respectively (Figure 5D).

Total digestible crude protein content

TDCP content was recorded at the highest 66.2 ± 0.11% in treatment T_1 (control) applied with 100% RDF (M) - 100% RDF (B) - 100% RDF (C), followed by treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) (65.7 ± 0.57%) during the first year (2018–19) of experimentation, whereas treatment T_7 recorded the highest values of TDCP (74.2 ± 0.69 and 71.3 ± 0.23%) during 2019–20 and 2020–21 year of experimentation. The treatment T_3 recorded the lowest values of TDCP during all 3 years of experimentation. In the present study, treatment T_7 resulted in a decrease of TDCP content to the tune of 0.75% compared to treatment T_1 during the first year (2018–19) of experimentation, whereas treatment T_7 resulted in an increase in TDCP content in the tune of 3.0 and 3.5% over treatment T_1 during the 2019–20 and 2020–21, respectively (Figure 5E).

Impact of integrated fertilization strategy on soil health, crop quality and cowpea equivalent yield

In 2018–19, the integrated application of FYM, PGPR, and foliar spray of panchagavya significantly influenced various aspects of the fodder maize-berseem-cowpea cropping system. Principal Component Analysis (PCA) and scatter plot matrices revealed two key components, PC1 and PC2, contributing to 98.67 and 1.19% of the variance, respectively (Figure 6A). Treatments clustered into groups I and II, where cluster I included treatment T_1 and cluster II comprised treatments T_2, T_4, T_5, T_6, and T_7. Positive correlations with PC1 and PC2 were observed in cluster I, while cluster II exhibited a positive correlation with PC1 and a negative correlation with PC2. Parameters were grouped into four clusters based on the biplot graph, with treatment T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) - PGPR + 3% foliar spray of panchagavya (B) - PGPR + 3% foliar spray of panchagavya (C) showed significant improvements in multiple parameters. The statistically analyzed data shown in the scatter plot matrix (Figure 6B) for 2018–19 showed that the treatments from T_2 to T_7 showed a strict

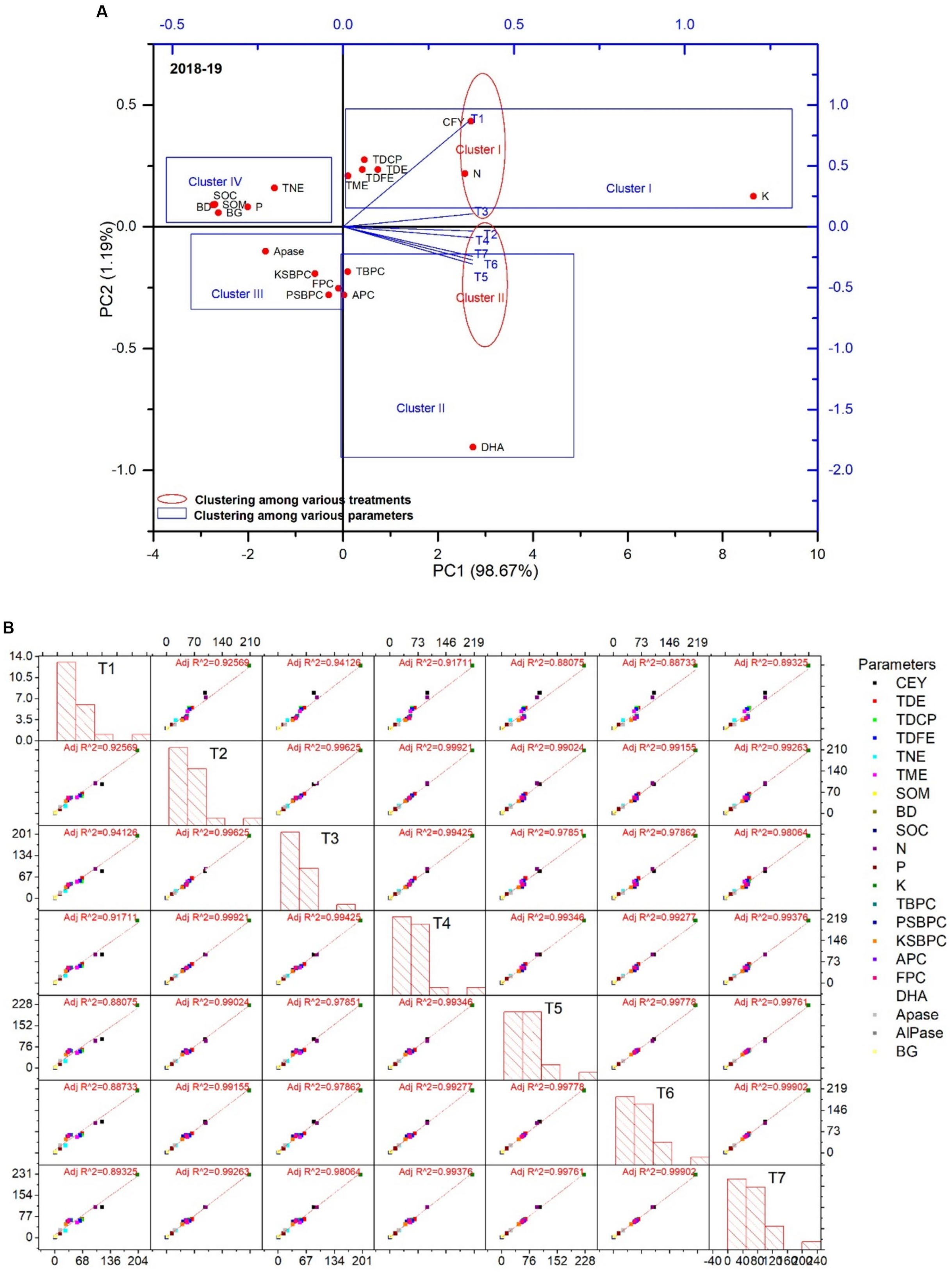

FIGURE 6
(A) Principal component analysis of various parameters and treatments in the fodder maize - berseem—cowpea cropping system under integrated nitrogen fertilization in organic farming during 2018–19. **(B)** Scatter plot matrix and regression analysis among various parameters and treatments during 2018–19.

regression coefficient (r^2) > 0.99. Based on the response to various parameters, the regression coefficient between treatments applied for N application through FYM alone and integrated N application through FYM, PGPR, and foliar spray of panchagavya were >0.99 (T_2 to T_7), >0.97 (T_3 to T_7), >0.99 (T_4 to T_7), >0.99 (T_5 to T_7), >0.99 (T_6 and T_7), while the regression coefficient (r^2) among the treatments applied recommended dose of fertilizer alone varied from 0.88 to 0.94.

In 2019–20, similar trends were observed, with two principal components, PC1 and PC2, contributing to 98.25 and 1.61% of the variance, respectively (Figure 7A). Treatment T_7 continued to exhibit substantial improvements across various parameters. During 2019–20, scatter plot matrix analysis (Figure 7B) indicated robust relationships (r^2 > 0.99) for treatments T_2 to T_7, emphasizing their potential for enhancing soil health and productivity. Based on the response to various parameters, the regression coefficient between treatments applied with FYM alone and integration of FYM with PGPR and foliar spray of panchagavya were > 0.99 (T_2 to T_7), >0.97 (T_3 to T_7), >0.99 (T_4 to T_7), >0.99 (T_5 to T_7), >0.99 (T_6 and T_7), while the regression coefficient (r^2) among the treatments applied with recommended dose of N through fertilizers alone varied from 0.84 to 0.92.

In 2020–21, principal components PC1 and PC2 contributed to 98.20 and 1.66% of the variance, respectively (Figure 8A). Treatments were organized into clusters I and II, resembling previous years, with treatment T_7 continuing to contribute significantly to various parameters. The treatment T_7 showed significant improvement among various parameters (microbial population counts, enzymatic activities, available nutrients in soil, SOC, SOM, energy fractions in the fodder, TDCP content, and CEY). Further during 2020–21, scatter plot matrix analysis (Figure 8B) revealed strong relationships (r^2 > 0.98) for treatments T_2 to T_7. Based on the response to various parameters, the regression coefficient between treatments applied with FYM alone and integration of FYM with PGPR and foliar spray of panchagavya were > 0.98 (T2 to T7), >0.95 (T3 to T7), >0.99 (T4 to T7), >0.99 (T5 to T7), >0.99 (T6 and T7), while the regression coefficient (*r*2) among the treatments applied with recommended dose of N through fertilizers alone varied from 0.84 to 0.94. The scatter plot matrix revealed that treatment T7 have a high potential for improving the soil health, energy fractions and TDCP content in fodder maize-berseem-cowpea cropping system along with higher productivity.

Moreover, the persistent cultivation under treatment T_7 over consecutive years resulted in notable outcomes, including decreased BD, increased CEY, SOC, SOM, enhanced nutrient availability, elevated soil microbial counts, improved enzymatic activities, and heightened digestible crude protein content (Figure 9). These findings underscore the long-term positive impact of the integrated approach on the sustainability and productivity of the cropping system.

Discussion

Significant improvement in soil microbial population was observed among all the treatments from T_2 to T_7 for TBPC, P-solubilizing bacterial count, APC, K-solubilizing bacterial population counts and FPC over treatment T_1 during 2018–19, 2019–20, and 2020–21. Treatment T_7 recorded the highest TBPC, PSBPC, KSBPC, APC, and FPC. The application of FYM increases the SOM and soil organic carbon directly related to the soil biota under the maize-wheat cropping system under western Indo-Gangetic Plains (Rasool et al., 2008). Continuous use of organic manure improves the organic matter content, which supports soil micro, meso, and macrofauna, thereby making the soil a living entity (Luan et al., 2019; Garg et al., 2024).

In the present study, treatments T_2 to T_7, which were applied with FYM either alone or in combination with PGPR and foliar spray of panchagavya, recorded significant improvements in soil DHA, BG activity, Apase, and Alpase activity over treatment T_1 during all 3 years of experimentation. The enhanced enzymatic activity can be attributed to the readily decomposable organic matter in FYM, which provides an accessible energy source for microbial metabolism, growth, and enzyme production (Zhu et al., 2021; Zhou et al., 2022). Further, inoculation of PGPR increases the decomposition of the soil organic compounds to provide the substrate for soil enzymatic, which increases the activity of different soil enzymes (Wang et al., 2020).

In the current study, SOC content and SOM content were recorded as highest under treatment T_7, T_6, T_5, T_4, and T_2 followed by treatment T_3 during 2018–19, 2019–20, and 2020–21, respectively. The increase in SOC and SOM content in treatments T_2 to T_7 was due to the continuous addition of organic manure, which contains carbon in a recalcitrant form which is attributed to the addition of organic manures that enhance the organic carbon and organic matter in the soil. Wankhede et al. (2021) reported that long-term application of organic manure increases the soil organic carbon under semi-tropical conditions in soybean-wheat cropping systems. Mustafa et al. (2021) reported increased organic carbon and organic matter content as compared to treatments applied with inorganic fertilizers in maize.

In this study, during 2018–19 and 2019–20, significant changes in BD were not observed but during 2020–21, significant changes were observed in the BD; treatments T_2 to T_7 recorded a decline in BD ranging from 4.86 to 9.09% over treatment T_1. The increase in organic matter content from applied organic manure reduced bulk density by enhancing macro-porosity, improving soil water infiltration, and increasing water-holding capacity. Similarly, Dhaliwal et al. (2019) reported that the application of organic manures leads to improvement in soil physical properties. Zhou et al. (2020) reported a strong relationship between an increase or decrease in organic matter content with soil physical degradation.

Nutrient availability of N, P, and K was increased under treatment T_7 during all 3 years of experimentation. The application of FYM enhances nutrient availability by slowly releasing organically bound nutrients over time. It also supplies organic carbon, which serves as an energy source for soil microbes, thereby promoting microbial and enzymatic activity and increasing the availability of nitrogen, phosphorus, and potassium in the soil. Similar findings were reported by Kumar et al. (2021) under a maize wheat cropping system and in a multi-crop system by Garg et al. (2024) in Indo Gangetic Plains in India. Further, PGPR consists of various beneficial microbial strains that contribute to nitrogen fixation and the solubilization of phosphorus and potassium, thereby enhancing the availability of these nutrients in the soil for plant uptake (Etesami and Adl, 2020; Wang et al., 2020) whereas, application of foliar spray of panchagavya contributes towards the supplementation of nutritional demands of the crop plants (Paramasivan et al., 2022), thereby reduces the dependence of plants on soil for nutrients and prevent the excessive nutrient mining from the root zone of crop plants.

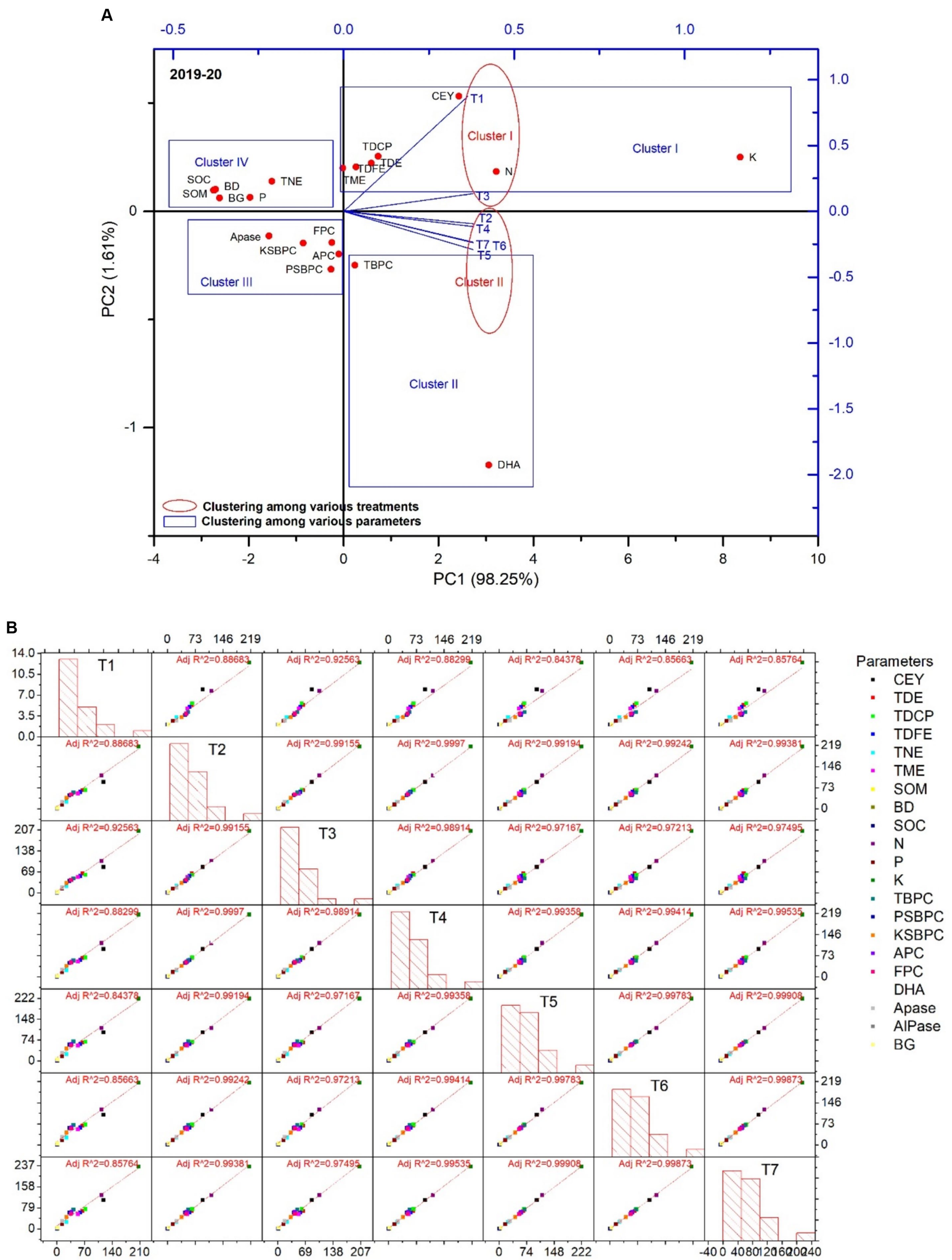

FIGURE 7
(A) Principal component analysis (PCA) of various parameters and treatments in the fodder maize—berseem - cowpea cropping system under integrated nitrogen fertilization in organic farming during 2019–20. **(B)** Scatter plot matrix and regression analysis among various parameters and treatments during 2019–20.

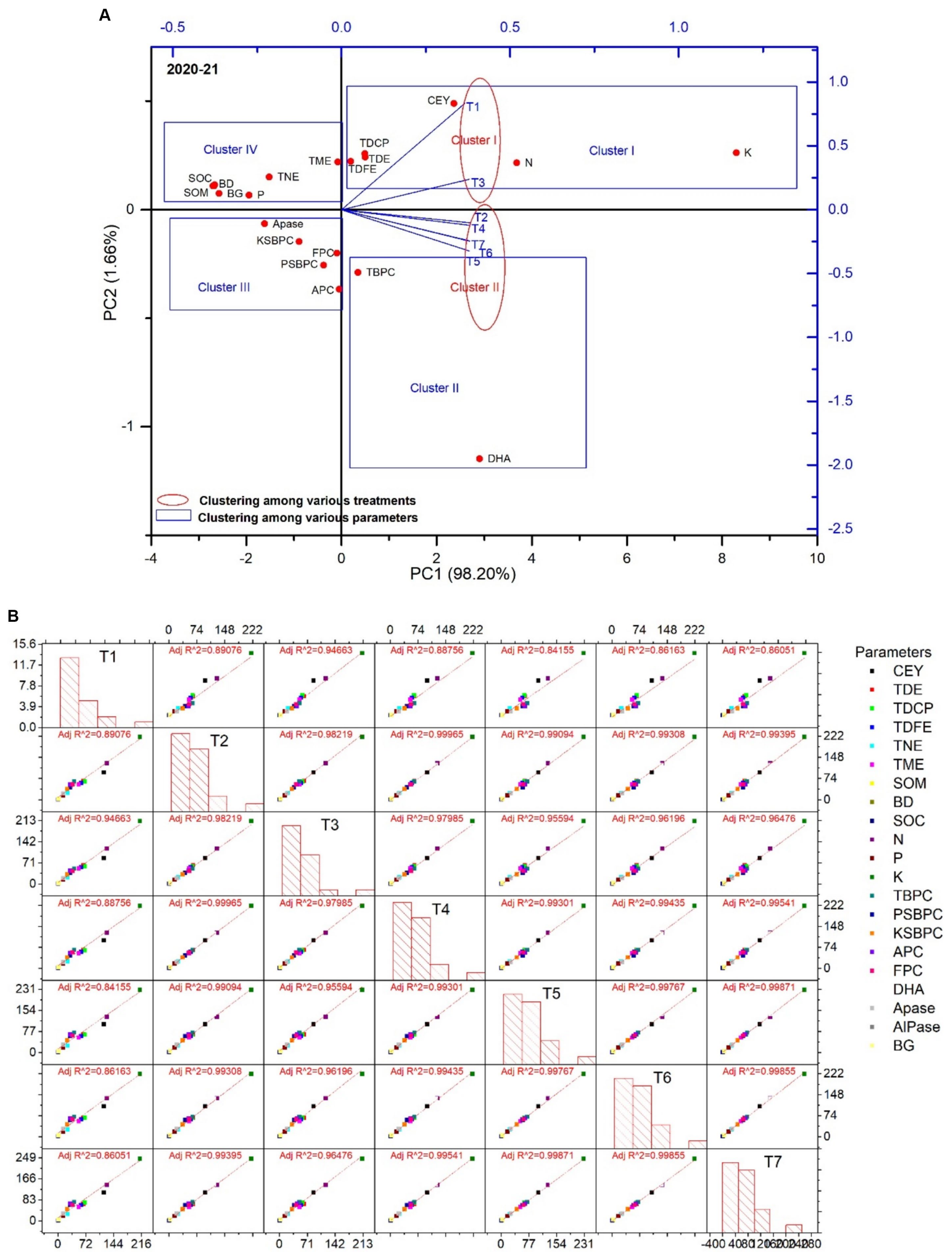

FIGURE 8
(A) Principal component analysis of various parameters and treatments in the fodder maize - berseem - cowpea cropping system under integrated nitrogen fertilization in organic farming during 2020–21. **(B)** Scatter plot matrix and regression analysis among various parameters and treatments during 2020–21.

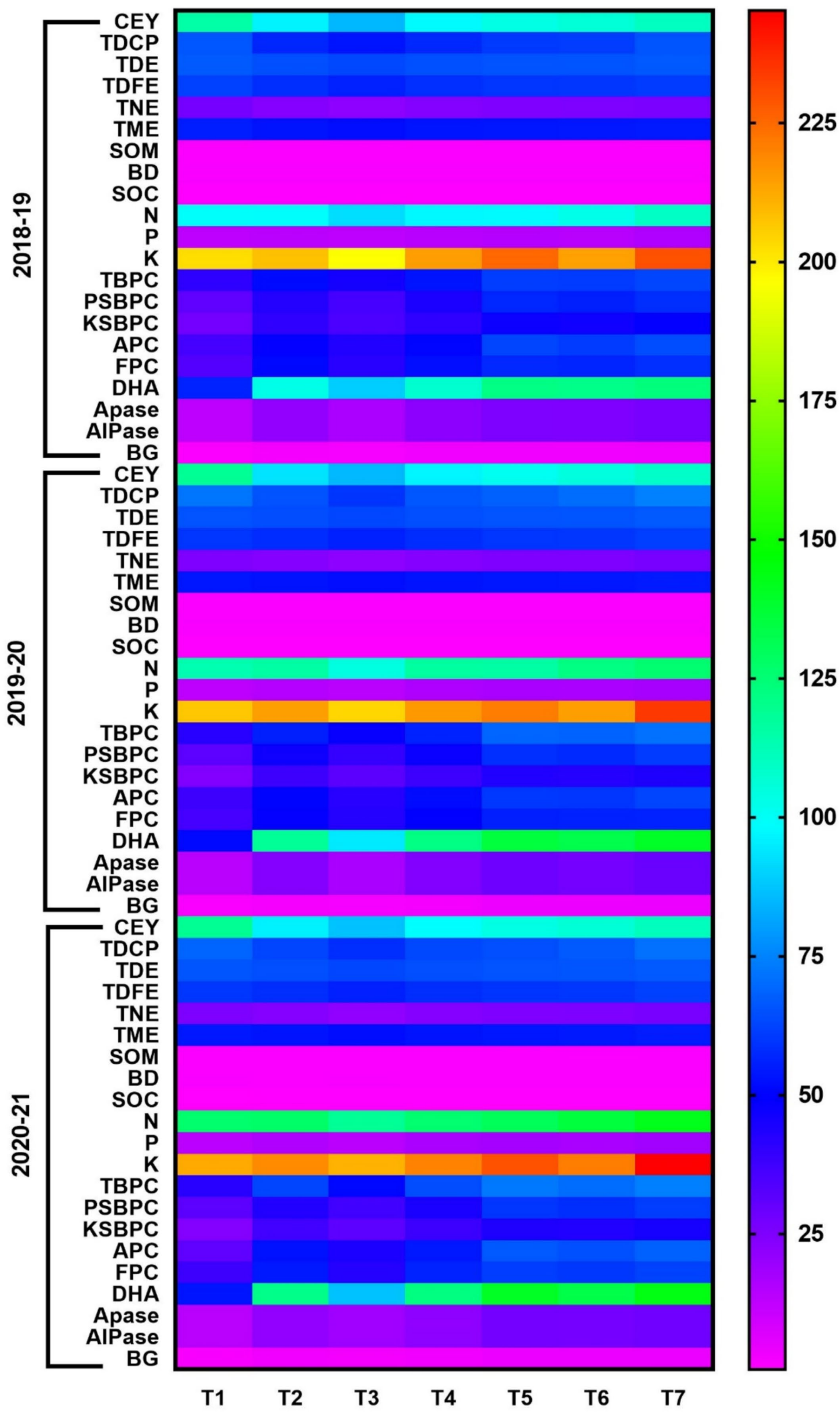

FIGURE 9
Expression patterns of energy fractions, soil properties, digestible crude protein, and cowpea equivalent yield in a fodder maize—berseem—cowpea cropping system under integrated nitrogen fertilization in organic farming over three consecutive years.

Fodder is an important source of energy for livestock production and maintenance. The nutritional deficiency greatly affects plants' normal growth and development (Bouain et al., 2019), thereby affecting the plants' energy fractions supplied to the livestock (Kaplan et al., 2019). In the present study, treatment T_1 applied with inorganic fertilizer recorded the highest TDE and was found at par with treatment T_7, whereas for TDFE, TME, and TNE, treatment T_1 recorded significant superiority over the remaining treatments during the first year of experimentation (2018–19), whereas treatment T_7 resulted in the highest amount of TDE, TDFE, TME, and TNE during the 2019–20 and 2020–21, respectively. The energy fractions in fodder are dependent on neutral detergent fibre content, acid detergent fibre content and digestible crude protein content of the fodder. In the current study, during the first year of experiment treatment, T_1 had higher values of energy fractions due to lower neutral detergent fibre, acid detergent neutral fibres and higher crude protein content due to higher nutrient availability. Similarly, under treatment, the T_7 applied with 100% RDN through FYM + PGPR + 3% foliar spray of panchagavya (M) – PGPR + 3% foliar spray of panchagavya (B) – PGPR + 3% foliar spray of panchagavya (C) nutrient requirement was met from the combined action of 100% RDN supplementation from FYM, PGPR, and further additional application of foliar spray of panchagavya that provided the additional amount of nutrients for crop growth and development resulted in higher crude protein content and reduction in fibre fractions neutral detergent fibre and acid detergent fibre. Similar findings were reported by Choudhary et al. (2024) who observed an increase in energy fractions of fodder crops attributed to higher crude protein content and reduced neutral and acid detergent fibre levels, which are indirectly influenced by nutrient availability for plant uptake and growth.

In the present study, the highest yield in treatment T_1 was due to the high amount of available N supply through fertilizers during all three (2018–19 to 2020–21) years of experimentation (Wang et al., 2019; Lu et al., 2021). During the first year, treatment T_7 recorded a significantly lower yield than treatment T_1, but during the second and third years of experimentation due to higher nutrient availability through increased microbial and enzymatic activities, increased decomposition of organic matter from FYM, activities of applied PGPR and additional supplementation of nutrients in the form of foliar spray of panchagavya resulted into increased nutrient uptake, growth, development, photosynthetic activities leading to increased green and dry fodder yield (Kumar et al., 2018; Baljeet Kumar et al., 2020; Gohil et al., 2023). In the case of berseem, treatment T_1 recorded higher yields due to the direct effects of applied N in the berseem crop whereas treatments T_7 and T_6 recorded higher yields due to residual effects of applied FYM in the preceding maize crop and application of PGPR and additional supplementation of nutrients through the foliar spray of panchagvya in berseem crop. Cowpea recorded maximum yield under treatment T_7 which was found at par with treatments T_1, T_6, and T_5 which was found significantly superior over all the other treatments during all 3 years of experimentation. Treatment T_1 recorded higher yields in cowpea primarily due to the direct effect of applied nitrogen. In contrast, treatments T_7 and T_6 achieved higher yields owing to the residual benefits of FYM applied in the preceding maize crop, along with the synergistic effects of PGPR and nutrient supplementation through foliar application of panchagavya. Kumar et al. (2020) reported that the application of FYM in rice crops resulted in residual effects on succeeding wheat crops and thereby enhanced the yield of wheat crops as well as improved the productivity of the rice-wheat system. PGPR improves nutrient availability imparts disease-pest resistance to the crop plants and improves the yield of the crop (Mishra et al., 2019) whereas foliar spray of panchagavya also provides additional nutrient supply to the crop plants (Gohil et al., 2023; Onte et al., 2025).

In the present study, treatment T_1 recorded the highest CEY compared to all the other treatments during all 3 years of experimentation (2018–19,2019–20, and 2020–21). Among treatments applied with integrated N application, treatment T_7 recorded the highest CEY during all 3 years of experimentation. The decrease in CEY was recorded at 4.33, 7.87, and 7.03% in treatment T_7 over T_1 during 2018–19, 2019–20, and 2020–21, respectively. Similar findings were reported by Krause et al. (2023).

For digestible crude protein content, treatment and T_7 recorded maximum followed by treatment T_6 during 2018–19. In 2019–20 and 2020–21, treatment T_7 recorded an increase in TDCP content to the tune of 3.05 and 3.48% over treatment T_1. Fertilizers provide an immediate and readily available source of nutrients, supporting normal plant growth and development while enhancing photosynthetic activity. Similar findings were reported in summer maize in China (Lu et al., 2021) and in crabgrass in two different physiographic regions (Sosinski et al., 2022). Further, treatment T_7 recorded a significant increase in TDCP content due to the increased nutrient availability from microbial and enzymatic activities, increased decomposition of organic matter through the combined effect of FYM application along with PGPR, and additional supplementation of nutrients in the form of foliar spray of panchagavya. Treatments, T_2 to T_6 due to low nutrient supply, reduced organic matter through FYM and without additional foliar supplementation of nutrients resulted in digestible crude protein content in fodder (Aher et al., 2022; Waqar et al., 2022).

Soil physicochemical and biological properties showed a strict and positive relative contribution in improving the energy fractions and fodder yields. Moreover, treatment T_7 showed distinction in effectiveness compared to fertilizers application alone and other combinations of FYM, PGPR, and foliar spray after N dose reduction through FYM. Applying FYM, PGPR adds organic matter and releases different growth hormones, resulting in enhanced microbial and enzymatic activity leading to sustained availability of nutrients for crop growth and development whereas application of foliar spray of panchagavya provides necessary nutritional supplementation to support the plant growth and development.

Conclusion

This study demonstrates that integrated application N application through FYM, PGPR, and panchagavya (T_7) in maize–berseem–cowpea cropping system significantly improved soil health, microbial activity, and nutrient availability, reinforcing the sustainability of organic nutrient management. While yield penalties were observed during the initial 2 years—particularly in fodder maize—these reductions were modest (up to 11.9%) and diminished by the third year. Notably, treatment T_7 achieved comparable or superior yields in berseem and cowpea, highlighting its potential as a resilient and ecologically sound alternative to chemical fertilization.

The findings affirm the original hypothesis that integrated nitrogen management under organic farming can maintain or enhance productivity while improving soil health and energy use efficiency. All stated objectives were successfully met, including enhancing ecosystem services and promoting sustainable intensification. This research provides evidence-based insights for policymakers and farmers seeking alternatives to conventional practices, particularly in organic systems aiming for long-term sustainability and reduced external input dependency.

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

SanK: Conceptualization, Investigation, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. SO: Data curation, Formal analysis, Investigation, Writing – original draft. YB: Conceptualization, Writing – review & editing. AA: Data curation, Writing – original draft. PP: Data curation, Formal analysis, Writing – original draft. KN: Writing – original draft, Formal analysis, Resources, Software, Data curation. KG: Writing – original draft, Visualization, Data curation. VM: Investigation, Writing – original draft, Resources, Methodology. RC: Writing – review & editing, Formal analysis. BM: Writing – review & editing, Formal analysis. MR: Writing – original draft, Data curation. SAK: Visualization, Writing – review & editing. SuK: Writing – original draft, Visualization. HO: Data curation, Writing – original draft. VK: Data curation, Visualization, Writing – review & editing. CS: Writing – original draft, Visualization, Methodology. EA: Visualization, Writing – review & editing. SM: Writing – review & editing, Data curation, Visualization. MH: Writing – review & editing, Data curation, Visualization. RM: Data curation, Writing – original draft, Visualization.

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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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1564945/full#supplementary-material

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