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Development of organic nutrients management system for profitable and soil-supportive French bean (*Phaseolus vulgaris* L.) farming in North Eastern Himalayas, India

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French bean (*Phaseolus vulgaris* L.) cultivation faces multipronged challenges of low farm productivity, poor economic returns, and soil health deterioration in the hilly ecosystem of India. Hence, the development of a cost-effective and soil-supportive French bean cultivation technology is highly warranted. Thus, a field experiment was conducted for two consecutive seasons in the Sikkim region of the Indian Himalayas to assess the impact of different organic nutrient sources on the production potential, profitability, and soil health of French bean. Eight organic nutrient management practices, *viz.,* farmers' practice, 100% recommended dose of nitrogen (RDN) through FYM, 100% RDN through mixed compost (MC), 100% RDN through vermicompost (VC), 50% RDN through FYM + 50% RDN through MC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through MC + 50% RDN through VC, and 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, were assigned in a three times replicated randomized complete block design. The results revealed that the supply of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC 33% recorded the highest pod yield (8.30 and 8.00 Mg ha^{-1}) and net returns (1,831 and 1,718 US$ ha^{-1}). Furthermore, the supply of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC 33% also had a positive impact on soil health. It was shown that an equal supply of RDN through FYM + MC + VC increases soil pH by 8.35%, SOC by 5.45%, available N by 6.32%, available P by 16%, available K by 9.92%, and micronutrients by 5–7% over farmers' practice. Thus, the supply of RDN through the integration of FYM + MC + VC in equal proportion is an economically robust and soil-supportive nutrients management practice for organic French bean production in the hilly ecosystem of North East India.

KEYWORDS

economic returns, organic farming, productivity, soil enzymes, vegetable

1. Introduction

Researchers and policy makers around the world are contending to achieve food and nutritional security along with environmental sustainability, particularly in hill and mountain ecoregions (Babu et al., 2020a). Soil quality deterioration contributes to an ever-widening loop of insufficient food production (Yadav et al., 2021a). To ensure food, nutritional, soil, and environmental security, contemporary production systems must move to eco-friendly production systems that combine a low ecological footprint with the production of more crops/commodities. Organic farming is a sustainable production approach that has less negative impacts on the environment, soil health, and energy consumption (Reganold and Wachter, 2016; Singh et al., 2021a). However, some researchers have observed lower crop productivity under organic farming than in the conventional farming system (De Ponti et al., 2012; Babu et al., 2023a), Yet the magnitudes of yield reduction mainly depend on the types and numbers of crops grown, agronomic management practices adopted, and soil and climatic conditions (Avasthe et al., 2020). The organic production system has good production potential to contribute to sustainable ecosystem services through better soil health (Singh et al., 2021b).

The major challenge in organic farming is the unavailability of quality organic nutrient sources for profitable crop production (Yadav et al., 2013a). Therefore, adequate nutrient supply is crucial for efficient crop production under organic farming (Babu et al., 2020b; Das et al., 2020). A satisfactory and consistent supply of nutrients to crops, from sowing to harvesting, is indispensable for better economic yield (Yadav et al., 2013b). Nutrient release and crop demand synchronization are critical in organic management conditions; thus, a complete understanding of nutrient release patterns from organic sources is critical to minimizing nutrient stresses (Babu et al., 2020b). Thus, the development and implementation of efficient organic fertilization protocols are pivotal for efficient organic crop production and to improve yield and income as well as overall soil health improvement (Saikia et al., 2018; Babu et al., 2020a).

The Indian Himalayan region is spread across the 13 Indian States/Union Territories (Jammu and Kashmir, Ladakh, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, Assam and West Bengal) and harbors ∼50 million people. The northeastern hill regions (NEHR) of India cover 26.23 Mha of the total geographical area of India. Agriculture in the NEHR is subsistence in nature and organic by default (Yadav et al., 2018). However, there is a huge amount of nutrient loss through runoff and leaching during the *Kharif* season, which creates a multinutrient deficiency in the soil (Singh et al., 2021a; Yadav et al., 2021b). The region is bestowed with abundant biomass due to its congenial environmental conditions, hence making it suitable for organic farming. In realizing the potential of organic farming in the region, the Government of India has launched the Central Sector Scheme Mission Organic Value Chain Development in the North Eastern Region (MOVCDNER) as a component of the 12th plan to promote organic farming in the region. Sikkim was named the first fully certified organic state in India by the Indian Government in 2016.

French bean (*Phaseolus vulgaris* L.) is a globally important leguminous crop and a rich source of dietary protein, vitamins, and different polyphenol compounds (Datt et al., 2013). It is one of the best vegetable crop for higher altitudes to cope with climate change (Babu et al., 2020d; Kumar et al., 2020; Singh et al., 2021b). In the Himalayan region, the French bean is a highly productive crop that responds well to inputs and has a high potential for intensive cropping systems (Gudade et al., 2022). However, the productivity and profitability of French bean is quite low under current agronomic management conditions mainly due to high intensity of weeds and poor nutrient management practices. Hence, adequate nutrient management is highly warranted to increase French bean productivity and profitability without deteriorating soil health.

Weeds generate huge quantities of biomass, which cannot be used as livestock feed due to their obnoxious nature. However, this nutrient-rich weed biomass can be used to make high-value organic manure. Co-composting of weed biomass with cow dung can potentially increase the crop yield and soil health and minimize the weed pressure in cropland (Singh et al., 2021b). Supplying the entire nutrient demand through a single organic source is exceedingly difficult under organic farming conditions (Yadav et al., 2013b). Hence, applying mixed compost developed through the co-composting of two or more nutrient sources in an integrated manner may reduce the production costs, increase crop productivity and profitability, and improve soil health (Singh et al., 2016). Several researchers have reported higher crop yield and better soil health with integrated organic nutrient management under different ecologies in various crops (Partha Sarathi et al., 2011; Yadav et al., 2013a; Das et al., 2017). However, these studies cannot be replicated in Sikkim region of Indian Himalayas due to variations in soil, climate, and management practices. Very little or no work in the Sikkim region of the Indian Himalayas has been performed so far on a comparative assessment of different organic sources on productivity, profitability, and soil health in acidic soils in French bean. Hence, it was hypothesized that the supply of the recommended nitrogen dose through the different organic sources in an integrated fashion will sustainably improve French bean productivity and profitability per unit of investment and soil health buildup. Keeping this in view, the present research work was undertaken with the following objectives: (1) To evaluate the effect of the integration of organic nutrient sources on the productivity and profitability of French bean, and (2) to study the effect of the supply of the recommended dose of nitrogen through different organic sources on soil health.

2. Materials and methods

2.1. Experimental site and climate

The field experiment was conducted for two consecutive seasons (2016 and 2017) at the research farm of ICAR Research Complex Sikkim Centre, Tadong, Sikkim. The research field was located at 1,300 m amsl at latitude 27°33′N and longitude 88°62′E (Figure 1). The climate of the study site was monsoonal with three distinct seasons, marked by a total annual rainfall of 2,996.9 mm. The average maximum temperature (29.1°C) of the study site was registered in August, while the average minimum temperature (7°C) was registered in January. The maximum relative humidity (91.7%) was recorded in July and the minimum in January (34.3%).

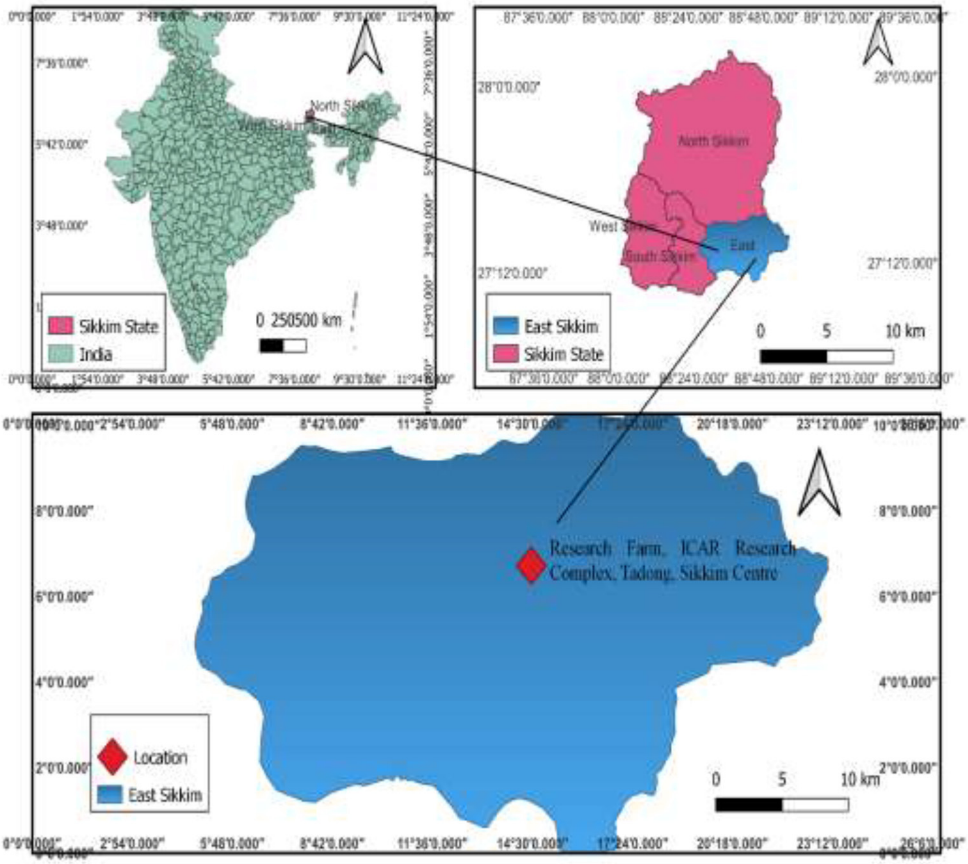

FIGURE 1
Study site in Eastern Himalayan region.

Before the commencement of the field experiment, the soil was sampled up to 0–15 cm depth for analysis of its physico-chemical and biological properties. The *Haplumbrept* soil of the study site was acidic (pH 5.82), with a high SOC content (1.71%), available N (364 kg ha^{-1}), P (17.4 kg ha^{-1}), K (223 kg ha^{-1}), Fe (6.42 mg kg^{-1}), Mn (7.96 mg kg^{-1}), Zn (1.22 mg kg^{-1}). The soil biological activities (0–15 cm depth) comprised SMBC (294 μg g^{-1} soil), DHA (20.9 μg TPF g^{-1} soil h^{-1}), acid phosphates activities (17.6 μg PNP g^{-1} soil h^{-1}), FDA (6.7 μg FDA g^{-1} soil h^{-1}), ureases (95 μg NH_4-N g^{-1}soil h^{-1}), and β-glucosidase activities (60.2 μg PNP g^{-1} soil h^{-1}).

2.2. Experimental design and crop management

Eight organic nutrient management practices, *viz.,* farmers' practice (FYM ∼50% RDN), 100% RDN through FYM, 100% RDN through mixed compost (MC), 100% RDN through vermicompost (VC), 50% RDN through FYM + 50% RDN through MC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through MC + 50% RDN through VC, and 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, were tested in a three times replicated randomized block design (RBD). French bean "SKR-57A" was sown manually at a seed rate of 100 kg ha^{-1} with a geometry of 30 cm × 10 cm during the second fortnight of September during both years. Thinning and gap-filling were performed 10 days after sowing (DAS) to maintain the optimum plant population. To provide an ideal weed-free environment for the crop, two hand weeding was performed at 20–25 and 40–45 DAS. Nutrient management was conducted as per the treatments. The recommended nitrogen (N) was @ 80 kg N ha^{-1}. The average nutrient composition (N, P and K) of the different manures are given in Supplementary Table 1. Irrespective of the fertility treatments, dolomite was applied @ 2 Mg ha^{-1} 10 days before the sowing of the crop for neutralizing the soil pH. Similarly, for control of red ant infestation, drenching with phytoneem @ 5 ml L^{-1} of water was performed. Meanwhile, the pod borer and aphids were managed by foliar application of Spinosad 45% EC @ 0.5 ml L^{-1}. Life saving irrigation was given during both years as and when required.

2.3. Preparation of mixed compost

Four predominant weed flora (*Artemisia vulgaris, Eupatorium odoratum, Ageratum conyzoides, and Galinsoga parviflora*) were collected from nearby areas. The collected weeds were heaped for a week, chopped with an electrically operated chaff cutter into 1–1.5 cm sizes, mixed thoroughly, and then stacked by spreading on the stone tiled floor. Fresh cow dung was collected from the dairy unit of the research farm. Thereafter, chopped weed biomass and cow dung were alternately placed in a 1-m-deep pit. The cow dung and weed biomass were mixed properly by adding a proper amount of water and then covered by a polythene sheet for decomposition. The heap was opened for heat release and aeration 48 h later. When the temperature and moisture became stationary below 45°C and 25%, respectively, the entire mass was kept for curing for about 20–25 days. Next, after 120–130 days, the matured co-composts were collected, processed, and stored for further chemical analysis and use in the field.

2.4. Yield measurement and financial analysis

Five plants were randomly selected and tagged from each plot to record the growth and yield-attributing parameters. The French bean green pods were ready for harvesting at 65–70 DAS. Thereafter, 2–3 pickings were performed at 8–10 days intervals. At each harvest, the green pod yield from the net plot was weighed separately and expressed as Mg ha^{-1}. Financial budgeting is the ultimate tool to judge the performance of any designed technology. The production system must be economically efficient for its wider adaptability. In the present investigation, the economic feasibility of different nutrient management systems was assessed in terms of the gross returns, net returns, benefit–cost ratio, and profitability. The cost of cultivation was computed based on the prevailing market prices of the inputs during the respective crop season. The gross returns were the monetary value of the output in terms of US dollar (US\$ ha^{-1}). Meanwhile, the net returns were obtained by subtracting the cost of cultivation from the gross returns, and the return per US\$ invested was obtained by dividing the gross returns by the cost of cultivation. The economics of the different treatments was calculated by using the following formulae:

$$\begin{aligned}&\text{Gross return (US \$ha}^{-1}\text{)}\\&= \text{Monetary return of pod yield (US \$ha}^{-1}\text{)}\\&+ \text{stover yield (US \$ha}^{-1}\text{)}.\end{aligned}$$

$$\text{Net return (US \$ha}^{-1}\text{)} = \text{Gross return (US \$ha}^{-1}\text{)} - \text{Total cost of cultivation (US \$ha}^{-1}\text{)}.$$

$$\text{Return per US\$ invested} = \frac{\text{Gross returns (US\$ ha}^{-1}\text{)}}{\text{Cost of cultivation (US\$ ha}^{-1}\text{)}}.$$

$$\mathit{Profitability}\ (US\$\ ha^{-1}\ day^{-1}) = \frac{\mathit{Net\ returns}\ (US\$\ ha^{-1})}{\mathit{Crop\ period}\ (days)}.$$

$$\text{Production efficiency}\left(\text{kg ha}^{-1}\text{ day}^{-1}\right) = \frac{\text{Pod yield of French bean (kg ha}^{-1}\text{)}}{\text{Crop period (days)}}.$$

2.5. Soil sampling

After completion of the experiment, the soil was sampled with a screw augur from the plow layer (0–15 cm depth) from each plot. Samples were collected from three places in each plot, mixed, and made into the composite soil sample. The collected samples were stored in zip-top plastic bags for carrying to the laboratory. After removing the visible pieces of crop residue and roots, the soil samples were air-dried and sieved through 2 mm sieve. Part of the representative soil samples were kept at 4°C for microbial analysis.

2.6. Analysis of physical properties of soil

The bulk density (pb) of the surface (0–15 cm) soil was determined by the core sampler (Piper, 1950) from three randomly chosen points of each plot. The procedure for determining the pb was followed according to that described by Chopra and Kanwar (1991). Aggregate stability was measured using wet sieving technique (Haynes, 1993). The results were expressed as the mean weight diameter (MWD), which is the sum of the fraction of soil remaining on each sieve after sieving for the standard time multiplied by the mean weight diameter of the adjacent sieve aperture, that is, the mean weight diameter (MWD) = (fraction of sample on sieve × mean inter sieve aperture). The upper and lower limits of the mean weight diameter, in this case, covered 6 and 1.15 mm, respectively.

2.7. Analysis of chemical properties of soil

The pH was determined in the soil water (1:2.5) suspension at 25°C using a glass electrode pH meter after equilibrating for 30 mins (Jackson, 1973). Soil organic carbon (SOC) was determined by the wet oxidation method (Walkley and Black, 1934). The available N, P, and K were estimated by the methods outlined by Prasad et al. (2006) and expressed in kg ha^{-1}. The diethylene tetra-amine penta-acetic acid (DTPA) extraction method was used to determine the available Fe, Mn, and Zn (Lindsay and Norwell, 1978).

2.8. Analysis of soil biological properties

Soil microbial activity, expressed as fluorescein diacetate hydrolysis (FDA) was determined (Green et al., 2006). Acid phosphomonoesterase activity were determined by the p-nitrophenol release by use of analog substrate methods (Tabatabai, 1994). The β-glucosidase activity was determined by the method described by Eivazi and Tabatabai (1988). Soil urease activity was assayed by the method of Tabatabai (1994). Soil microbial biomass carbon (SMBC) was estimated following the chloroform fumigation–extraction method (Vance et al., 1987). Dehydrogenase activity was estimated by monitoring the rate of production of tri-phenyl formazan (TPF) from tri-phenyl tetrazolium chloride (TTC), which was used as an electron acceptor (Klein et al., 1971).

2.9. Principal component analysis

To detect the effect of different organic sources of nutrients on yield attributes and soil properties, a principal component analysis (PCA) was conducted using the biplot method in Matlab R2019b version 9.7 (Math Works Inc., USA). An orthogonal set of novel orthogonal variables titled (PC) was assigned to significant information extracted from the data using PCA, which is a multivariate analytical tool that analyzes data through numerous interrelated quantitative dependent variables and shows the configuration of the relationship between the observations and the variables. The components of the PCs with high eigenvalues are best suited for identifying variation in the system, retaining only the components with eigenvalues ≥ 1.

2.10. Statistical analysis

In this study, all the data were analyzed by using the general linear model procedures within the Statistical Analysis System 9.3 software package (SAS Institute, Cary, NC). The comparison of treatment means was performed using the least significant difference (LSD) test at $p < 0.05$. The significance of the treatment effects was evaluated by using an F-test, and the significance of differences was assessed by calculating the least significant difference (LSD) using the formula given below:

$$LSD = \sqrt{2EMS \times t \ at \ a \ 5\% \ level \ of \ significance}/n.$$

Where MSE = mean square error, n = the number of observations of that factor for which LSD is to be calculated, and t = value of percentage point of “t” distribution for error degrees of freedom at a 5% level of significance.

3. Results

3.1. Growth parameters

Significantly higher plant height (40.9 cm and 41.3 cm) was recorded under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC as compared to farmers’ practice and 100% RDN through FYM but it remained at par with other treatments. Integrated supply of the recommended nitrogen dose in equal proportion through the application of FYM + MC + VC increased the plant height by 25.6% (2-year mean) as compared to farmers’ practice (Table 1). During the first year, significantly less days to 50% flowering (34 days) was observed in farmers’ practice followed by 50% RDN through MC + 50% RDN through VC, 50% RDN through FYM + 50% RDN through VC, and 33% RDN through FYM + 33% RDN through MC + 50% RDN through VC, while during the second year, less days to 50% flowering (35 days) was observed in farmers’ practice, which was statistically at par with 50% RDN through MC + 50% RDN through VC, 50% RDN through MC + 50% RDN through VC and 33% RDN through FYM +33% RDN through MC + 33% RDN through VC and significantly higher than other treatments, respectively. Based on two years of study, farmers’ practice recorded significantly less days to 50% flowering (34.3 days) followed by 50% RDN through FYM + 50% RDN through MC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through MC + 50% RDN through VC, and 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC as compared to other treatments, respectively.

3.2. Yield attributes and crop productivity

During the first year, a significant maximum number of branches plant^{-1} (5.30) was observed with the supply of RDN through farmyard manure (FYM) + mixed compost (MC) + vermicompost (VC) in equal proportion, followed by 100% RDN through FYM (Table 1). However, during the second year, a significantly higher branches plant^{-1} (5.37) was registered under 100% RDN through MC as compared to the other treatments, except for 100% RDN through VC and 50% RDN through FYM + 50% RDN through MC. The integrated supply of RDN through FYM 33% + MC 33% + VC 33% recorded a significantly higher number of branches plant^{-1} (5.34) (2 years mean), followed by 100% RDN through VC and 50% RDN through FYM + 50% RDN through MC. A significantly higher number of pods plant^{-1} (8.90 and 9.03, respectively) was recorded under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, as compared to other treatments, but remained statistically at par with 100% RDN through VC during both the years of study. The maximum pod weight (11.5 g) was attained under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, which was statistically at par with 100% RDN through VC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through MC + 50% RDN through VC5, and 100% RDN through FYM and significantly higher than other treatments during the first year. Meanwhile, during the second year, a significantly higher pod weight (11.8 g) was noticed under 33% RDN through FYM +33% RDN through MC + 33% RDN through VC as compared to other treatments, respectively. On a 2 years mean basis, the maximum pod weight (11.7 g) was noticed under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, which was statistically at par with 100% RDN through VC and 50% RDN through FYM + 50% RDN through VC and significantly higher than other treatments, respectively. Across the study, the fresh pod yield of French bean under different organic sources of nutrients varied from 3.67 to 8.30 Mg ha^{-1}. The supply of RDN through FYM + MC + VC in equal proportion recorded a significantly higher fresh pod yield (8.30 and 8.00 Mg ha^{-1}, respectively), which was statistically at par with 100% RDN through VC and significantly higher than other treatments, respectively (Table 1). During both years of the study, the lowest fresh pod yield (3.93 and 3.67 Mg ha^{-1}, respectively) was recorded under farmers’ practice.

3.3. Economic returns

The plot that received 100% RDN through VC incurred the maximum production cost as compared to the organic nutrients applied through other sources; the increase was 5.7–37.3% higher (2 years mean basis) (Figure 2). On the contrary, the plot that

TABLE 1 Effects of conjoint application of organic sources of nutrients on growth, yield attributes, and yield of French bean crop.

Treatment	Plant height at 60 DAS (cm)			Days to 50% flowering			Branches plant^{-1}			Pods plant^{-1}			Pod length (cm)			Pod weight (g)			Fresh pod yield (Mg ha^{-1})		
	2016	2017	Pooled mean	2016	2017	Pooled mean	2016	2017	Pooled mean	2016	2017	Pooled mean	2016	2017	Pooled mean	2016	2017	Pooled mean	2016	2017	Pooled mean
Farmers' practice	33.0	32.3	32.7	33.9	34.6	34.3	4.10	4.17	4.14	5.93	5.73	5.83	8.47	8.20	8.34	8.60	8.63	8.62	3.93	3.67	3.80
100% RDN through FYM	36.8	37.3	37.1	37.7	38.3	38.0	4.77	4.87	4.82	7.43	6.90	7.17	9.70	9.73	9.72	10.7	10.3	10.5	7.43	7.13	7.28
100% RDN through MC	39.0	39.8	39.4	35.3	36.3	35.8	5.20	5.23	5.22	7.97	8.27	8.12	9.30	9.27	9.29	10.6	10.5	10.6	6.53	6.27	6.40
100% RDN through VC	39.0	38.4	38.7	37.1	37.9	37.5	5.10	5.17	5.14	8.70	8.60	8.65	9.90	9.97	9.94	11.0	10.8	10.9	8.10	7.83	7.97
50% RDN through FYM + 50% RDN through MC	40.1	40.9	40.5	35.8	36.1	36.0	4.97	5.07	5.02	7.63	7.87	7.75	9.63	9.83	9.73	10.6	10.5	10.6	6.97	7.07	7.02
50% RDN through FYM + 50% RDN through VC	39.9	40.6	40.3	34.9	35.6	35.3	4.73	4.87	4.80	7.53	7.60	7.57	9.63	9.87	9.75	10.8	10.8	10.8	7.53	7.20	7.37
50% RDN through MC + 50% RDN through VC	40.5	41.2	40.9	34.1	35.0	34.6	4.70	4.77	4.74	8.00	7.83	7.92	9.37	8.93	9.15	10.7	10.5	10.6	7.03	6.90	6.97
33% RDN through FYM + 33% RDN through MC + 33% RDN through VC	40.9	41.3	41.1	36.4	37.2	36.8	5.30	5.37	5.34	8.90	9.03	8.97	10.6	10.3	10.5	11.5	11.8	11.7	8.30	8.00	8.15
SEm±	1.18	1.36	1.27	0.45	0.81	0.63	0.18	0.14	0.16	0.21	0.27	0.24	0.27	0.30	0.29	0.29	0.32	0.31	0.22	0.20	0.21
LSD ($p = 0.05$)	3.57	4.13	3.85	1.35	2.45	1.90	0.55	0.43	0.49	0.61	0.75	0.68	NS	NS	NS	0.88	0.91	0.90	0.67	0.63	0.65

FYM, farmyard manure; MC, mixed compost; VC, vermicompost; RDN, recommended dose of nitrogen.

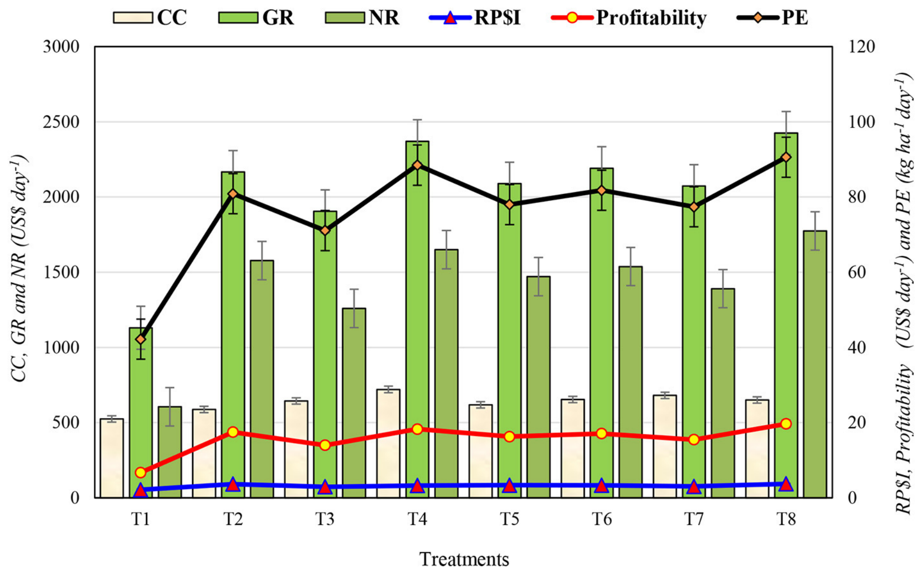

FIGURE 2
Effect of the conjoint application of different organic sources of nutrients on profitability of French bean crop (2 years pooled mean value). CC, cost of cultivation; GR, gross return; NR, net return; RP$I, return per US$ invested; PE, production efficiency; T1—farmers' practice (FYM ~50% RDN); T2—100% RDN through FYM; T3—100% RDN through mixed compost (MC); T4—100% RDN through vermicompost (VC); T5—50% RDN through FYM + 50% RDN through MC; T6—50% RDN through FYM + 50% RDN through VC; T7—50% RDN through MC + 50% RDN through VC; T8—33% RDN through FYM + 33% RDN through MC + 33% RDN through VC.

received ~50% RDN through FYM (farmer's practices) had the least cost of cultivation (528–522 US$ ha^{-1}) during both the years. Gross returns from different organic sources of nutrients varied between 1,131 and 2,426 US$ ha^{-1}. The integrated supply of RDN through FYM + MC + VC in equal proportion (33% + 33% + 33%) recorded significantly higher gross returns (2,485 US$ ha^{-1}and 2,366 US$ ha^{-1}), followed by 100% RDN through VC (2,426 US$ ha^{-1} and 2,316 US$ ha$^{-1)}$ and 50% RDN through FYM + 50% RDN through VC (2,255 US$ ha^{-1}and 2129US$ ha$^{-1)}$, respectively. Similarly, the application of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC recorded maximum net returns (1,831 US$ ha^{-1}); however, it was statistically at par with 100% RDN through VC, 50% RDN through FYM + 50% RDN through VC, and 100% RDN through FYM and remained significantly higher than other treatments in the first year. During the second year, significant maximum net returns (1,718 US$ ha^{-1}) were registered under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC. The return per US$ invested in different organic sources of nutrients varied from 2.08 to 3.80 across the study year (Figure 2). However, during the first year, a significant maximum return per US$ invested (3.80) was noticed under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC followed by 100% RDN through FYM. Meanwhile, during the second year, the highest return per US$ invested (3.65) was observed under the same application of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, which was statistically at par with 100% RDN through FYM and 50% RDN through FYM + 50% RDN through VC and significantly higher than rest of the treatments, respectively. Across the study year the conjoint application of organic sources of nutrients had a significant effect on the profitability of the French bean crop. During both the years, the application of 33% RDN through FYM + 33% RDN through MC +33% RDN through VC recorded significantly higher profitability (20.3 US$ ha^{-1} day^{-1} and 19.1 US$ ha^{-1} day^{-1}), followed by 100% RDN through VC. Concerning production efficiency, the application of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC recorded the maximum production efficiency (92.2 kg ha^{-1} day^{-1}); however, it remained statistically at par with 100% RDN through VC but significantly superior over the treatments. Similarly, during the second year, a significantly higher production efficiency of 88.9 kg ha^{-1} day^{-1} was recorded under the 33% RDN through FYM + 33% RDN through MC +33% RDN through VC, followed by 100% RDN through VC.

3.4. Soil health

The application of different organic sources of nutrients had failed to affect the soil pb significantly after two years of cropping. Soil aggregation was measured and expressed in terms of the mean weight diameter (MWD), soil aggregates (>0.25 and <0.25 mm), and total water-stable aggregates (TWSA), which were influenced significantly ($p < 0.05$) by the conjoint application of the organic sources of nutrients (Figure 3). The application of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC recorded the significantly highest amount of the percentage of >0.25 mm soil aggregates (38.6%) at 0–0.15 m soil depth, followed by 100% RDN through VC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through FYM + 50% RDN through MC, 50% RDN through MC + 50% RDN through VC, and 100% RDN through FYM. The significantly highest value of the percentage of <0.25 mm soil aggregates (49.1%) and TWSA (87.7%) at 0–0.15 m

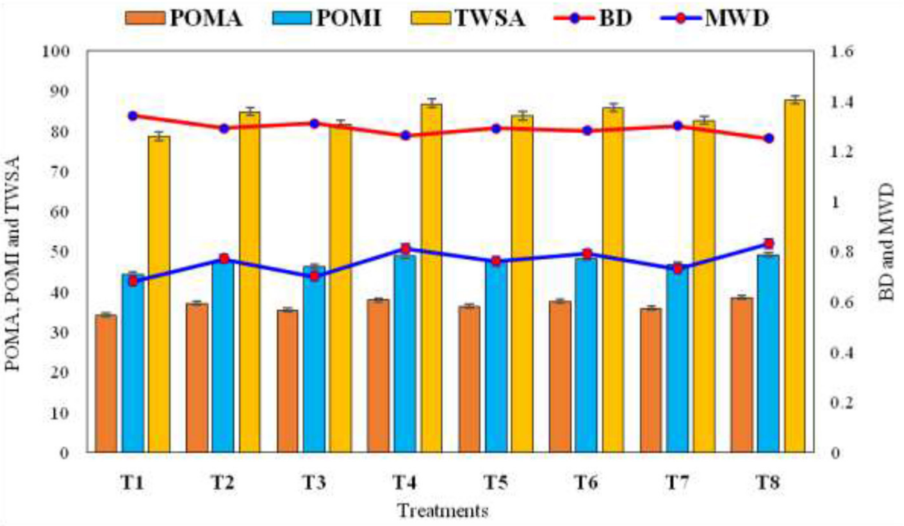

FIGURE 3
Effect of the conjoint application of different organic sources of nutrients on the physical properties of the soil after completion of the two years cropping system. POMA, percentage of macroaggregates (>0.25 mm); POMI, percentage of microaggregates (<0.25 mm); TWSA, total water-stable aggregates; BD, bulk density (Mg m^{-3}); MWD, mean weight diameter (mm); T1—farmers' practice (FYM ~50% RDN); T2—100% RDN through FYM; T3—100% RDN through mixed compost (MC); T4—100% RDN through vermicompost (VC); T5—50% RDN through FYM + 50% RDN through MC; T6—50% RDN through FYM + 50% RDN through VC; T7—50% RDN through MC + 50% RDN through VC; T8—33% RDN through FYM + 33% RDN through MC + 33% RDN through VC.

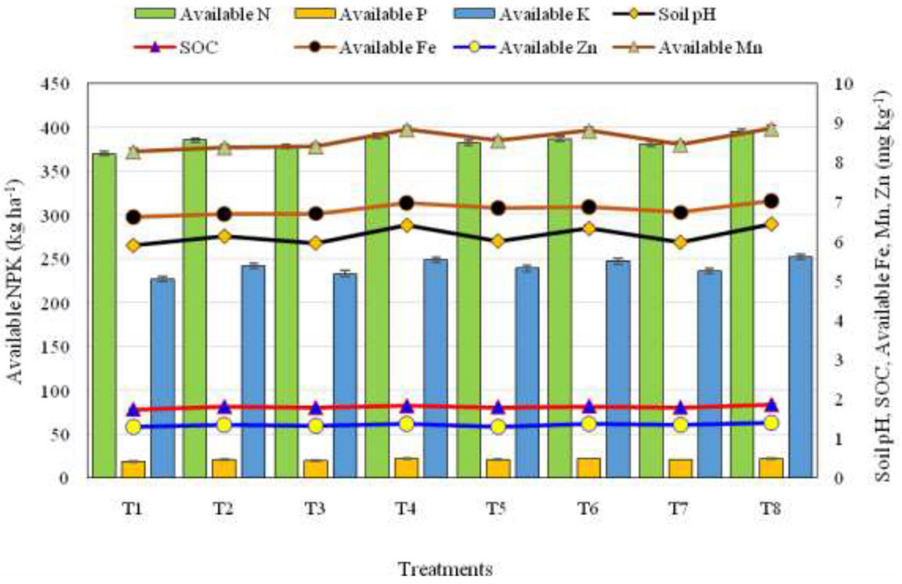

FIGURE 4
Effect of the conjoint application of different organic sources of nutrients on the chemical properties of the soil after completion of the two years cropping system. SOC, soil organic carbon (%); T1—farmers' practice (FYM ~ 50% RDN); T2—100% RDN through FYM; T3—100% RDN through mixed compost (MC); T4—100% RDN through vermicompost (VC); T5—50% RDN through FYM + 50% RDN through MC; T6—50% RDN through FYM + 50% RDN through VC; T7—50% RDN through MC + 50% RDN through VC; T8—33% RDN through FYM + 33% RDN through MC + 33% RDN through VC.

soil depth was noticed under FYM 33% + MC 33% + VC 33% RDN, followed by 100% RDN through VC, as compared to farmers' practice. The maximum MWD (0.83 mm) was noticed under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, which was statistically at par with 100% RDN through VC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through FYM + 50% RDN through MC, and 100% RDN through FYM and significantly higher than other treatments, respectively.

Continuous application of different organic sources for two years had a significant effect on the soil pH (Figure 4). Significantly

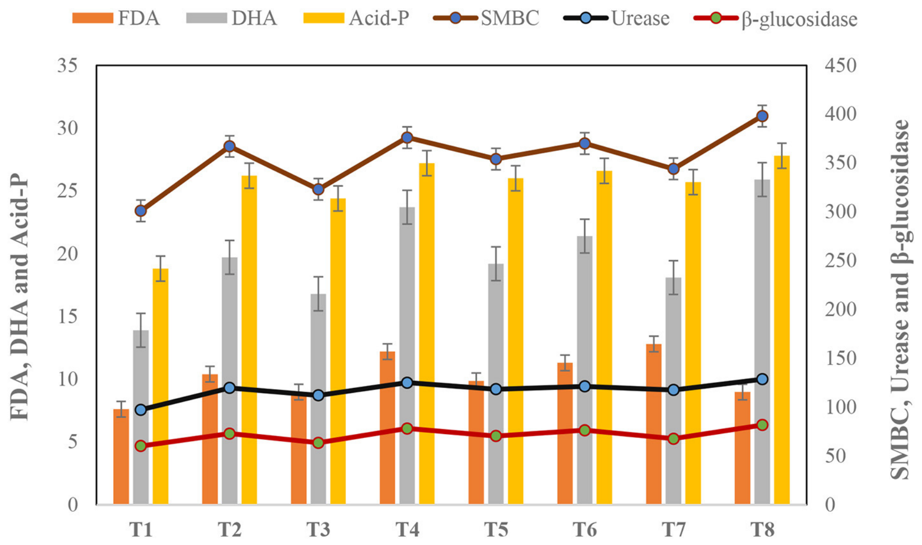

FIGURE 5
Effect of the conjoint application of different organic sources of nutrients on the biological properties of the soil after completion of the two years cropping system. SMBC, soil microbial biomass carbon (μg g^{-1} soil); FDA, mg kg^{-1} soil h^{-1}; DHA, μg TPF g^{-1} soil h^{-1}; Acid-P, μg PNP g^{-1} soil h^{-1}; Urease, μg NH$_4$-N g^{-1}soil h^{-1}; β-glucosidase, μg PNP g^{-1} soil h^{-1}; T1—farmers' practice (FYM ~50% RDN); T2—100% RDN through FYM; T3—100% RDN through mixed compost (MC); T4—100% RDN through vermicompost (VC); T5—50% RDN through FYM + 50% RDN through MC; T6—50% RDN through FYM + 50% RDN through VC; T7—50% RDN through MC + 50% RDN through VC; T8—33% RDN through FYM + 33% RDN through MC + 33% RDN through VC.

higher soil pH (6.43) and SOC was registered under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC. The integration of different organic manures had a significant effect on the available N, P, and K in the soil at 0–15 cm soil depth after the end of the two cropping seasons (Figure 4). Significantly higher available N (395 kg ha^{-1}) in the soil was noticed under the integrated supply of RDN through FYM + MC + VC in equal proportion, followed by 100% RDN through VC, 50% RDN through FYM + 50% RDN through VC, 50% RDN through FYM + 50% RDN through MC, and 100% RDN through FYM, respectively. Similarly, significantly higher available P (22.3 kg ha^{-1}) and available K (252 kg ha^{-1}) were also observed under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC.

The integrated use of organic manures had a significant impact on soil micronutrient availability. Significantly higher amounts of available Fe (7.03 mg kg^{-1}), available Zn (1.40 mg kg^{-1}), and available Mn (8.85 mg kg^{-1}) were recorded under 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC, followed by 100% RDN through VC and 50% RDN through FYM + 50% RDN through VC, respectively. Furthermore, the application of different organic sources of nutrients in integration had a significant effect on SMBC, FDA, DHA, acid-P, urease, and β-glucosidase in the soil at 0–15 cm soil depth after the end of two years of French bean cultivation (Figure 5). A conjoint supply of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC exhibited significantly higher SMBC (398 μg g^{-1} soil) acid-P (27.8 μg PNP g^{-1} soil h^{-1}) in the soil, followed by 100% RDN through VC and 50% RDN through FYM + 50% RDN through VC, respectively.

3.5. Correlation analysis

A Pearson's correlation analysis was conducted between the soil's physical, chemical, and biological properties to predict the relationship and dependency between the variables. The results indicated that all the soil parameters showed the existence of a highly significant ($p < 0.01$) positive correlation among them. However, the pb exceptionally exhibited a highly significant ($p < 0.01$) negative correlation with the rest of the parameters under investigation, indicating a desirable soil character required for an ideal soil physical condition (Table 2).

3.6. Principal component analysis

In our study, the PCA exercised on the tested parameters explained up to 98.4% of total variability, thereby extracting two principal components, PC1 and PC2, which explained 71.8% and 26.6% of the total variability with an eigenvalue >1. The biplot (Table 3, Figure 5) generated from principal component analysis clearly showed that the available N, SOC, K, and P had a strong loading on PC1 (Table 3, Figure 6), while PC2 exhibited comparatively greater loadings on acid-P and soil pH, respectively.

TABLE 2 Correlation matrix between soil physical, chemical, and biological properties.

	BD	POMA	POMI	TWSA	MWD	Soil pH	SOC	Available N	Available P	Available K	Available Fe	Available Zn	Available Mn	SMBC	FDA	DHA	Acid-P	Urease	β-glucosidase
BD	1.000	−0.979	−0.976	−0.983	−0.971	−0.909	−0.955	−0.933	−0.995	−0.957	−0.920	−0.974	−0.958	−0.977	−0.971	−0.991	−0.961	−0.967	−0.972
POMA	−0.979	1.000	0.979	0.995	0.987	0.888	0.911	0.932	0.986	0.963	0.935	0.961	0.954	0.973	0.957	0.977	0.959	0.959	0.979
POMI	−0.976	0.979	1.000	0.995	0.992	0.923	0.941	0.950	0.982	0.982	0.963	0.990	0.990	0.976	0.983	0.987	0.935	0.926	0.999
TWSA	−0.983	0.995	0.995	1.000	0.995	0.910	0.931	0.947	0.990	0.978	0.955	0.981	0.977	0.980	0.975	0.987	0.952	0.947	0.994
MWD	−0.971	0.987	0.992	0.995	1.000	0.895	0.902	0.956	0.974	0.962	0.947	0.985	0.983	0.971	0.970	0.973	0.949	0.939	0.994
Soil pH	−0.909	0.888	0.923	0.910	0.895	1.000	0.891	0.780	0.917	0.964	0.957	0.937	0.939	0.924	0.948	0.947	0.768	0.782	0.910
SOC	−0.955	0.911	0.941	0.931	0.902	0.891	1.000	0.883	0.962	0.943	0.903	0.929	0.910	0.945	0.949	0.965	0.900	0.901	0.933
Available N	−0.933	0.932	0.950	0.947	0.956	0.780	0.883	1.000	0.924	0.885	0.840	0.941	0.924	0.897	0.901	0.916	0.964	0.947	0.950
Available P	−0.995	0.986	0.982	0.990	0.974	0.917	0.962	0.924	1.000	0.974	0.943	0.972	0.959	0.986	0.978	0.996	0.954	0.958	0.979
Available K	−0.957	0.963	0.982	0.978	0.962	0.964	0.943	0.885	0.974	1.000	0.981	0.970	0.970	0.970	0.977	0.986	0.878	0.880	0.976
Available Fe	−0.920	0.935	0.963	0.955	0.947	0.957	0.903	0.840	0.943	0.981	1.000	0.956	0.970	0.969	0.978	0.959	0.832	0.822	0.964
Available Zn	−0.974	0.961	0.990	0.981	0.985	0.937	0.929	0.941	0.972	0.970	0.956	1.000	0.993	0.974	0.988	0.983	0.919	0.914	0.987
Available Mn	−0.958	0.954	0.990	0.977	0.983	0.939	0.910	0.924	0.959	0.970	0.970	0.993	1.000	0.967	0.983	0.973	0.895	0.883	0.989
SMBC	−0.977	0.973	0.976	0.980	0.971	0.924	0.945	0.897	0.986	0.970	0.969	0.974	0.967	1.000	0.993	0.986	0.927	0.924	0.978
FDA	−0.971	0.957	0.983	0.975	0.970	0.948	0.949	0.901	0.978	0.977	0.978	0.988	0.983	0.993	1.000	0.988	0.904	0.899	0.982
DHA	−0.991	0.977	0.987	0.987	0.973	0.947	0.965	0.916	0.996	0.986	0.959	0.983	0.973	0.986	0.988	1.000	0.929	0.933	0.982
Acid-P	−0.961	0.959	0.935	0.952	0.949	0.768	0.900	0.964	0.954	0.878	0.832	0.919	0.895	0.927	0.904	0.929	1.000	0.994	0.938
Urease	−0.967	0.959	0.926	0.947	0.939	0.782	0.901	0.947	0.958	0.880	0.822	0.914	0.883	0.924	0.899	0.933	0.994	1.000	0.925
β-glucosidase	−0.972	0.979	0.999	0.994	0.994	0.910	0.933	0.950	0.979	0.976	0.964	0.987	0.989	0.978	0.982	0.982	0.938	0.925	1.000

POMA, percentage of macroaggregates (>0.25 mm); POMI, percentage of microaggregates (<0.25 mm); TWSA, total water-stable aggregates; BD, bulk density (Mg m^{-3}); MWD, mean weight diameter (mm); SMBC, soil microbial biomass carbon (µg g^{-1} soil); FDA, mg kg^{-1} soil h^{-1}; DHA, µg TPF g^{-1} soil h^{-1}; Acid-P, µg PNP g^{-1} soil h^{-1}; Urease, µg NH_4-N g^{-1}soil h^{-1}; β-glucosidase, µg PNP g^{-1} soil h^{-1}.

TABLE 3 Principal component analysis of physical, chemical, and biological properties of soil (after completion of two years).

Principal components		PC1	PC2
Initial Eigenvalues	Total	13.64	5.07
	% of Variance	71.80	26.66
	Cumulative %	71.80	98.46
Extraction sums of squared loadings	Total	13.64	5.07
	% of Variance	71.80	26.66
	Cumulative %	71.80	98.46
Factor loadings[a]			
Eigen vectors[b]		**PC1**	**PC2**
BD		0.794	−0.607
POMA		0.698	0.178
POMI		0.683	0.170
TWSA		0.796	0.440
MWD		0.711	−0.584
Soil pH		0.864	0.603
SOC		0.983	−0.588
Available N		0.998	0.179
Available P		0.973	−0.003
Available K		0.980	0.525
Available Fe		0.806	−0.421
Available Zn		0.817	−0.576
Available Mn		0.798	−0.440
SMBC		0.979	0.108
FDA		0.813	−0.580
DHA		0.783	0.156
Acid-P		0.709	0.675
Urease		0.972	0.161
β-glucosidase		0.707	0.409

POMA, percentage of macroaggregates (>0.25 mm); POMI, percentage of microaggregates (<0.25 mm); TWSA, total water-stable aggregates; BD, bulk density (Mg m^{-3}); MWD, mean weight diameter (mm); SMBC, soil microbial biomass carbon (μg g^{-1} soil); FDA, mg kg^{-1} soil h^{-1}; DHA, μg TPF g^{-1} soil h^{-1}; Acid-P, μg PNP g^{-1} soil h^{-1}; Urease, μg NH_4-N g^{-1} soil h^{-1}; β-glucosidase, μg PNP g^{-1} soil h^{-1}.

In the Ist quadrant, the higher loading variables were found to be clustered together in a group, and these parameters were highly correlated to each other.

4. Discussion

Crop production capacity mainly depends on the nature of genotypes, climatic and agronomic management practices (Ghani et al., 2022a). French bean is a nutrient-loving short-duration winter crop that requires better nutrient management practices to explore its full potential under organic management conditions (Kumar D. et al., 2015; Singh and Chaudhary, 2016). There are significant opportunities to increase soil fertility, input-use efficiency, and crop productivity by adopting the conjoint application of organic sources of nutrients with field-specific recommendations (Babu et al., 2020c). Organic nutrient management is considered an important activity, as it helps to enhance the growth and productivity of the French bean crop and to improve the physical, chemical, and biological properties of soil (Singh et al., 2018). In French beans, instead of a single source of nutrients, applying different organic sources of nutrients in an integrated manner has been shown to increase crop productivity and improve soil health (Sharma et al., 2014; Singh et al., 2016). The constant supply of nutrients through organic sources into the active nutrients pool of soils developed a vigorous root system, resulting in the better growth and development of plants and better diversion of photosynthates from the source to sink; thus, the combined use of organic sources might be much more advantageous for healthy growth and timely flowering in crops (Aziz et al., 2019; Ghani et al., 2022b). In the present study, the conjoint application of organic sources of nutrients had a significant effect on the plant height and days to 50% flowering. The integrated supply of the recommended nitrogen dose through FYM, MC, and VC (FYM 33% + MC 33% + VC 33% RDN) increased the plant height and duration of days to 50% flowering compared to single source. The integration of vermicompost, FYM, rock phosphate, and *Rhizobium* facilitates the adequate nutrient supply to French bean, resulting in better crop growth (Sharma et al., 2014). In contrast, the significantly poor French bean growth under the suboptimal nutritional treatment may have been because the root system might not have been active for efficient nutrient uptake during the period of active crop growth and development stages, resulting in reduced plant height and the crop reaching an early flowering stage (Guo et al., 2019). Under poor nutrient management conditions, leaf senescence started earlier due to the inadequate nutrient supply to the crops (Yadav et al., 2013b).

The combined application of FYM with vermicompost has been shown to result in 23% more crop yield and better soil health (Saikia et al., 2018). In the present study, the integration of different organic nutrient sources significantly increased the number of branches per plant, pods per plant, pod weight, and fresh pod yield over farmers' practice. The integrated use of FYM + VC gave 5.87% and 22.4% higher yields over the sole application of VC and FYM, respectively (Gulati and Barik, 2011). The conjoint application of organic sources of nutrients helped to provide adequate nutrient availability in the soil for a long time, which resulted in more cell differentiation, meristematic cell division, and translocation of food materials in plants, thereby resulting in a higher production of yield attributes and ultimately more yield (Singh et al., 2018). The combined application of organic sources of nutrients might have resulted in more growth hormones released that helped in the optimum fertilization of flowers and increased pollen grain viability, thereby increasing the pods per plant (Sajid et al., 2011; Singh et al., 2021b). The increase in seed yield under adequate nutrients supply might be ascribed mainly to the combined effect of higher plant height, more dry matter accumulation at different stages, more branches per plant, pods per plant, and higher pod weight, which were the result of the better translocation of photosynthates from

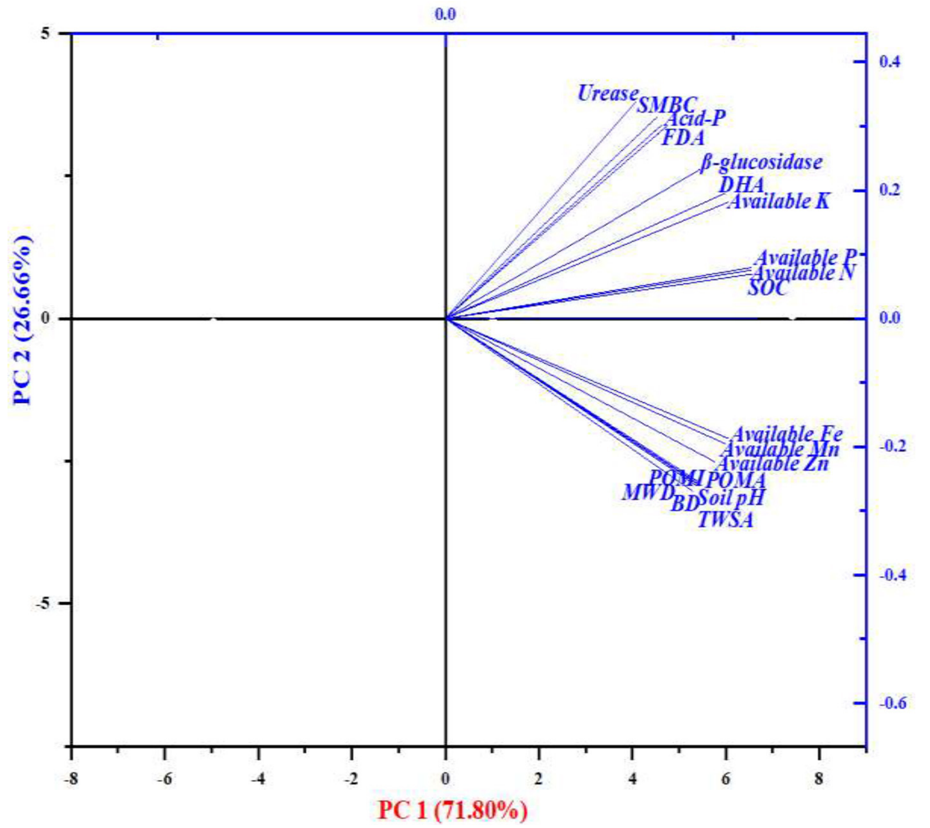

FIGURE 6
PCA of the physical, chemical, and biological properties of the soil. POMA, percentage of macroaggregates (>0.25 mm); POMI, percentage of microaggregates (<0.25 mm); TWSA, total water-stable aggregates; BD, bulk density (Mg m^{-3}); MWD, mean weight diameter (mm); SMBC, soil microbial biomass carbon (μg g^{-1} soil); FDA, mg kg^{-1} soil h^{-1}; DHA, μg TPF g^{-1} soil h^{-1}; Acid-P, μg PNP g^{-1} soil h^{-1}; Urease, μg NH$_4$-N g^{-1}soil h^{-1}; β-glucosidase, μg PNP g^{-1} soil h^{-1}.

the source to sink, and ultimately pod yield was increased (Singh et al., 2016, 2021a).

In the current study, the application of FYM 50% RDN resulted in the minimum cost of cultivation (525 US$ ha^{-1}) due to less input application, while the application of VC 100% RDN recorded the maximum cost of cultivation. The higher cost of cultivation due to VC was attributed to the higher cost of VC (Babu et al., 2020b). However, the integration of FYM + MC + VC in equal proportion as per the nitrogen content recorded considerably higher gross returns, net returns, and returns per US$ invested (73.5%), meaning it had greater profitability over the other nutrient management options. This may be attributed to the favorable effects of organic sources of nutrients on soil physico-chemical and biological properties, which augment the economic yield (Babu et al., 2023b). Datt et al. (2013) reported that the combined use of FYM + VC recorded 17.2% and 36.6% higher net returns over VC and FYM alone, respectively.

Integrated organic nutrient management helped to improve the soil properties, including those of physical, chemical, and biological nature (Patil et al., 2012). Among the physical properties, the soil pb and soil aggregation are very important components of soil health. In the present investigation, the conjoint application of organic sources of nutrients had a significant effect on the soil aggregation at the end of the two cropping cycles. The integrated supply of the recommended nitrogen dose through FYM 33% + MC 33% + VC 33% increased the soil aggregates >0.25 mm by 11.4%, soil aggregates <0.25 mm by 9.51%, TWSA by 10.4%, and MWD by 18%, as compared to farmers' practice. This might be due to the incorporation of mixed compost in the soil increasing the SOC and aeration that results in lower pb and better soil aggregation (Kumar R. et al., 2015). The application of integrated organic manure and straw has shown a positive effect on the stability of the aggregates in the soil (Singh et al., 2020).

Integrated use of the organic nutrient had a positive impact on the soil pH in acidic soil. The combined use of different organic sources might release several acids and bases, which may slightly modify the soil pH in acidic soil. Organic inputs are an important source of plant nutrients, especially N, and the supply of N from applied manures makes an important contribution to the nitrogen demand of growing crops (Jarvan et al., 2014). The supply of the recommended nitrogen dose through FYM 33% + MC 33% + VC 33% had a significant impact on the SOC available N, available P, available K, and micronutrients (Fe, Zn, and Mn) over farmers' practice. The organic nutrients that fertilized the plots gave better soil health, because organic sources of nutrients help to improve the water regimes, adsorption of nutrients, and soil structure (Babu et al., 2020b). Singh et al. (2018) reported that higher available N, P, and K were found in the plots where cattle dung manure was applied on a nitrogen equivalent basis.

The microbiomes and enzymes present in the soil play an important role in balancing the soil properties, ultimately helping in the overall process of decomposition in the soil system. In the present study, the soil biological properties in the surface layer (0–15 cm) were significantly affected by the conjoint application of organic sources of nutrients after the two cropping cycles. It was demonstrated that the integrated use of different organic sources may provide a constant substrate to the soil microbes, which may increase the soil enzymatic reactions. The integrated supply of nitrogen through FYM 33% + MC 33% + VC 33% considerably improved the SMBC, FDA, DHA, Acid-P, urease, and β-glucosidase over farmers' practice. The application of organic manures in the soil increases the soil's organic carbon content, which is an important source of food for soil microbiomes that results in more microbial population and enzymatic activity (Babu et al., 2020c).

Principal components analysis (PCA) is a statistical tool used to recognize patterns in data and analyze the resemblances and variances between the data (Mishra et al., 2017). In our study, the biplot (Figure 5) generated from the principal component analysis clearly showed that available N, SOC, K, and P had a strong loading on PC1, while PC2 exhibited comparatively greater loadings on acid-P and soil pH, respectively. In the Ist quadrant, the higher loading variables were found to be clustered together in a group, and these parameters were highly correlated with each other.

5. Conclusions

The findings prove the hypothesis that the integration of different organic sources of nutrients enhances French bean growth, productivity, and economic returns as well as soil healthy build-up. The combined use of various organic nutrient sources improves the plant growth, yield-attributing parameters, and fresh pod yield of French bean over farmers' practice. The integrated supply of the recommended dose of nitrogen through FYM 33% + MC 33% + VC 33% increases gross returns, net returns, and return per US$ invested compared to the single source-dependent nitrogen supply. Furthermore, the application of 33% RDN through FYM + 33% RDN through MC + 33% RDN through VC increases soil aggregation, soil pH, SOC, nutrient availability, and soil enzymatic reactions.

Thus, this study has suggested that the supply of 100% of the nitrogen demand of French bean through the integration of FYM + MC + VC in equal proportion (33% each) is economically viable and the best alternative option for profitable organic French bean production and maintaining the soil health in long run in the acidic soils of the Eastern Himalayas.

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

RS and AK: conceptualization, experimentation, and data analysis. SB: visualization, experimentation, data curation, writing of original and first draft, review, and editing. RA: supervision and project administration. SR and AD: data curation, review, and editing. CS, VS, and IB: review and editing. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1115521/full#supplementary-material

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