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Long-term impact of biofertilization on soil health and nutritional quality of organic *basmati* rice in a typic ustchrept soil of India

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Healthy soils are the foundation for producing healthy food and creating a healthy environment. Therefore, we assessed the changes in the physical and chemical properties of soil, and their long-term impact on yield, quality, and nutritional status of rice grains in an organic *basmati* rice-based cropping system in a typic Ustchrept Soil of India. The experiment was laid out in a strip plot design with three replications. The vertical strips consisted of two rice-based cropping systems, namely, *basmati* rice-wheat-mung bean (RWM) and *basmati* rice-wheat-*sesbania* (RWS), whereas seven combinations of different organic materials and biofertilizers (BF) were assigned to horizontal strips, *viz.*, control (no manure application), farmyard manure (FYM), vermicompost (VC), FYM + crop residues (CR), VC + CR, FYM + CR + BF, and VC + CR + BF. The results revealed that soil moisture content (SMC), soil organic carbon (SOC), soil total N, and soil available P, Fe, Zn, Mn, and Cu were significantly higher under the RWS system than in RWM. The application of organic manures either alone or in conjunction with CR and BF significantly lowered the soil pH (~3.0%), EC (43.1%–45.8%), and BD (3.3%–9.2%) as compared to the control. Water holding capacity (WHC), SMC, and SOC were increased by 5.7%–14.7%, 8.7%–49.3%, and 35.3%–76.5%, respectively under single or co-application of FYM/VC with CRs and BFs as compared to control. Similarly, sole or conjoint application of organic manures, CR, and BF significantly enhanced the soil available macro (N, P, and K) and micro (Fe, Zn, Mn, and Cu) nutrients over the control. Grain yield, protein content, N uptake, and cooking quality parameters were significantly higher under the RWS system than under RWM. However, the Zn concentration and its uptake by grains were significantly higher under the RWM system over RWS. The grain yield was significantly increased by 25.8%–49.2% under different organic nutrient management options over control. The single or conjoint application of FYM/VC with CR and BF increased the hulling, milling, head rice recovery, and protein concentration in grain by 9.4%–9.8%, 23.2%–28.4%, 22.7%–25.5%, and 9.6%–10.7%, respectively over control. The concentration of N, P, K, Fe, Zn, Mn, and Cu was significantly improved by 9.7%–11.3%, 45.5%–63.6%, 16.7%–20.8%, 66.9%–74.1%, 72.9%–81.9%, 87.1%–97.0%, and 48.9%–67.2%, respectively under co-application of FYM/VC with CR and BF compared to control. Thus, our results indicate that improved soil properties could significantly increase the physical and

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nutritional quality of *basmati* rice grain. Therefore, adopting *basmati* rice-based cropping systems with different organic nutrient sources can sustain soil health, end global hunger, produce nutritious food, and create a healthy environment.

KEYWORDS

basmati rice, grain quality, micronutrients, organic nutrient management, soil health

1 Introduction

Soil is a complex, heterogeneous, and non-renewable natural resource that provides fundamental ecosystem services for living beings (Brevik et al., 2020). It is a medium for plant growth and food production, a recycling hub for nutrients and organic matter, a habitat for soil microorganisms, a foundation for infrastructures, and a system for water supply and purification (Abrahams, 2002; Zornoza et al., 2015). Despite the fundamental services being provided by soil, unsustainable land use patterns caused widespread degradation of agricultural soils *via* loss of organic carbon, compaction, salinization, contamination, nutrient exhaustion, structural deterioration, etc., (Kibblewhite et al., 2008). Hence, the preservation of soil fertility and its health is crucial for sustainable food production. Moreover, soil health is directly or indirectly related to human health. Directly by the inhalation, ingestion, and absorption of the soil and indirectly through the quality and quantity of food produced from the soil (Brevik, 2009; Oliver and Gregory, 2015; Steffan et al., 2018). Therefore, the restoration and maintenance of soil health poses greater importance for the supply of essential nutrients, improves the immune system, and enhances human health.

Nutrient sufficiency is imperative for the good health, longevity of life, and productive lives of plants, animals, and human beings. The primary source of nutrient availability to people is the food produced from soil (Welch, 2002; Shrestha et al., 2020). If soils fail to produce quality food to fulfill the nutritional requirements of human beings, people's health will deteriorate and it will also affect national development. The global yields of staple food grains significantly increased during the 1960s. However, the pace between growth in calorie productivity and the production of nutrients needed for a balanced human diet has been ignored (Steffan et al., 2018). Moreover, it has been documented that climate change-induced increased atmospheric CO_2 concentration will further restrict the nutrient concentration in crops and alter the protein content, vitamins, and nutrients content in crops (Myers et al., 2014; Zhu et al., 2018). Hence, nutritional security together with sustainable soil health will be the greatest challenge to future food production systems.

The decreasing nutrient concentration in crops is a global threat and raised concerns about nutrient deficiency or hidden hunger (Dhaliwal et al., 2019a). Worldwide, more than 2.0 billion people are suffering from hidden hunger or multiple nutrient deficiencies that cause serious health issues, especially in children and pregnant women (Pirzadeh et al., 2010; Detterbeck et al., 2016; Brevik et al., 2020). Today, more focus is given to dietary supplementation than to enriching existing food crops through soil management. There are approximately 17 elements derived from the soil that are indispensable for crop growth and productivity, and most of these are also necessary for human health (Bala et al., 2018; Huang et al., 2020; Agyin-Birikorang et al., 2022). These nutrients are consumed by people through the direct consumption of plant-based diets (Abrahams, 2002). Therefore, restoration and management of soil health are important to supply essential nutrients to crops and to produce nutrient-rich good quality food.

Rice is one of the most important staple food crops, safeguarding the food and nutritional security of the world (Fukagawa and Ziska,

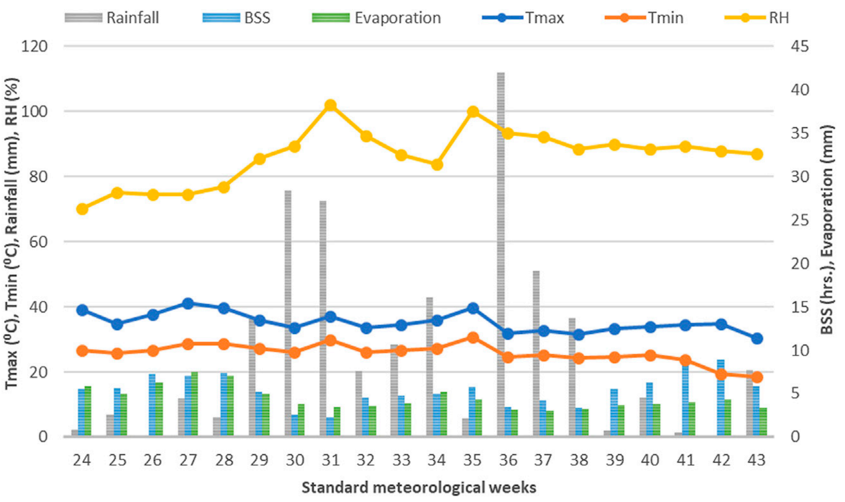

FIGURE 1
Average weekly rainfall, Tmax, Tmin, RH, evaporation, and BSS during crop growing season. Tmax: maximum temperature; Tmin: minimum temperature; RH: relative humidity; and BSS: bright sunshine hours season.

TABLE 1 Different physicochemical properties of the soil before commencing the experiment.

Soil properties	Values
Textural class	Sandy clay loam (sand-52.81%, silt-22.5%, clay-25.4%)
pH (1:2.5 soil: water ratio)	8.16
Electrical conductivity (dS m^{-1} 25°C)	0.79
Water Holding Capacity (%)	36.4
Bulk Density (Mg m^{-3})	1.50
Organic Carbon (g kg^{-1})	5.10
Available N (kg ha^{-1})	163.7
Available P (mg kg^{-1})	8.42
Available K (mg kg^{-1})	187.0
DTPA extractable micronutrients (mg kg^{-1})	
Fe	21.3
Zn	1.24
Mn	8.30
Cu	3.20

DTPA: diethylene triamine pentaacetic acid.

2019; Huang et al., 2020; Khanam et al., 2020). Nutrient deficiency is predominant in people who solely consume rice in their diet; and rice being one of the main foods consumed worldwide, its importance with respect to nutrition and human health remains a keen area of interest. However, the adoption of intensive cropping systems with imbalanced fertilizer application and lower use of organic manures depleted organic matter and induced macro and micronutrient deficiencies (Dhaliwal et al., 2019a; Brevik et al., 2020). This jeopardizes the potential and capacity of soil to fulfill the nutritional demand of future generations. It has been documented that intensive cropping systems caused an initial Zn deficiency and a later Fe and Mn deficiency in many agricultural land use systems (Dhaliwal et al., 2019a). Globally, approximately 50% of cereal-producing soils have low Zn availability, indicating an urgent need for replenishment of Zn and other microelements in cereal-centric systems (Cakmak, 2008). Organic agriculture is a holistic strategy to restore soil fertility, improve soil properties, including the build-up of soil organic matter (SOM), and enhance nutrient uptake and concentration in grains. The inclusion of legumes as green manure in the rice-wheat cropping system has been reported to improve soil physicochemical properties, macro, and micronutrients availability in the soil, and uptake by crops (Dhaliwal et al., 2019a; Dhaliwal et al., 2019b). The application of organic manure has been found to improve soil health and enhance the availability of primary (N, P, and K) and micronutrients (Zn, Fe, Cu, and Mn) in the soil (Dhaliwal and Walia, 2008; Dhaliwal et al., 2019a). Rutkowska et al. (2014) observed a significant effect of long-term mineral fertilizers and organic manures on pH, SOM, and available macro and micronutrients. The absorption of nutrients by the crops depends on the availability of nutrients in the soil pool, which is controlled by soil physicochemical and biological properties (Dhaliwal et al., 2019b). Organic nutrients-based management practice is an environment-friendly and economically viable agronomic approach. It is a potential way to achieve soil and nutritional security and sustainable development goals (SDGs) of the United Nations. Therefore, the present study was undertaken in a 16-year-old organic rice-based cropping system with the hypothesis that implementation of organic nutrient management in the rice-based system might lead to improvements in soil physicochemical environment and SOC, and thereby, lead to a higher nutrient concentration in rice grains. The objectives of this research were to appraise the effect of organic nutrient sources on soil physicochemical properties, SOC, grain yield, nutrient uptake by crop, and grain quality.

2 Materials and methods

2.1 Site description and meteorological characteristics

The study area was located at the research farm of the ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India. The altitude of the experimental site is 250 m above the mean sea level with 28.4°N latitude and 77.1°E longitude. The climate of the region is semiarid categorized under the subtropical zone, having hot summers and cold winters, with an average annual rainfall of 750 mm, most of which occurs during the rainy season (July to September), and average annual pan evaporation of 850 mm. The climatic variables recorded during the experimental period were collected from the Agrometeorological observatory of the ICAR-IARI, New Delhi and are depicted in Figure 1. The mean maximum and minimum temperatures during the crop-growing season were 34.8°C and 25.4°C, respectively. The total rainfall received during the field experimentation was 1,413.7 mm. The present research was carried out in a 16-year-old organic field experiment at the ICAR-IARI, New Delhi, India. This experiment on *basmati* rice-based cropping systems under organic cultivation was started in 2003. The initial period from 2003 to 2005 was considered a transitional period and from 2006 onwards, the true organic field experiment was started. Different rice-based cropping systems with or without legumes were followed at the experimental site before the present investigation (Supplementary Table S1). The soil (*Typic* Ustochrept) of the research site is non-saline having a sandy clayey loam texture (Bouyoucos, 1962). The basic physicochemical properties of the soil at the beginning of the experiment are shown in Table 1.

2.2 Experimental design and treatment details

The experiment was laid out in a split-block or strip plot design with three replications (Supplementary Table S2). The vertical strips consisted of two rice-based cropping systems, namely, *basmati* rice-wheat-mung bean (RWM) and *basmati* rice-wheat-*sesbania* (RWS), whereas seven combinations of different organic materials and biofertilizers (BF) were assigned to horizontal strips *viz.*, 1. control, 2. farmyard manure (FYM) equivalent to 80 kg N ha^{-1}, 3.

vermicompost (VC) equivalent to 80 kg N ha^{-1}, 4. FYM + crop residue (CR) of the previous crop at a rate of 2.5 t ha^{-1} for each rice and wheat, 5.VC + CR, 6. FYM + CR + BF, and 7. VC + CR + BF (Supplementary Table S3). *Sesbania* was cultivated as a green manure crop, while mung bean was raised as green manure as well as for grain purposes. The varieties *Pusa basmati 1,692, Pusa Vishal, and Sesbania* sp. were used for rice, mung bean, and *sesbania*, respectively. Biofertilizers *viz.*, *Azospirillum*, phosphate solubilizing bacteria (PSB), potassium solubilizing bacteria (KSB), and *Cellulolytic culture* (*Aspergillus awamori, Trichoderma viride, Phanerochaete chrysosporuim*, and *Aspergillus wolulens*) were used for rice, while *Azotobacter*, PSB, KSB, and *Cellulolytic culture* in wheat and *Rhizobium*, PSB and KSB in mung bean/ *sesbania* were applied. *The cellulolytic culture* was used only in the crop residue applied treatments (Supplementary Table S2).

2.3 Experimental methods for soil and plant samples

The soil samples were collected randomly from three places in each treatment from the plow layer (0–15 cm) of the soil after the crop harvest. The air-dried samples were processed and analyzed for different physical and chemical soil properties. The core sampler method was used to determine the soil bulk density (BD) and expressed as Mg m^{-3} (Hartge and Blake, 1986). Soil pH and electrical conductivity (EC) were determined through the 1: 2.5 soil: water suspension method described by Jackson (1973). The water holding capacity (WHC) of soil was measured by the method described by Keen and Raczkowski (1921). Soil moisture content (SMC) was determined *via* the gravimetric method at 0–15 cm soil depth. The SOC was measured by the rapid titration method given by Walkley and Black (1934). Soil available N was determined by the alkaline permanganate ($KMnO_4$) method developed by Subbiah and Asija (1956). Available P by 0.5 M sodium bicarbonate ($NaHCO_3$) having pH 8.5 (Olsen et al., 1954) and 1 N neutral ammonium acetate (NH_4OAc-K) method was used to extract available K (Jackson, 1973). Soil-available micronutrients (Fe, Zn, Mn, and Cu) were determined by the diethylenetriamine pentaacetic acid (DTPA) developed by Lindsay and Norvell (1978). SOC stock was calculated by using the following equation (Datta et al., 2015):

$$SOC\ stock = OC \times BD \times Depth \times Area$$

Where, SOC stock was expressed as Mg ha^{-1}, OC is the SOC content (g C kg^{-1}), BD is bulk density (Mg m^{-3}), soil depth in m (0.15 m), and area in m^2 (10,000 m^2).

The grain yield was recorded from 2 m × 2 m from each plot and expressed as t ha^{-1} at a 12% moisture level. Hulling, milling, and head rice recovery (HRR) were calculated by using the following formulas:

$$\text{Hulling (\%)} = \frac{Weight\ of\ brown\,rice\ (g)}{Weight\ of\ rough\,rice\ (g)} \times 100$$

$$\text{Milling (\%)} = \frac{Weight\ of\ milled\,rice\ (g)}{Weight\ of\ rough\,rice\ (g)} \times 100$$

$$\text{HRR (\%)} = \frac{Weight\ of\ whole\ milled\,rice\ (g)}{Weight\ of\ rough\,rice\ (g)} \times 100$$

Ten milled grains before cooking were randomly selected and used for measuring length and breadth on graph paper using a “Photo Enlarger” with a magnification of ×3. The actual mean of grain length and breadth was expressed in mm. The same procedure was also followed for the length and breadth measurement of rice grain after boiling it in a water bath (Thermotech temperature controller TH-013) for 8–10 min. The modified Kjeldahl method was used to measure the total N concentration in rice grain (Prasad et al., 2006). A coefficient factor of 5.95 was used to determine the crude protein (CP) content of rice grain, which was obtained by multiplying grain N concentration with the factor (Juliano, 1985). Total P and K in rice grains were estimated by the Vanado-molybdo phosphoric acid yellow color method and the flame photometry method, respectively, on a sulfuric-nitric perchloric tri-acid digest of plant material (Prasad et al., 2006). The micronutrient (Fe, Zn, Mn, and Cu) concentration in rice grains was determined by a wet-digestion (di-acid digestion) procedure on an anatomic absorption spectrophotometer (Prasad et al., 2006).

2.4 Statistical analysis

All the experimental data pertaining to soil properties and crop quality were statistically assessed using the analysis of variance (ANOVA) in SAS 9.3 software (SAS Institute Inc., Cary, NC, United States). The significance of treatment means was tested using the F–test (Gomez and Gomez 1984). The least significant difference (LSD) was worked at a 5% ($p = 0.05$) level of significance to evaluate differences between treatment means. A Pearson’s correlation matrix was constructed among the soil properties and plant nutrients status studied using the data analysis tool pack of Microsoft Excel (2007).

3 Results

3.1 Soil properties influenced by cropping systems and nutrient management

3.1.1 Soil pH

Basmati rice-based cropping systems under organic agriculture registered no significant effect on soil pH at 0–15 cm soil profile (Figure 2). However, the continuous application of organic manures either alone or in combination with CR and BF showed a statistically significant ($p \leq 0.05$) effect on soil pH. The trend for soil pH under varied nutrient management treatments was CT > VC > FYM > VC + CR > FYM + CR > VC + CR + BF > FYM + CR + BF. The lowest soil pH of 7.98 recorded under FYM + CR + BF, was approximately 3.0% lower than that of the control. Thus, the incorporation of organic manures either alone or *via* conjoint application was found to be superior in reducing soil pH relative to the control.

3.2 Electrical conductivity

The electrical conductivity (EC) of the soil at 0–15 cm soil depth under rice-based cropping systems was not significantly affected.

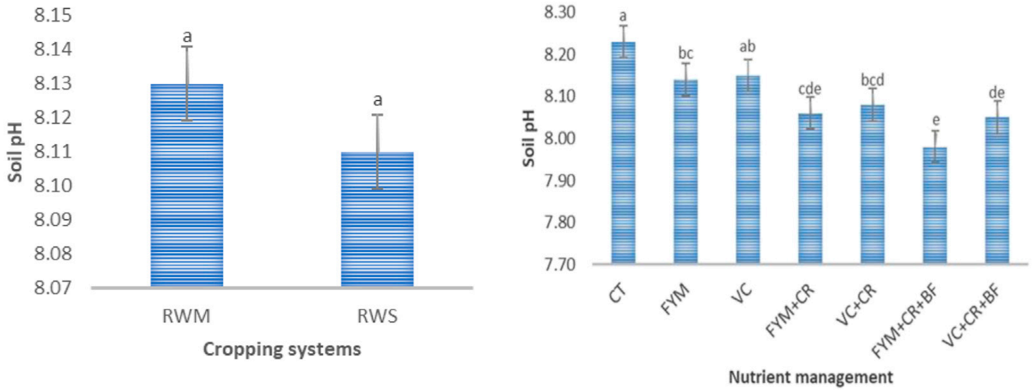

FIGURE 2
Long-term effect of cropping systems and organic nutrient management on soil pH. RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

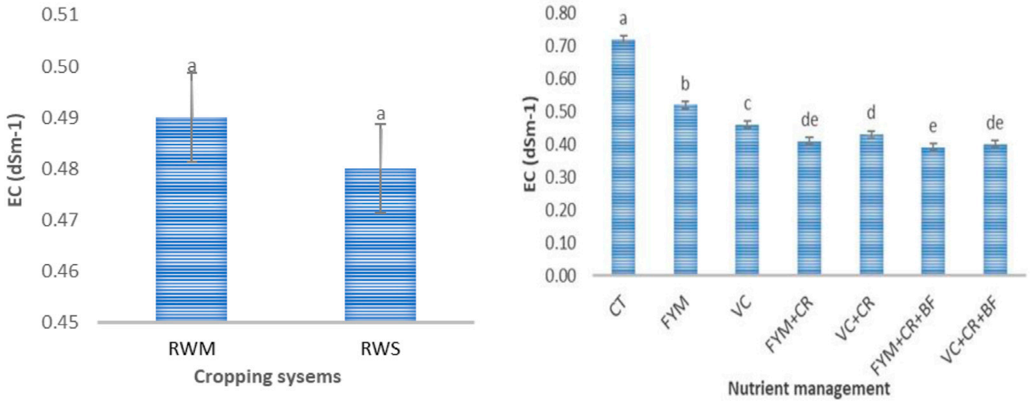

FIGURE 3
Long-term effect of cropping systems and organic nutrient management on soil EC. EC: electrical conductivity; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

However, EC under different organic nutrient management was significantly varied (Figure 3). The EC under different nutrient management treatments was in the order of CT > FYM > VC > VC + CR > FYM + CR > VC + CR + BF > FYM + CR + BF. The application of FYM and VC significantly ($p \leq 0.05$) decreased the EC by 27.8% and 36.1%, respectively in comparison to the control. A significant ($p \leq 0.05$) reduction of 40.3%–45.8% in soil EC was also observed under conjoint application of FYM/VC with CR and BF to the control.

3.3 Bulk density

The soil bulk density (BD) at 0–15 cm depth was found non-significant under organic basmati rice-based cropping systems. However, the BD was statistically significant ($p \leq 0.05$) under varied nutrient management options (Figure 4). The sole or co-application of organic manures with CR and BF decreased the BD by 3.3%–9.2% relative to the control. The lowest BD of 1.39 Mg m^{-3} was observed in VC + CR + BF treatment while the highest was seen in the control (1.53 Mg m^{-3})

3.4 Water holding capacity

Basmati rice-based cropping systems registered a significant effect on the water-holding capacity (WHC) of soil (Figure 5). The inclusion of *sesbania* as a green manure crop in the rice-based system recorded higher WHC (54.9%) as compared to the RWM system (52.8%). However, the addition of organic manures either alone or in conjunction with CR and BF showed significant ($p \leq 0.05$) improvement in WHC over the control. The maximum

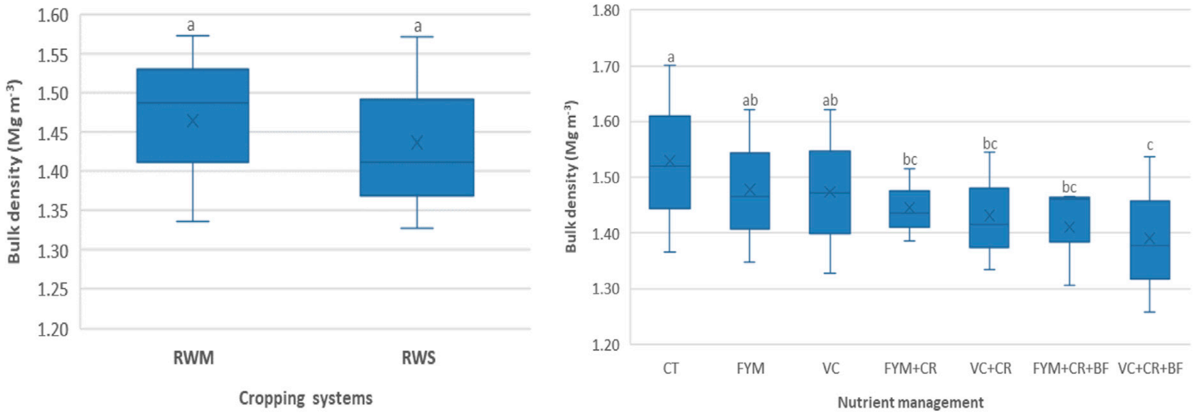

FIGURE 4
Long-term effect of cropping systems and organic nutrient management on soil BD. BD: bulk density; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

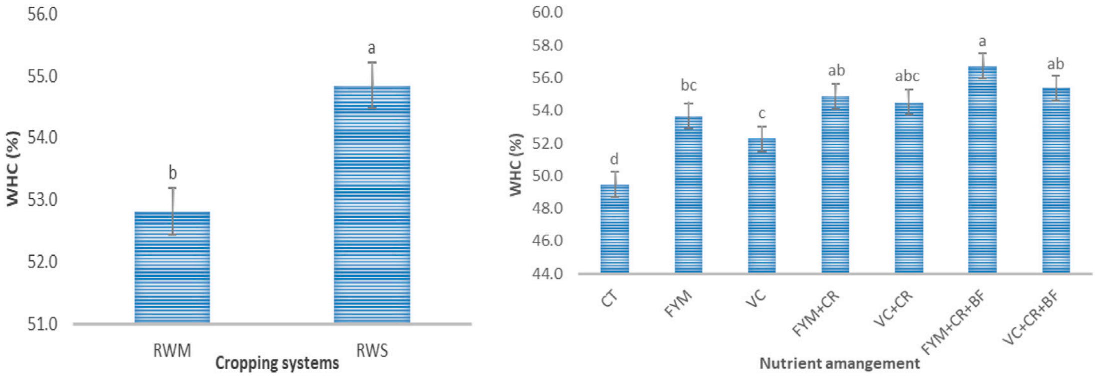

FIGURE 5
Long-term effect of cropping systems and organic nutrient management on WHC. WHC: water holding capacity; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

WHC was found in FYM + CR + BF (56.7%) followed by VC + CR + BF (55.4%) and FYM + CR (54.9%). The application of FYM alone or in combination with CR and BF was found superior over VC-based treatments. The trend was FYM + CR + BF > VC + CR + BF > FYM + CR > VC + CR > FYM > VC > CT under varied nutrient management options.

3.5 Soil moisture content

The effect of rice-based cropping systems and different organic nutrient sources on gravimetric soil moisture content (SMC) was found significant ($p \leq 0.05$) at 0–15 cm soil depth (Figure 6). The inclusion of *sesbania* as a green manure crop in the rice-based system conserved 5.5% higher SMC as compared to the RWM system. Among the nutrient management, the application of organic manures either alone or in combination with CR and BF recorded greater SMC over the control. The highest SMC of 26.6% was observed in FYM + CR + BF being closely followed by VC + CR + BF (25.7%). The minimum SMC was recorded in the control. The trend of SMC was FYM + CR + BF > VC + CR + BF > FYM + CR > VC + CR > FYM > CT under different nutrient management options.

3.6 Soil organic carbon (SOC) and SOC stock

The SOC and SOC stock were significantly ($p \leq 0.05$) affected by *basmati* rice-based cropping systems in 0–15 cm soil depth. The highest SOC and its stock were recorded under RWS (Figure 7). The application of organic manures alone or in conjunction with CR and BF showed significant ($p \leq 0.05$) improvement in SOC and its stock

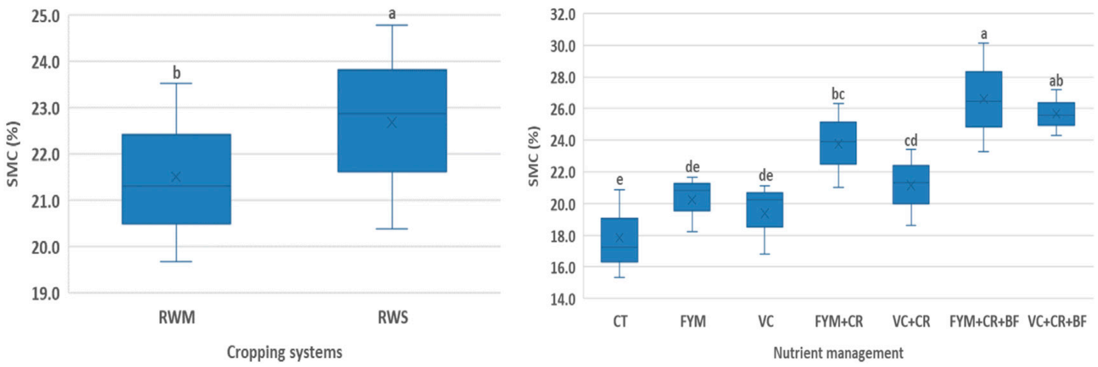

FIGURE 6
Long-term effect of cropping systems and organic nutrient management on SMC. SMC: soil moisture content; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

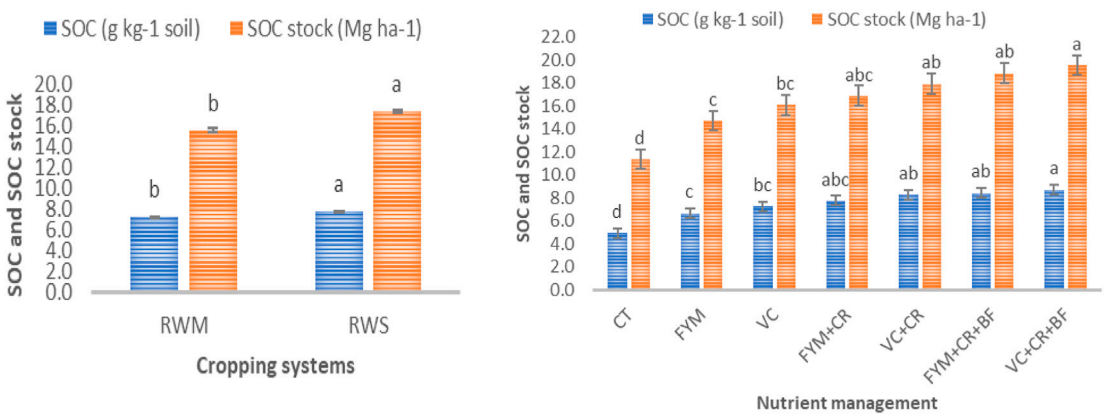

FIGURE 7
Long-term effect of cropping systems and organic nutrient management on SOC and SOC stock. SOC: soil organic carbon; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

over control (Figure 7). The SOC content and its stock were significantly ($p \leq 0.05$) increased by 35.3%–76.5% and 29.5%–72.0%, respectively under sole or conjoint application of organic manures as compared to the control. The maximum SOC and its stock were observed in VC + CR + BF. The lowest SOC (4.9 g kg^{-1} soil) and SOC stock (11.4 Mg ha^{-1}) were recorded in the control.

3.7 Soil available N, P, and K

The effect of *basmati* rice-based cropping systems on soil available N and K was not significant (Figure 8). However, the soil available P was significant ($p \leq 0.05$). The maximum soil available N and P were observed under the RWS system. The inclusion of mung bean in the rice-based system recorded maximum soil available K. Among the nutrient management options, the application of organic manures either alone or in combination with CR and BF was found statistically significant ($p \leq 0.05$) for soil available N, P, and K content. The application of organic manures recorded greater soil available N, P, and K content than the control (Figure 8). The application of organic manures improved the soil available N by 28.4%–62.8% relative to the control. The single or conjoint application of organic manures enhanced the soil available P by 1.6–2.5 times relative to the control. Similarly, the application of organic manures either alone or in combination with CR and BF improved the soil available K. The maximum soil available K was recorded in VC + CR + BF, which was at par with the FYM + CR + BF. The application of organic manures increased the soil available K by 20.1%–58.8% over the control. The lowest soil available N, P, and K content were observed in the control.

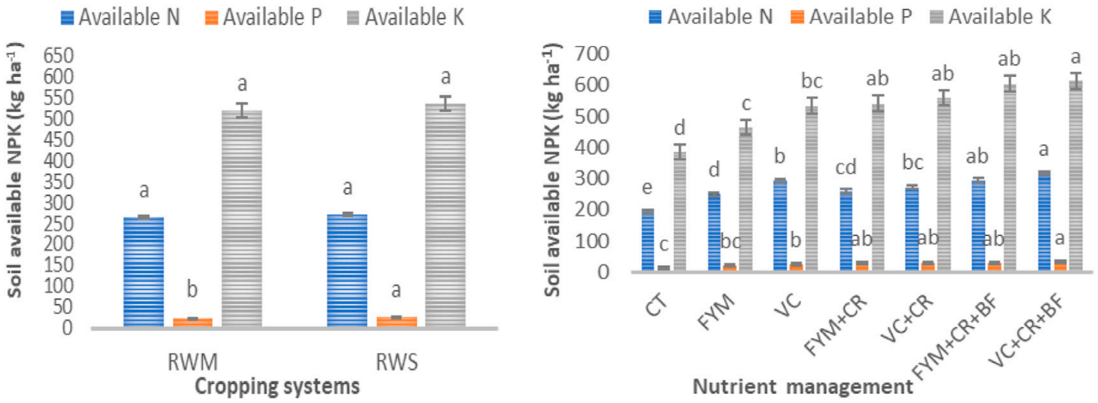

FIGURE 8
Long-term effect of cropping systems and organic nutrient management on soil available N, P, and K. RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

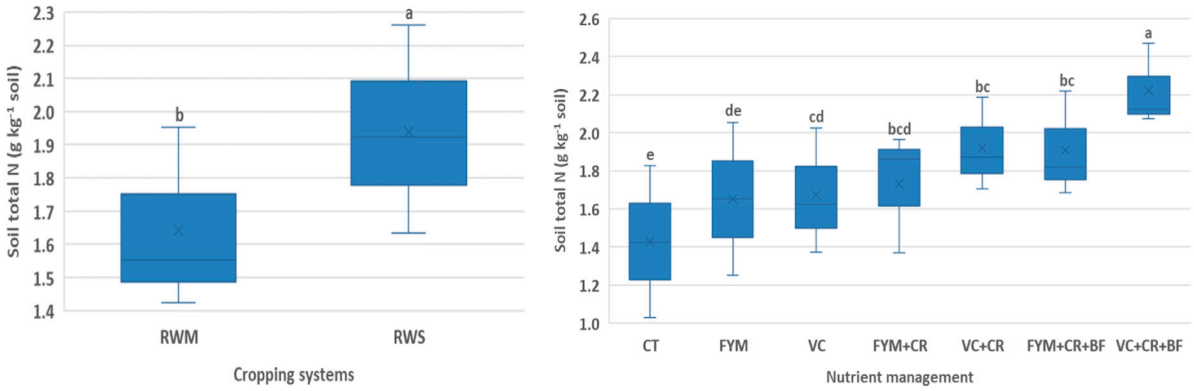

FIGURE 9
Long-term effect of cropping systems and organic nutrient management on soil total N. RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

3.8 Soil total nitrogen

The inclusion of legumes (*sesbania* and mung bean) in the *basmati* rice-wheat cropping system significantly ($p \leq 0.05$) influenced the total N content of the soil (Figure 9). The highest total N content (1.94 g kg^{-1} soil) in the soil was found under the RWS system, which was 18.3% greater than the RWM system. Similarly, the single or conjoint application of organic manures with CR and BF significantly ($p \leq 0.05$) improved the soil's total nitrogen content (Figure 9). The total soil N content was increased by 15.4%–55.2% under varied nutrient management options relative to the control. The highest total soil N content was recorded in VC + CR + BF (2.22 g kg^{-1} soil) followed by VC + CR (1.92 g kg^{-1} soil) and FYM + CR + BF (1.91 g kg^{-1} soil). The lowest total N content in the soil was found in the control.

3.9 Soil available micronutrients (Fe, Zn, Mn, and Cu)

The availability of micronutrients, namely, Fe, Zn, Mn, and Cu, in the soil was found significantly ($p \leq 0.05$) different under *basmati* rice-based cropping systems (Figure 10). The maximum soil available Fe (32.7 mg kg^{-1} soil), Zn (2.8 mg kg^{-1} soil), Mn (13.5 mg kg^{-1} soil), and Cu (4.3 mg kg^{-1} soil) were observed under the RWS system. Among the nutrient management options, the application of organic manures either alone or in combination with CR and BF significantly ($p \leq 0.05$) affected the soil available Fe, Zn, Mn, and Cu content over control (Figure 10). The maximum soil available Fe and Zn contents were recorded in FYM + CR + BF, which was at par with the application of VC + CR + BF. The application of organic manures

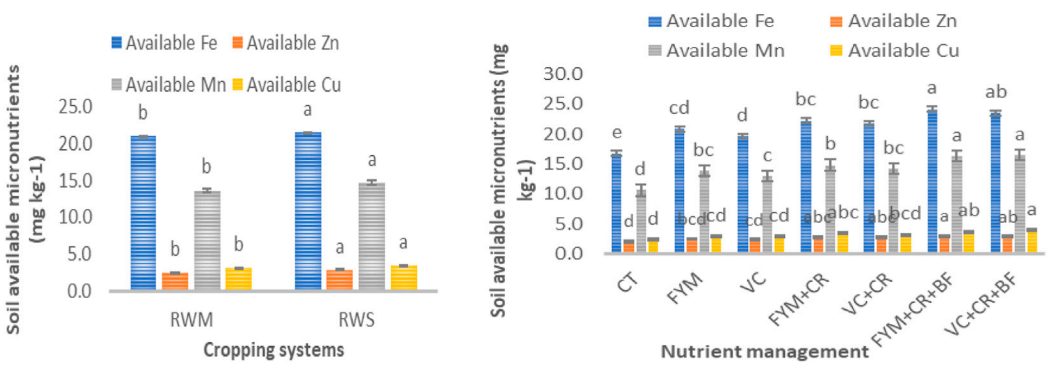

FIGURE 10
Long-term effect of cropping systems and organic nutrient management on soil available Fe, Zn, Mn, and Cu. RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

improved the soil available Fe and Zn by 17.4%–44.1% and 12.3%–41.0%, respectively as compared to the control. Treatments comprised of FYM alone or in combination with CR and BF recorded a higher magnitude of soil available Fe and Zn than VC treatments. However, the maximum soil available Mn and Cu contents were observed in VC + CR + BF as compared to the rest of the treatments. The application of organic manures improved the soil available Mn and Cu content by 22.1%–55.2% and 19.0%–66.5%, respectively over the control. Treatments comprised of VC alone or in combination with CR and BF recorded higher soil available Mn and Cu than FYM treatments. The lowest soil available Fe, Zn, Mn, and Cu contents were recorded in the control.

3.10 Crop productivity, grain quality, and nutrients concentration in grain

3.10.1 Grain yield, kernel length, breadth, and protein content

Grain yield, kernel length before cooking (KLBC), kernel length-breadth ratio before cooking (KLBRBC), kernel length-breadth ratio after cooking (KLBRAC), and protein concentration of *basmati* rice were significantly ($p \leq 0.05$) influenced by rice-based cropping systems (Table 2). The inclusion of *sesbania* as green manure in the rice-wheat system recorded significantly higher grain yield, KLBC, KLBRBC, KLBRAC, and protein content than the RWM system. Among the nutrient management options, either single or

TABLE 2 Long-term effect of cropping systems and organic nutrient management on kernel length, breadth, and protein content of *basmati* rice.

Treatment	Grain yield (t ha^{-1})	KLBC (mm)	KBBC (mm)	KLBRBC	KLAC (mm)	KBAC (mm)	KLBRAC	Protein concentration (%)
Cropping system								
RWM	4.78b	8.29b	1.91a	4.34b	15.46a	2.34a	6.53b	7.63b
RWS	4.94a	8.42a	1.91a	4.40a	15.79a	2.37a	6.67a	8.11a
SEM±	0.01	0.01	0.001	0.004	0.12	0.01	0.01	0.08
CD ($p = 0.05$)	0.07	0.03	NS	0.02	NS	NS	0.06	0.46
Nutrient management								
CT	3.64e	8.22d	1.88c	4.25c	14.87d	2.28d	6.44d	7.40c
FYM	4.58d	8.27cd	1.89bc	4.28bc	15.29cd	2.32cd	6.49cd	7.59bc
VC	4.83c	8.33bc	1.88c	4.38a	15.47bc	2.35bc	6.50cd	7.78abc
FYM + CR	5.12b	8.39 ab	1.90b	4.37 ab	15.64bc	2.36abc	6.57bcd	7.99 ab
VC + CR	5.17b	8.42a	1.93a	4.42a	15.87 ab	2.37abc	6.65abc	8.04a
FYM + CR + BF	5.24b	8.43a	1.93a	4.44a	15.96 ab	2.38 ab	6.73 ab	8.11a
VC + CR + BF	5.43a	8.44a	1.94a	4.44a	16.31a	2.41a	6.82a	8.19a
SEM±	0.08	0.02	0.01	0.03	0.19	0.02	0.06	0.14
CD ($p = 0.05$)	0.24	0.07	0.02	0.09	0.58	0.06	0.17	0.42

KLBC: kernel length before cooking; KBBC: kernel breadth before cooking; KLBRBC: kernel length-breadth ratio before cooking; KLAC: kernel length after cooking; KBAC: kernel breadth after cooking; KLBRAC: kernel length breadth ratio after cooking; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); BF: biofertilizer(s); statistical method: analysis of variance for strip-plot design in SAS, 9.3 software; sample size (n) = 42; SEM: standard error of the mean; and CD: critical difference.

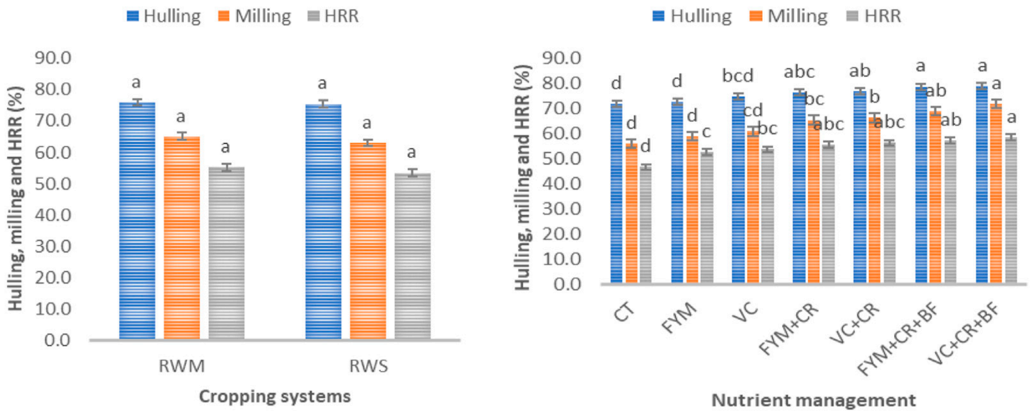

FIGURE 11
Long-term effect of cropping systems and organic nutrient management on hulling, milling, and HRR. HRR: head rice recovery; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s). Statistical method: analysis of variance for strip-plot design in SAS 9.3 software; $n = 42$. Values with a different capital letter indicate a significant difference among the different treatments at $p < 0.05$ by the LSD test. Bars represent means ± SEM.

conjoint application of organic manures significantly ($p \leq 0.05$) improved the grain yield and kernel quality characters *viz.*, KLBC, kernel breadth before cooking (KBBC), KLBRBC, kernel length after cooking (KLAC), kernel breadth after cooking (KBAC) KLBRAC, and protein content of *basmati* rice (Table 2). The highest grain yield was recorded in VC + CR + BF, which was statistically equivalent to FYM + CR + BF. The application of organic manures either alone or in combination with CR and BF enhanced the grain yield by 25.8%–49.2% as compared to the control. The highest KLBC was recorded in VC + CR + BF, which was statistically equivalent to FYM + CR + BF and VC + CR. A similar trend was also observed in the case of KBBC and KLBRBC. Similarly, the continuous application of VC + CR + BF recorded the highest KLAC, KBAC, and KLBRAC, which was closely followed by FYM + CR + BF, VC + CR, and FYM + CR. The application of organic manures increased the protein concentration in grain by up to 10.7% as compared to the control. The maximum protein content was recorded in VC + CR + BF, which was statistically equivalent to FYM + CR + BF and VC + CR.

3.11 Hulling, milling, and head rice recovery

The inclusion of legumes in *the basmati* rice-based cropping system had no significant effect on hulling, milling, and head rice recovery (HRR) of rice (Figure 11). However, the effect of the

TABLE 3 Long-term effect of cropping systems and organic nutrient management on N, P, and K concentrations and their uptake by rice grain.

Treatment	N concentration in grain (%)	N uptake by grain (kg ha^{-1})	P Concentration in grain (%)	P Uptake by grain (kg ha^{-1})	K Concentration in grain (%)	K Uptake by grain (kg ha^{-1})
Cropping system						
RWM	1.28b	61.51b	0.14a	6.79a	0.27a	12.81a
RWS	1.36a	67.50a	0.15a	7.64a	0.27a	13.12a
SEM±	0.01	0.71	0.01	0.38	0.002	0.09
CD ($p = 0.05$)	0.08	4.34	NS	NS	NS	NS
Nutrient management						
CT	1.24c	45.31e	0.11d	4.12e	0.24c	8.84e
FYM	1.28bc	58.51d	0.12cd	5.70d	0.25bc	11.59d
VC	1.31abc	63.20c	0.14bc	6.96c	0.26bc	12.77c
FYM + CR	1.34 ab	68.62b	0.15bc	7.44bc	0.26bc	13.49bc
VC + CR	1.35a	69.82b	0.16 ab	8.07bc	0.27 ab	13.84b
FYM + CR + BF	1.36a	71.36 ab	0.16 ab	8.60 ab	0.28 ab	14.45b
VC + CR + BF	1.38a	74.69a	0.18a	9.60a	0.29a	15.80a
SEM±	0.02	1.65	0.01	0.36	0.01	0.38
CD ($p = 0.05$)	0.07	5.08	0.03	1.10	0.02	1.17

RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); BF: biofertilizer(s); statistical method: analysis of variance for strip-plot design in SAS, 9.3 software; $n = 42$; SEM: standard error of the mean; and CD: critical difference.

TABLE 4 Long-term effect of cropping systems and organic nutrient management on yield attributes and yield of *basmati* rice.

Treatment	Fe concentration in grain (mg kg^{-1} grain)	Fe uptake by grain (g ha^{-1})	Zn concentration in grain (mg kg^{-1} grain)	Zn uptake by grain (g ha^{-1})	Mn concentration in grain (mg kg^{-1} grain)	Mn uptake by grain (g ha^{-1})	Cu concentration in grain (mg kg^{-1} grain)	Cu uptake by grain (g ha^{-1})
Cropping system								
RWM	115.12a	567.75a	36.00b	179.89b	34.61a	173.01a	10.74a	51.20a
RWS	116.64a	576.85a	40.64a	199.17a	38.86a	191.08a	12.40a	61.66a
SEM±	4.60	23.50	0.48	3.12	0.75	4.25	0.42	1.82
CD	NS (p = 0.05)	NS	2.92	18.96	NS	NS	NS	NS
Nutrient management								
CT	85.50c	310.79d	26.30d	95.64c	23.57d	85.67d	8.78c	32.02d
FYM	108.65bc	496.29c	32.63bcd	150.34bc	29.09cd	139.85cd	11.96abc	56.13c
VC	95.65bc	461.20c	30.48cd	146.56bc	31.34bcd	144.00bcd	12.23abc	57.68bc
FYM + CR	118.45b	607.10b	44.27abc	226.48a	39.85abc	205.75abc	9.97bc	51.47c
VC + CR	111.42b	579.53b	41.25abc	212.96 ab	42.87abc	219.34 ab	10.28bc	52.52c
FYM + CR + BF	148.83a	776.76a	47.83a	247.94a	44.09 ab	239.27a	13.08 ab	71.04b
VC + CR + BF	142.67a	774.44a	45.48 ab	246.79a	46.44a	240.43a	14.68a	77.31a
SEM±	7.73	38.39	4.75	24.78	4.81	24.97	2.04	5.32
CD (p = 0.05)	23.82	118.29	14.65	76.34	14.82	76.94	6.28	16.40

RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); BF: biofertilizer(s); statistical method: analysis of variance for strip-plot design in SAS, 9.3 software; n = 42; SEM: standard error of the mean; and CD: critical difference.

continuous application of various organic manures on hulling, milling, and HRR of *basmati* rice was found statistically significant ($p \leq 0.05$) (Figure 11). The highest hulling, milling, and HRR were recorded in VC + CR + BF. The conjoint application of organic manure with CR and BF improved the hulling, milling, and HRR of *basmati* rice by 6.8%–9.8%, 5.3%–28.5%, and 13.2%–25.5%, respectively as compared to the control. The trend for hulling, milling, and HRR was VC + CR + BF > FYM + CR + BF > VC + CR > FYM + CR > VC > FYM > CT. The lowest hulling, milling, and HRR were recorded in the control.

3.12 N, P, and K concentrations and their uptake by grain

The N concentration and its uptake into rice grain were found statistically significant ($p \leq 0.05$) under legume-inclusive *basmati* rice-based cropping systems (Table 3). However, the effect of *basmati* rice-based cropping systems on P and K concentrations and their uptake into grain were not significant (Table 3). The highest N concentration and its uptake into rice grain were observed in the RWS system. Among the nutrient management options, the continuous application of different organic manures showed a statistically significant ($p \leq 0.05$) effect on N, P, and K concentrations and their uptake into the grain (Table 3). The N content and its uptake into grain were significantly increased by 3.2%–11.3% and 29.1%–64.8%, respectively under various nutrient management options over the control. The continuous application of VC + CR + BF registered the highest P concentration and its uptake into the grain. The P uptake into grain under different nutrient management treatments was increased by 38.3%–133.0% relative to the control. Similarly, the application of VC + CR + BF registered the highest K content and its uptake into the grain. The K concentration and its uptake into grain were enhanced by 4.2%–20.8% and 31.1%–78.7%, respectively than that of the control. The lowest N, P, and K contents in grain and their uptake into grain were recorded in the control.

3.13 Fe, Zn, and Cu concentrations and their uptake by grain

The legume-inclusive *basmati* rice-based cropping systems affect Zn concentrations in the grain (Table 4); however, no effects were observed on Fe, Mn, and Cu concentrations. The highest Zn concentration and its uptake by grain were observed in the RWS system. Among the nutrient management options, the continuous application of different organic manures showed a statistically significant ($p \leq 0.05$) effect on Fe, Zn, Mn, and Cu concentrations and their uptake into the grain (Table 4). The highest Fe and Zn concentrations and uptake by grains were recorded in FYM + CR + BF, being statistically equivalent to VC + CR + BF. The concentrations of Fe and Zn in rice grains under varied nutrient management treatments were increased by 11.9%–74.1% and 15.9%–81.9%, respectively over the control. Similarly, the uptakes of Fe and Zn were enhanced by 44.8%–149.9% and 49.9%–159.2%, respectively. The concentrations of Mn and Cu under various nutrient management treatments were improved by 23.4%–97.0% and 13.6%–67.2%, respectively relative to the control. The lowest Fe, Zn, Mn, and Cu contents and uptake into grain were recorded in the control.

TABLE 5 Correlation matrix of different soil (pH, EC, BD, WHC, and SMC) and grain quality (KLBC, KBBC, N, P, K, Fe, Zn, Cu, and Mn contents) parameters under different cropping systems and nutrient management treatments.

Parameters	pH	EC	BD	WHC	SMC	Grain yield	KLBC	KBBC	N content	P Content	K Content	Fe content	Zn content	Cu content	Mn content
pH	1														
EC	0.22	1													
BD	0.02	0.17	1												
WHC	−0.42**	−0.65**	−0.31**	1											
SMC	−0.35**	−0.57**	−0.07	0.44***	1										
Grain yield	−0.54***	−0.83***	−0.25	0.74***	0.68***	1									
KLBC	−0.41***	−0.41***	−0.47***	0.51***	0.40***	0.51***	1								
KBBC	−0.24	−0.34**	−0.67***	0.42***	0.43***	0.49***	0.58***	1							
N content	−0.19	−0.22	−0.39**	0.44***	0.27	0.36**	0.60***	0.41***	1						
P content	−0.50***	−0.41***	−0.45***	0.51***	0.54***	0.60***	0.56***	0.49***	0.37**	1					
K content	−0.29	−0.55***	−0.14	0.28	0.68***	0.61***	0.30	0.36**	0.23	0.50***	1				
Fe content	−0.30**	−0.42***	−0.30	0.48***	0.50***	0.52***	0.27	0.37**	0.22	0.48***	0.43***	1			
Zn content	−0.09	−0.54***	−0.21	0.32**	0.43***	0.46***	0.29	0.31**	0.19	0.22	0.48***	0.37**	1		
Cu content	−0.19	−0.21	−0.35**	0.41***	0.36**	0.30	0.47***	0.36**	0.36**	0.39**	0.26	0.18	0.06	1	
Mn content	−0.07	−0.54***	−0.30	0.34**	0.45***	0.48***	0.34**	0.36**	0.22	0.27	0.49***	0.39**	0.99***	0.11	1

***- significant at ≤ 0.001 level (2-tailed) ** - significant at ≤ 0.01 level (2-tailed); *n* = 42; statistical method: Pearson's correlation matrix; EC: electrical conductivity; BD: bulk density; WHC: water holding capacity; SMC: soil moisture content; KLBC: kernel length before cooking; KBBC: kernel breadth before cooking; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s).

TABLE 6 Correlation matrix of different soil (SOC, total N and available N, P, K, Fe, Mn, Zn, and Cu) and grain quality (protein content and N, P, K, Fe, Zn, Cu, and Mn contents) parameters under different cropping systems and nutrient management treatments.

Parameters	SOC	Total N	Avail N	Avail P	Avail K	Avail Fe	Avail Mn	Avail Zn	Avail Cu	Protein content	N content	P Content	K Content	Fe content	Zn content	Cu content	Mn content
SOC	1																
Total N	0.36**	1															
Avail N	0.38**	0.38***	1														
Avail P	0.48***	0.34**	0.38***	1													
Avail K	0.39**	0.23	0.49***	0.43***	1												
Avail Fe	0.59***	0.40***	0.42***	0.58***	0.66***	1											
Avail Mn	0.41***	0.37**	0.55***	0.51***	0.61***	0.70***	1										
Avail Zn	0.48***	0.40***	0.22	0.33**	0.21	0.73***	0.35**	1									
Avail Cu	0.23	0.49***	0.12	0.22	0.15	0.58***	0.28	0.78***	1								
Protein content	0.21	0.28	0.36**	0.34**	0.37**	0.47***	0.45***	0.38**	0.28	1							
N content	0.21	0.28	0.36**	0.34**	0.37**	0.47***	0.45***	0.38**	0.28	1	1						
P content	0.41***	0.32**	0.37**	0.62***	0.46***	0.66***	0.61***	0.52***	0.42***	0.37**	0.37**	1					
K content	0.43***	0.10	0.50***	0.48***	0.60***	0.50***	0.66***	0.06	−0.12	0.23	0.23	0.50***	1				
Fe content	0.13	0.22	0.21	0.40***	0.38**	0.55***	0.47***	0.24	0.04	0.22	0.22	0.48***	0.43***	1			
Zn content	0.25	0.10	0.26	0.33**	0.24	0.35**	0.34**	0.17	−0.01	0.19	0.19	0.22	0.48***	0.37**	1		
Cu content	0.45***	0.31**	0.39***	0.63***	0.56***	0.69***	0.74***	0.40***	0.28	0.42***	0.42***	0.64***	0.55***	0.52***	0.32**	1	
Mn content	0.28	0.10	0.28	0.36**	0.27	0.43**	0.38**	0.26	0.06	0.22	0.22	0.27	0.49***	0.39**	0.99***	0.35**	1

***- significant at ≤ 0.001 level (2-tailed) ** - significant at ≤ 0.01 level (2-tailed); $n = 42$; statistical method: Pearson's correlation matrix; SOC: soil organic carbon; Avail N: available N; Avail P: available P; Avail K: available K; Avail Fe: available Fe; Avail Mn: available Mn; Avail Zn: available Zn; Avail Cu: available Cu; RWM: rice-wheat-mung bean; RWS: rice-wheat-sesbania; CT: control; FYM: farm yard manure; VC: vermicompost; CR: crop residue(s); and BF: biofertilizer(s).

3.14 Correlation matrix

Significant ($p \leq 0.01$ and $p \leq 0.001$) correlations were registered among most of the soil and grain quality parameters (Tables 5, 6). Soil pH was significantly ($p \leq 0.001$) and negatively correlated with grain yield (r = −0.54***), KLBC (r = −0.41***), and grain P content (r = −0.50***). Soil EC also showed significant ($p \leq 0.001$) and negative correlations with grain yield, KLBC, and grain P, K, and micronutrient concentrations. Similarly, soil BD also registered a significant and negative correlation with KLBC (r = −0.47***), KBBC (r = −0.67***), and grain P concentration (r = −0.46***). The WHC and SMC were positively correlated with grain yield, KLBC, and grain Fe and Cu contents and with grain yield, KLBC, KBBC, and grain P, K, and Cu contents, respectively (Table 5). Similarly, grain yield and kernel length and breadth before cooking positively correlated with grain macro and micronutrient concentrations. SOC showed a significant ($p \leq 0.01$ and $p \leq 0.001$) and positive correlation with soil total N content, soil available N, P, K, Fe, Mn, and Zn contents, and grain P, K, and Cu contents (Table 6). Soil total N content positively correlated with soil available macro and micronutrients except for soil available K. A significant ($p \leq 0.01$ and $p \leq 0.001$) and positive correlation of soil available N and P with soil available P, K, Fe, and Mn contents, protein content, and macro and micronutrients concentrations in grain were also observed (Table 6). The soil available K also registered a significant ($p \leq 0.01$ and $p \leq 0.001$) and positive correlation with soil available Fe and Mn contents, grain protein content, and grain N, P, K, Fe, and Cu contents. The soil available Fe and Mn also showed a significant ($p \leq 0.01$ and $p \leq 0.001$) and positive correlation with grain protein content, and grain macro and micronutrient contents. We also found a significant ($p \leq 0.01$ and $p \leq 0.001$) and positive correlation of soil available Zn and Cu with grain protein content, grain N, P, and Cu concentrations, and grain P and Cu contents, respectively (Table 6).

4 Discussion

4.1 Soil properties influenced by cropping systems and nutrient management

Soil pH, EC, BD, WHC, SMC, SOC, and soil-available macro and micronutrients are vital for facilitating a better soil environment for crop growth and producing nutritious food (Dhaliwal et al., 2019b; Gu, et al., 2022). This study showed that the inclusion of legume as green manure in basmati rice-based cropping systems and co-application of organic manures with CR and BF significantly improved the SMC, SOC, total N, and available P, Fe, Zn, Mn, and Cu contents in the soil, which affected the grain quality. The lower soil pH under the *sesbania* green manure-based cropping system and long-term application of organic manures might be attributed to the addition of organic matter to the soil, which enhanced microbial decomposition and subsequently produced CO_2 and aromatic and aliphatic hydroxyl organic acids and thus reduced soil pH (Srinivasarao et al., 2018; Meena et al., 2020). The application of organic manures helps in buffering the soil through mineralization and decomposition of organic matter, which releases free cations and regulates the reactions in the soil (Meena et al., 2020; Yadav et al., 2021). The long-term application of organic manures in conjunction with CR and BF resulted in improved soil aggregation (Chaudhary et al., 2017). Moreover, the accumulation of organic matter in the soil also improved soil aggregation and reduced BD (Kumawat et al., 2022). Similarly, the addition of a large volume of organic matter through green manure incorporation, organic manures, and CRs resulted in higher numbers of micro and medium-sized pores, and improved infiltration, SMC, and WHC of soil (Kuotsu et al., 2014; Dhaliwal et al., 2019a). A 5-year field study carried out by Sharma et al. (2000) observed significant improvement in the WHC of soil with the application of organic manures and CRs. Further, the addition of organic matter through green manuring, FYM, VC, and CRs and their decomposition produces polysaccharides, which increase the stable and well-distributed aggregates into the soil, facilitating greater SMC and WHC of soil (Kannan et al., 2013; Yadav et al., 2020). The greater WHC in VC-comprising treatments over FYM-containing treatments showed that the type of organic manure also influences the SMC and WHC. Several researchers also documented that long-term application of FYM, VC, CR, BF, and green manure improves the number of water storage pores, soil aggregation, structure, and moisture retention capacity, and thus increases the WHC of soil (Bhattacharyya et al., 2008; Mitran et al., 2018; Meena et al., 2020; Nima et al., 2020).

SOC is an important indicator of good soil health and it regulates the physicochemical properties and biological processes of the soil (Jat et al., 2019; Babu et al., 2020a). The addition of higher organic matter through the application of C-rich organic biomass, such as green manure, FYM, VC, and CR together with BFs, increased the build-up of SOC (Chaudhary et al., 2017). The build-up of SOC in the soil is primarily determined by the carbon input through the addition of organic biomass and carbon stabilization in the soil (Babu et al., 2020a). The conjoint application of VC + CR, FYM + CR + BF, and VC + CR + BF was found superior in enhancing SOC content and SOC stock over the rest of the treatments. Our findings are corroborated by the results of Meena et al. (2020) who reported that legume-inclusive cropping systems and the continuous addition of organic manures significantly improved the SOC content in the soil. Babu et al. (2020a) also reported that the addition of higher organic biomass through organic manures increased SOC content. Moreover, the dominance of fungi and actinomycetes under anaerobic soil conditions slowed down the decomposition rates of organic matter, which led to greater SOC stock. The addition of organic material with high cellulose and lignin content, and C: N ratio together with lower microbial activities also enhanced the SOC stock in paddy soil (Meena et al., 2020). The increased accumulation of SOC content and SOC stock in soil under green manure-inclusive cropping systems and organic management practices has also been documented by many researchers (Xin et al., 2016; Dhaliwal et al., 2019a; Babu et al., 2020a; 2020b; Nima et al., 2020; Ansari et al., 2022).

Our results indicate that the addition of organic manures significantly improved the availability of macro and micronutrients in the soil. The amount of organic and inorganic fractions of N added through different organic materials and their mineralization rate determine the availability of N in the soil (Meena et al., 2020). The increased microbial-mediated transformation of organically bound N into inorganic forms led to increased availability of N in the soil in the treatments comprising organic manures, CRs, and BFs. The solubilization of native phosphate by organic acids produced during microbial decomposition of organic matter under green manure and organic manure amended treatments enhanced the availability of P and K in the soil (Solaiman et al., 2012; Nima et al., 2020; Yadav et al., 2021). Further, the formation of the protective layer of sesquioxide by the addition of higher organic matter lowers the P and K fixation in the soil and thus enhances their availability (Nagar et al., 2016; Kumawat et al., 2022). The direct addition of N, P, and K through the sole or combined application of organic nutrient sources in an active pool of soil may lead to increased total N and availability of N, P, and K in the soil (Babu et al., 2020a; Nima et al., 2020). Our results are corroborated by many previous studies that reported higher N, P, and K contents in organically managed soils under varied agro-climatic conditions (Sharma et al., 2005; Aulakh et al., 2016; Dhaliwal et al., 2019b; Jat et al., 2019). Similarly, the improved availability of DTPA extractable Fe, Zn, Mn, and Cu under legume-inclusive cropping systems and organic nutrient sources comprising treatments could be ascribed to lower soil pH and higher organic matter that developed reduced soil conditions and released CO_2 and organic acids. The increased microbial activities also enhanced the micronutrient availability in the soil under legume-inclusive cropping systems and organically amended treatments (Nima et al., 2020). In addition, the amount of organic biomass added to the soil was higher under the RWS system than in the RWM system which led to increased availability of micronutrients under the *sesbania* green manure-based cropping system. The increased availability of Fe and Zn under FYM comprising treatments over VC-based treatments might be attributed to a higher concentration of Fe and Zn in FYM than that of VC. The higher concentration of Mn and Cu in VC than in FYM resulted in increased availability of these nutrients under VC comprising treatments. Moreover, the higher micronutrient content under long-term application of organic manures could be ascribed to enhanced biochemical processes, which led to improved mineralization of organic matter, decreased redox potential, and improved soil environment (Chaudhary and Narwal, 2005; Sidhu and Sharma, 2010; Agegnehu et al., 2016; Moharana et al., 2017).

4.2 Crop productivity, grain quality, and nutrients concentration in grain

Crop yield is a key indicator that reflects improvement in soil health (Gu et al., 2022). The present study showed the superiority of the *sesbania* green manure inclusive cropping system and conjoint application of various organic nutrient sources over their sole use as well as over the control. The improved soil physical properties under green manure and organic nutrient management developed a better soil environment for crop growth and development, which in turn resulted in higher grain yield of rice (Sharma et al., 2021). The continuous application of FYM and VC alone or in combination with CR and BF reduced the soil pH, EC, and BD and improved the WHC and SMC in the soil, which created favorable soil conditions for the absorption of essential nutrients, translocation, and their utilization thereby producing more biomass and resulting in increased crop productivity over the control (Meena et al., 2020). Moreover, the induced microbial activities and faster process of mineralization of organic matter increased the availability of necessary nutrients during the crop growth period (Srinivasarao et al., 2018). The improved N fixation, an increased supply of essential plant nutrients including macro and micronutrients, and improved overall soil health due to the addition of green manure, FYM, CR, and VC into the soil led to higher grain yield of *basmati* rice (Banik et al., 2006; Aulakh et al., 2016; Neema et al., 2020).

Agronomic management, such as cropping systems and organic nutrient management, can alter the above and below-ground environment and thus, can affect the grain quality of crops (Nayak et al., 2017). The kernel length, breadth, length:breadth ratio before and after cooking, and protein content in grain were significantly improved under the *sesbania* green manure-based cropping system and integrated nutrient management options. The increase in kernel length and breadth before and after cooking could be attributed to the increased availability of macro and micronutrients in the soil and their uptake and translocation due to the application of nutrient-rich organic manure and the incorporation of organic manures (Shivay and Prasad, 2012; Nayak et al., 2017). The ensured and synchronized supply of essential nutrients in proper quantity at critical growth stages of the crop through the continuous application of organic nutrient sources resulted in improved kernel length and breadth before as well as after cooking (Davari and Sharma, 2010; Pooniya and Shivay, 2015).

The grain protein content is known as an important factor for measuring the nutritional quality of *basmati* rice grain. The incorporation of green manure and conjoint application of different organic nutrient sources significantly improved the protein content in rice grains. The increased protein content in the *sesbania* green manure-based cropping system and organic nutrient management options could be attributed to increased N supply and its uptake during critical periods of crop growth and development (Guet al., 2015; Dhillon et al., 2018). Further, the increased protein content in grain is associated with the application of N-intensive and easily decomposable and mineralizable organic nutrient sources (Dhaliwal et al., 2019b). The increased availability, absorption, and translocation of N induce the transformation of photosynthates into protein, as N had a significant effect on grain protein content (Aulakh et al., 2016; Meena et al., 2022). Rao et al. (2006) also reported that a continuous supply of N together with increased uptake and assimilation by plants under organically amended treatments resulted in higher protein content in rice grains.

Physical grain qualities hulling, milling, and HRR are also important parameters that reflect soil fertility status. This study showed significant improvement in hulling, milling, and HRR of *basmati* rice under *sesbania* green manure-based cropping systems and varied organic nutrient sources. The increased uptake and mobilization of nutrients, especially N, under *sesbania* green manure-based cropping systems and different organic nutrient sources resulted in improved hulling, milling, and HRR of *basmati* rice grains (Nayak et al., 2017; Meena et al., 2022). Further, the increased physical quality of rice grains might be attributed to increased N concentration in grains, which in turn increased the protein content and reduced the breakage loss of grains. The higher concentration of protein in grains imparts strength to grains, which leads to higher HRR and other recoveries (Pooniya and Shivay, 2015). In addition, the increased availability and uptake of P, K, and micronutrients with the incorporation of the *sesbania* green manure and continuous application of organic nutrient sources also contributed to increased hulling, milling, and HRR of rice grains over the control.

Nutrient concentrations and their uptake by crops are the primary basis to determine the nutritional quality of food grains and the fertility status of the soil. The continuous incorporation of *sesbania* green manure and the addition of organic nutrient sources either alone or in combination with CR and BF aggravated the rate of N mineralization and produced varied nitrogenous compounds *viz.*, amino acids, nitrate-N, ammoniacal-N, etc., into the soil, which increased the uptake of N and N concentration in rice grains (Didawat et al., 2022). The decomposition of organic matter releases different organic acids, such as oxalic acid, citric acid, and tartaric acid, which may increase inorganic P in the rhizosphere and thus increase P uptake and P content in rice grain (Zhao et al., 2020). It has been reported that organic acids also enhance mineral weathering and induce K solubilization and mobilization (Li et al., 2019). Moreover, the build-up of nutrients reservoirs under long-term *sesbania*-based cropping systems and conjoint application of organic nutrient sources increased crop growth and root proliferation, which resulted in greater uptake and concentration of N, P, and K in the rice grain (Didawat et al., 2022). The higher N, P, and K concentrations in grain and their uptake with the incorporation of green manure and combined application of organic nutrient sources might be due to increased N fixation, P and K solubilization, and mobilization of higher amounts of nutrients in rapidly available form. The enhanced availability of nutrients in the root zone led to increased crop growth and biomass production, which resulted in higher nutrient uptake and concentration in grain (Shivay et al., 2015; Jat et al., 2019). Yadav et al. (2020) reported that *sesbania* green manuring improved the physicochemical properties of soil and increased the nutrient availability in the soil, which led to a higher concentration of nutrients in grain and their uptake by wheat. Our findings are in agreement with the results of (Pooniya and Shivay, 2015; Singh and Shivay, 2016; Yadav et al., 2018).

Micronutrient concentrations in grain and their uptake by rice were found significantly higher with the continuous incorporation of *sesbania* green manure and application of organic manures in conjunction with CR and BF over the control. This might be because the long-term application of organic manures improved the soil's physical properties, changed soil reactions, and increased nutrient solubility and available nutrient stock, enabling greater uptake and concentration of micronutrients in rice grains (Didawat et al., 2022). Further, the increased soil organic matter influenced the availability of micronutrients and their uptake by crops due to the chelation of micronutrients, which improved the root-accessible forms of these nutrients and avoided the formation of insoluble forms such as carbonates and oxides in the soil (Dhaliwal et al., 2019b). Moreover, the synergistic effect between macro and micronutrients, the uninterrupted and increased supply of nutrients led to higher nutrient uptake and their concentrations in grain (Kumar et al., 2017). Our results are corroborated by the findings by Soni et al. (2000) and Singh and Ram, (2005) who reported higher micronutrient concentration under green manure incorporation and application of organic manures. Yadav et al. (2018) reported that adequate SMC increased nutrient solubility and availability, and enhanced the micronutrient concentration in grain and their uptake by wheat. An increase in Fe, Zn, Mn, and Cu concentrations in grain due to the addition of organic manures and the inclusion of legumes in rice-wheat cropping systems has also been reported by Dhaliwal et al. (2019a).

5 Conclusion

The importance of healthy soil to produce nutritious food is globally accepted by the scientific community. The long-term incorporation of *sesbania* green manure and conjoint application of organic manures with CR and BF improved the soil physicochemical properties, namely, soil pH, EC, BD, SMC, and WHC. The addition of higher organic matter also increased SOC, SOC stock, and available macro and micronutrients in the soil. The use of organic sources improved the soil physicochemical properties, SOC, and availability of nutrients which in turn increased the grain yield, kernel quality, protein content, and macro and micronutrient content in grain and their uptake by *basmati* rice. Soil properties and grain quality are related to each other and are important indicators of soil health. This study indicates that the inclusion of *sesbania* as green manure and the continuous application of organic manures in the intensive rice-wheat system is a sustainable and environment-friendly agronomic approach to maintaining soil fertility and producing nutritious food for human consumption.

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 authors.

Author contributions

AK: Investigation, data analysis, and original draft writing. DK: Conceptualization, methodology, and editing. YS: Investigation and editing. AB, IR, DY, and AK: Review and editing. All authors contributed to the manuscript revision, and read 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/fenvs.2023.1031844/full#supplementary-material

SUPPLEMENTARY TABLE S1
Cropping history of the experimental field from 2001-2021.

SUPPLEMENTARY TABLE S2
Experimental design and treatments details.

SUPPLEMENTARY TABLE S3
Layout of experimental design.

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