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Effect of organic farming on the restoration of soil quality, ecosystem services, and productivity in rice–wheat agro-ecosystems

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Excess use of hazardous agrochemicals and inorganic fertilizers resulted negative impact on environmental outcomes and degraded soil function, biological diversity, and ecosystem services. A 15-year long-term (2004–05 to 2017–18) field experiment was conducted to improve the ecosystem services with soil quality restoration and stabilization of yield through agronomic manipulation in the rice (*Oryza sativa*)–wheat (*Triticum aestivum*) system under Indo-Gangetic Plains (IGP). Three crop management practices (i) organic crop management, (ii) inorganic crop management, and (iii) integrated crop management were evaluated at four locations (i) Jabalpur, (ii) Ludhiana, (iii) Pantnagar, and (iv) Modipuram in a factorial randomized block design and replicated thrice at each location. Among the spatial variation, the highest soil quality indicators like soil microbial biomass carbon (0.52 mg g^{-1}), fungal (46.2 CFU × 10^4 CFU), bacterial (54.2 CFU × 10^6 CFU), and actinomycetes viable cells (23.0 CFU × 10^6 CFU), and nutrients (available N and available P) were observed at Pantnagar than other location. The soil *p*H varied from 7.2 to 8.3, and the lowest bulk density (ρb) was recorded at Jabalpur and Modipuram. Subsequently, higher system productivity (8,196.7 kg ha^{-1}) and net returns were obtained in Pantnagar > Ludhiana, and it was 44.1–63.4% higher than in Modipuram and Jabalpur. Among the crop management, organic crop management significantly improved ($p < 0.05$) ρb, soil organic carbon, available N, available P, and available K by 3.7%, 33.3%, 16.4%, 37.8%, and 20.3% over inorganic crop management, respectively. Similarly, the highest bacterial, fungal, and actinomycetes viable cell counts were found under the organic plots, followed by integrated plots. In terms of productivity, integrated crop management (ICM) had increased the system productivity by 4.7%–6.7%

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and net returns by 22.2% and 23.5% over inorganic and organic crop management. Similarly, the highest sustainability yield index (SYI) was recorded in integrated crop management (0.77) as compared to inorganic (0.74) and organic management (0.75). The soil quality index was estimated as 0.60, 0.53, and 0.54 in organic, inorganic, and ICM, respectively. Hence, the study indicated that the application of organic amendments under organic or integrated crop management improves the system's resiliency and sustainability. Therefore, the study concludes that towards organic approach (integrated application of organic amendments with a gradual reduction in mineral fertilizers) is better suitable for keeping the rice–wheat system productivity and sustainable in the long term.

KEYWORDS

crop management, soil quality and health, system productivity, economics, ecosystem services (ES), yield sustainability

1 Introduction

The Green Revolution's (GR) future is centered on technologies that ensure food security for the burgeoning population without harming the environment (Phillips, 2014). The glory of GR in India was based on the use of high-yielding varieties (HYVs), chemical fertilizers, pesticides, and farm mechanization that led to unprecedented pressure on our natural resource base, including the natural way of controlling pests and diseases (Tripathi et al., 2020). Land degradation is primarily caused by an over-reliance on agrochemicals in agri-food production systems, which has accelerated the loss of regulating and supporting ecosystem services and deteriorated environmental sustainability (Suárez et al., 2021), making it more difficult to achieve sustainable development goals (SDGs). Indiscriminate use of inorganic fertilizers and chemicals also polluted the groundwater resources, contributing to land degradation and unsustainable farming in the long term (Panwar et al., 2021). An intensive cropping system without nature-oriented crop management and a lack of nutrient recycling through crop biomass enhanced nutrient mining and deteriorated the soil health, as well as daunted the physical, chemical, and biological properties of soil (Yadav et al., 2021; Ansari et al., 2022b). In India, 97.85 m ha (29.7%) of the total geographical area underwent land degradation in one or other forms due to conventional farming practices (Sengupta, 2021). The survey conducted by the National Sample Survey Organization (NSSO, 2013) indicates that the dependency of farmers on seeds, fertilizers, and pesticides from outside farms makes farming costlier. However, maintaining soil fertility has become a major concern in India. To ensure sustainable food security and reduce the environmental cost of agriculture, soil health management is critical. Utilizing organic manures, green manuring, and crop residue recycling is necessary to simultaneously improve the regulating, supporting, and provisioning ecosystem services in order to increase the effectiveness of chemical fertilizers and to improve crop responsiveness to the applied fertilizers. Under integrated crop management, the combination of synthetic and natural inputs was tested where in addition of organic inputs helps increase the use efficiency of synthetic inputs due to the betterment of soil physical properties and thereby water retention and absorption. This integrated crop management (ICM) practice involving integrated nutrient, weed, pest, and water management can also be referred to as toward organic approach where a successive reduction in the chemical inputs such as mineral fertilizers and pesticides is possible.

Organic crop management is more of a description of the nature-oriented agricultural practices used on a farm, and these methods combine tradition, innovation, and science. Organic crop management, in simple terms, requires a shift from intensive use of synthetic chemical fertilizers, insecticides, fungicides, herbicides, plant growth regulators (PGRs), and genetically engineered plants to extensive use of animal manures, beneficial soil microbes, bio-pesticides, bio-agents, and indigenous technological knowledge, based on scientific principles of agricultural systems (Ravisankar et al., 2021, 2022). With the increasing awareness about the safety and quality of foods, long-term sustainability of the system, and accumulating evidence of being equally productive, the integrated and organic crop management approach has emerged as an alternative system of farming that addresses little towards the sustainable development goals (SDGs) *viz.* good health and well-being (SDG–3), clean water and sanitation (SDG–6), affordable and clean energy (SDG–7), responsible consumption and production (SDG–12), climate action (SDG–13), life below water (SDG–14), and life on land (SDG–15) toward achieving sustainability and ensuring profitable livelihood option. According to Bhattacharya and Chakraborty (2005), integrating organic and inorganic agriculture would be the optimal approach after observing a number of issues with conventional farming in India. Based on their results, the industrial nitrogen fixation (INF) is 40 mt year^{-1} which accounts for only 15.3% of total nitrogen fixation. On the other hand, the quantity of biological nitrogen fixation (BNF) is 175 mt annum^{-1} contributing to 67.3% of the total amount. The plant also uses nutrients from organic sources through mineralization, and billions of microorganisms are available in the soil for this job. India is endowed with various types of naturally available organic forms of nutrients in different parts of the country and which will help for organic crop management.

Globally, cereal-based systems share 74% in terms of providing calories. Rice–wheat is a major cereal system in India and is being practiced in about ~13.5 m ha (Mahajan and Gupta, 2009), but there is a temporal decline in the response of nutrients, and across the systems, it has been observed that the response of 13.4 kg yield kg^{-1} of NPK in 1960 has come down to 2.7 kg kg^{-1} (Gangwar et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) realized that agriculture as it is practiced today (conventional agriculture, modern agriculture, or GR agriculture) accounts for about one-fifth of the anthropogenic greenhouse effect and generates roughly 50% and 70% of all anthropogenic methane and nitrogen oxide emissions, respectively (Charyulu and Biswas, 2010; Yadav et al., 2020).

Therefore, soil quality stabilization has emerged as a major challenge to sustain soil fertility with agronomic manipulation of crop management practices (Ansari et al., 2022b). Legumes used as green manuring are quickly decomposable and have the added benefit of fixing atmospheric nitrogen. Fast-growing legumes with high nitrogen-fixing prolificacy, such as *Sesbania* green manuring, can be included in rice–wheat cropping systems as sustainable alternative nutrient management and for restoring soil land productive capacity (Meena et al., 2018). After growing green manure crops or incorporating them, crop productivity is improved by nutrient pumping from deeper soil horizons to the furrow soil layer (Stagnari et al., 2017). *Sesbania* green manure crops have the ability of quick growth, deep roots, strong nitrogen fixation, and little lignin, which is effective at recycling nutrients (Dwivedi et al., 2017). The probability of incorporating *Sesbania* green manures into the system increased as a result of the stabilization of soil quality becoming necessary when nutrient imbalances and nutrient mining increased due to inadequate sustainable management practices. The absence of legumes in the cereal-based system would diminish the potential niche that is accessible in these cropping systems. As a result of the enhancement of soil's biological, physical, and chemical properties, biomass recycling has become crucial to control and sustain soil quality.

Sustainable crop management approaches can improve soil carbon storage, nitrogen availability, biological features of soil, and yield stability. Restoration of soil organic C and maintenance of agronomic productivity are difficult due to inadequate soil and crop management practices (Ansari et al., 2022a). Organic manure and green manure are employed to improve and sustain soil organic carbon (SOC), soil biological activity, soil microbial diversity, and chemical characteristics throughout (Yuan and Yue, 2012). However, using organic manure and growing fast with high nitrogen-fixing fecundity as green manure in cereal-based cropping systems has been deemed a viable and long-term solution for restoring soil fertility and system productivity (Yadav et al., 2021). *Sesbania*, as fast-growing, deep-rooted, high nitrogen-fixing, and low lignin-containing crops, are effective in capturing and recycling nutrients (Meena et al., 2018).

Thus, modern agriculture is more marketized and has both advantages and disadvantages. Meeting the SDGs by 2030 is very important, and the agriculture sector will play a vital role in achieving the same. The government of India is implementing National Mission on Sustainable Agriculture involving integrated and organic management approaches covering all the states and union territories (Panwar et al., 2020). India is the largest country in terms of the number of organic producers worldwide and the ninth largest country in terms of the total amount of arable land used for organic farming. The Sikkim state of India has been brought under complete organic certification and production since 2016 (Aulakh and Ravisankar, 2017). By March 2021, 2.66 million hectares of land had been converted to organic farming and was third-party certified, while 0.73 million ha was brought under the Participatory Guarantee System (PGS) of certification. At the moment, about 2.4 percent of the net cultivated land is either under-certified or transitioning to organic farming. In the past 6 years, the area under organic farming has grown at an annual growth rate of 22% (Ravisankar et al., 2021). A better option for national food security, higher household income, and climate resilience is the "toward organic" (integrated crop management) approach for input-intensive areas (food hubs) and the "certified organic" approach by integrating tradition, innovation, and science in the *de facto* organic areas (hill and rainfed/dryland regions), which will further enhance safe food production and meet the social values. Continuous practice of raising the crops organically shows good potential to sequester C (up to 63% higher C stock in 10 years), higher soil organic carbon (22% increase in 6 years), reduction in energy requirement (by about 10%–15%), and increase in water-holding capacity (by 15%–20%), thereby promoting climate resilience farming and addressing SDGs (Sharma et al., 2021).

However, systematic research on agronomic manipulation of crop management coupled with green manuring in the rice–wheat system under different agroecosystems was evaluated to find the changes in soil quality, microbial diversity, ecosystem services, and yield sustainability. Therefore, a field experiment was executed for 15 successive years (2004–05 to 2017–18) at Jabalpur (Madhya Pradesh), Ludhiana (Punjab), Pantnagar (Uttarakhand), and Modipuram (Uttar Pradesh) under the All India Network Programme on Organic Farming (flagship program of the Indian Council of Agricultural Research) to assess the effect of agronomic manipulation on soil quality, ecosystem services, and productivity in the rice–wheat system. The sites represent the various agro-ecosystems in which the rice–wheat cropping system is practiced. Findings from the study will aid in the development and implementation of appropriate agronomic management practices and policies in the rice–wheat system in Indo-Gangetic Plains.

2 Materials and methods

2.1 Description of the site, soil characteristics, and weather

This study was conducted on a research farm at four locations *viz.* ICAR-Indian Institute of Farming Systems Research, Modipuram (29.84′°N, 77.46′°E), Uttar Pradesh; Punjab Agricultural University, Ludhiana (24.35′°N, 74.42′°E), Punjab; GB Pant University of Agriculture and Technology, Pantnagar (29.00′°N, 79.30′°E),Uttarakhand; and Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur (24.30′°N, 80.15′°E), Madhya Pradesh. The experimental site is presented in Figure 1. The experimental sites of Modipuram and Pantnagar are representing the part of the Upper Gangetic Plain region, having sandy loam texture soil (52.5% sand, 30.9% clay, and 16.6% silt) of Gangetic alluvial origin, very deep (> 20 m), well-drained, and with flat (1% slope) topography. Similarly, the sites of Ludhiana and Jabalpur are part of the Trans-Gangetic Plain region and Central Plateau and Hill region, respectively. Initial soil parameters for all the locations were (0 cm–15 cm depth) analyzed at the onset of the experiment and are presented in Supplementary Table S1. According to Köppen's climate classification, the sites of Modipuram, Ludhiana, and Pantnagar are humid subtropical. However, the climate of Jabalpur is classified as Mediterranean with hot summer. The average annual minimum temperature of Jabalpur, Ludhiana, Pantnagar, and Modipuram varied from 6.0°C to 19.6°C, 16.9°C to 18.6°C, 11.5°C to 20.1°C, and 16.2°C to 23°C, and the maximum temperature varied from 27.8°C to 40.0°C, 29.3°C to 30.6°C, 27.2°C to 31.9°C, and 29.9°C to 37.8°C, respectively. Similarly, the total annual rainfall during the study period (2004–05 to 2017–18) varied from 1,038.0 mm annum^{-1} to 1857.9 mm annum^{-1}, 505.1 mm annum^{-1} to 1,248.4 mm annum^{-1}, 844.6 mm annum^{-1} to 2,247.6 mm annum^{-1}, and 244.8 mm annum^{-1} to 1,012.2 mm annum^{-1}, respectively. Around 75% of this is received through the southwest monsoon during July–September. The year-wise weather data are presented in Figure 2. The soil of all the experimental sites was neutral to mild alkaline and non-saline conditions.

2.2 Treatment detail

Long-term field experiments were conducted under the All India Network Programme on Organic Farming (AINP–OF) for successive fifteen years during 2004–05 to 2017–18 in rice–wheat cropping systems under various agro-ecosystems. The field experiment was conducted at four locations, namely, Jabalpur, Pantnagar, Ludhiana, and Modipuram, under the Upper, Trans Indo-Gangetic Plains (IGP), and Central Plateau regions. At all the locations, a field experiment was conducted under three crop management practices (i) organic crop management, (ii) inorganic crop management, and (iii) integrated crop management, which were evaluated in larger plots of 150 m^2. The treatment-wise crop management practices are presented in Supplementary Table S2. National Standards for Organic Production (NSOP) were followed under organic management while choosing the inputs for application. In the present investigation, soil quality parameters of rice–wheat cropping systems were studied from Modipuram, Ludhiana, Pantnagar, and Jabalpur locations.

2.3 Crop management

The rice field was ploughed twice by a disc harrow, puddled twice by a puddler in standing water (5 –7 cm), and leveled. Under organic crop management, 7.84 t ha^{-1} farm yard manure (FYM), 3.13 t ha^{-1} vermicompost, and 853 kg non-edible oilcake (neem cake) were added at final field preparation. Under inorganic crop management, 26.2 kg P ha^{-1} through DAP, 50 kg K ha^{-1} through muriate of potash, and 29.2 kg N ha^{-1} through urea (46% N) were added at the time of final puddling. The remaining 80 kg N ha^{-1} was

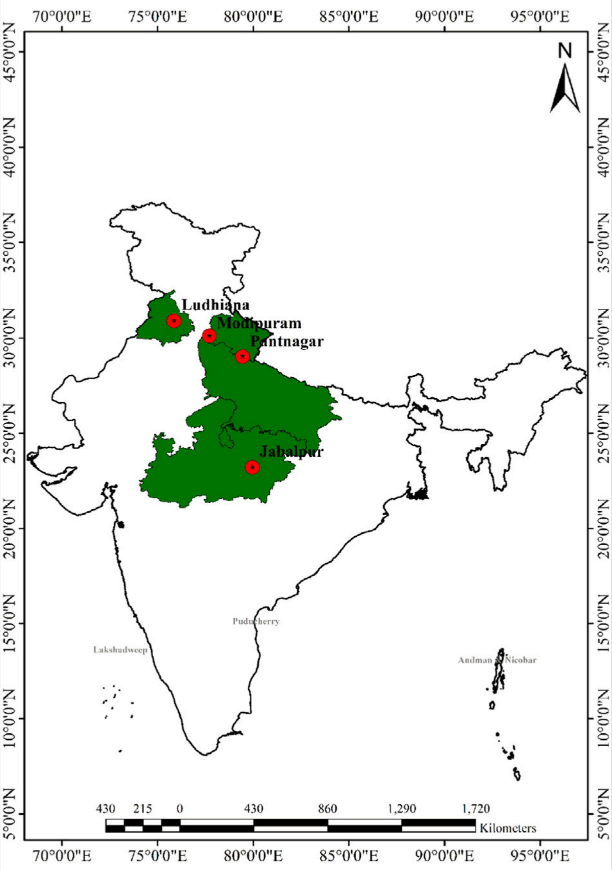

FIGURE 1
Location of the experimental sites.

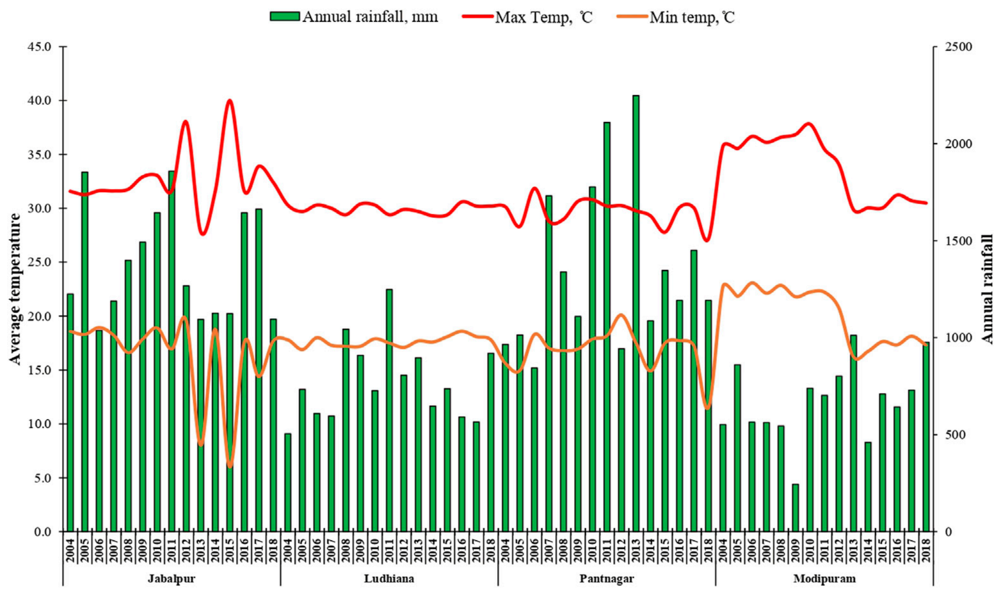

FIGURE 2
Weather data on the experimental site.

top-dressed in two equal splits at 20 days after transplanting (DAT) and 45 DAT. Similarly, under integrated crop management treatment (ICM), 5.88 t ha^{-1} FYM, 2.34 Mg ha^{-1} vermicompost, 13.1 kg P ha^{-1} through DAP, and 25 kg K ha^{-1} through muriate of potash were added during the final puddling. Nitrogen at 55 kg ha^{-1} through urea was top-dressed in two equal splits at 20 DAT and 45 DAT. 25-day-old seedlings of rice cv. Pusa Basmati–1 (Modipuram), Punjab Basmati-3 (Ludhiana), Pusa Basmati-1 (Pantnagar), and Pusa Basmati–1 (Jabalpur) at 20 cm × 15 cm spacing (2 seedlings hill^{-1}) were transplanted during the first fortnight of July. In wheat, organic manure (FYM, vermicompost, and oilcake) and chemical fertilizers for P and K were basally applied at the time of field preparation in respective treatments. Top dressing of N at 80 kg ha^{-1} and 55 kg ha^{-1} in two equal splits was performed at 21 days after sowing (DAS) and 45 DAS. Wheat cv HI 8713 (Modipuram), PBW–725 (Ludhiana), UP–2572 (Pantnagar), and MPO–1106 (Jabalpur) were sown at 22.5 cm row spacing using at 100 kg ha^{-1} seed rate during the third week of November. In rice and wheat, weeds were managed by two-hand weeding at 25 and 50 DAT/DAS. The rice and wheat crops were harvested in the second fortnight of October and the second fortnight of April, respectively. The crops were raised as per the recommended standard package of practices.

2.4 Soil sampling and analysis

Soil samples were collected at the initial stage and analyzed for initial soil properties in 2004–05 from 0 to 15 cm soil depth. After completion of 15 successive rice–wheat cycles in 2017–18 at Jabalpur, Ludhiana, Pantnagar, and Modipuram under each treatment (organic, inorganic, and integrated crop management), soil bulk density (ρb) was determined *in situ* using the core method (5.15 cm height and 4.7 cm diameter) after oven drying at 105°C ± 1°C (Blake and Hartge, 1986). Soil *p*H was determined using a 1:2.5 soil:water suspension (pH meter; Eutech pH 700-Eutech Instruments, Singapore). The available N (AvN) was determined using the KMnO$_4$ oxidation method (Subbiah and Asija, 1956), and the SOC content was determined using the K$_2$Cr$_2$O$_7$ wet oxidation method (Walkley and Black, 1934). The available P (AvP) was extracted using the Olsen and Sommers method (Olsen and Sommers, 1982). The available K (AvK) of NH$_4$OAc was determined using a flame photometer (ESICO-1382, India).

Soil samples from 0 to 15 cm depth were collected after last harvest (2018) from different crop management plots in four locations, namely, Jabalpur (Madhya Pradesh), Ludhiana (Punjab), Pantnagar (Uttarakhand), and Modipuram (Uttar Pradesh), to study the effect of different crop management practices on the soil microbial population. The total viable count of bacteria, fungi, and actinomycetes was estimated by serial dilution and plating methods. Nutrient agar (NA), Martin's Rose Bengal agar (MRBA), and Kenknight and Munaier's medium (KM) were used for bacteria, fungi, and actinomycetes, respectively. The plates of NA and MRBA were kept at 28°C ± 2°C and KM media plates at 35°C. The viable counts were taken after 24 h, 48 h, and 120 h for bacteria, fungi, and actinomycetes, respectively. The microbial biomass carbon was estimated by the fumigation extraction method given by Vance et al. (1987).

2.5 Soil quality index

The soil quality index (SQI) was calculated by using the approach given by Banerjee et al. (2015). To summarize, all of the soil indicators studied (soil *p*H, ρb, SOC, MBC, AvN, AvP, AvK, fungi, bacteria, and actinomycetes) were treated with principal component analysis (PCA) to reduce dimensionality while maintaining the most variation in the dataset. The first PC accounted for the largest variability, while the remaining PCs explained the residual variability. Based on factor loading values, the essential underlying variables for each PC were discovered. Under each PC, variables with absolute values of less than 20% of the maximum weighted factor were kept. The correlation matrix was used to verify the interlinkage of the extracted variables under respective PCs, and the most prominent variables from each PC were chosen for SQI development. After homothetic translation of each value within a mutual scale ranging from 0.1 to 1.0, the weighted addition for the final computation of index SQI for location and crop management was computed individually. All other indicators, except for ρb and pH, were treated as 'more is better' for all treatment combinations.

2.6 Computation of carbon stocks, system productivity, and the sustainability index

Carbon stocks, system productivity in terms of rice equivalent yield, and the sustainability yield index (SYI) were computed by using Eqs. (1,3)

$$\mathrm{REY}\ (kg/ha) = rice\ grain\ yield + \frac{(wheat\ grain\ yield\ (kg/ha) x\ market\ price\ of\ wheat)}{market\ price\ of\ rice\ (INR)}, \tag{1}$$

$$\mathrm{SYI} = \frac{(y-\sigma)}{ymax}, \tag{2}$$

where, y, σ, and ymax represents the average yield of treatment over the years, standard deviation, and observed maximum yield over the years.

$$\text{Carbon stock} = \rho b(\mathrm{g\ cm^{-3}}) * \mathrm{C\ concentration}(\%) * \mathrm{soil\ depth(cm)},\ \mathrm{Mg\ ha^{-1}}. \tag{3}$$

2.7 Data analysis

The data from soil analysis and grain yield measurement were processed for analysis of variance (ANOVA) in a factorial RBD using R version 9.2 to examine the statistical significance of the treatments (location and agronomic manipulation in crop management). Using R, the LSD of the mean was calculated using Duncan's multiple-range test (DMRT) ($p < 0.05$). At the $p < 0.05$ level of significance in DMRT, values in a column that are followed by a comparable letter in lowercase are not substantially different. By examining data on soil quality indicators (soil physical, chemical, and biological qualities) from various treatments, principal component analysis (PCA) was utilized to reduce dimensionality while maintaining the maximum variance in the studied dataset. Variables with factor loadings and PCs with multiple eigenvalues were determined to be the best variables for describing system properties. As a result, PCs with eigenvalues greater than 1.0 were chosen for further investigation since they were thought to be more informative than the rest (Kaiser, 1960). The first PC described the most variability, while the remaining PCs explained the majority of the leftover variability (Table 1).

TABLE 1 Details of the rotated component matrix–eigenvalues and rotated sums of squared loadings in our present study.

Principal component	PC1	PC2	PC3
Eigenvalues	4.52	3.24	1.85
% of variance	45.2	32.4	18.5
Cumulative variability (%)	45.2	77.6	96.1
Factor loading			
Soil pH	−0.679	−0.627	0.135
Pb	0.839	0.538	0.045
SOC	−0.299	0.807	0.506
AvN	0.918	0.384	0.068
AvP	0.593	0.168	0.778
AvK	−0.841	0.34	−0.386
MBC	−0.317	0.817	0.473
Fungi	0.702	0.552	−0.448
Bacteria	0.017	0.80	−0.592
Actinomycetes	0.879	−0.049	−0.192

Pb: bulk density, SOC: soil organic carbon, AvN: available nitrogen, AvP: available phosphorus, AvK: available potassium, MBC: microbial biomass carbon (mg g−1).

3 Result

3.1 Spatial and crop management amendment variability on soil pH, ρb, and nutrients

The spatial variability influenced the soil parameters. The soil *p*H varied from 7.2 (Jabalpur) to 8.3 (Modipuram). Similarly, ρb varied from 1.33 g $\mathrm{cm^{-3}}$ to 1.57 g $\mathrm{cm^{-3}}$. The highest was recorded at Ludhiana, and the minimum was recorded at the rest of the locations, which are statistically on par with each other. The highest SOC (10.6 g $\mathrm{kg^{-1}}$ of soil) and AvP (58.2 kg $\mathrm{ha^{-1}}$) were recorded at Pantnagar, while minimum SOC and AvP were recorded at Ludhiana (5.1 g kg^{-1} of soil) and Jabalpur (16.2 kg ha^{-1}), respectively. The highest AvN was recorded at Ludhiana (338.9 kg ha^{-1}), followed by Pantnagar (318.8 kg ha^{-1}). The highest AvK was recorded at Jabalpur (282.8 kg ha^{-1}), followed by Modipuram (273.7 kg ha^{-1}). Among the crop management practices, 0.2 unit of soil pH was optimized under ICM as compared to the rest of the treatments. Soil ρb was lower with the application of organic amendments under organic crop management (1.36 g cm^{-3}), followed by ICM (1.41 g cm^{-3}), as compared to inorganic crop management (1.41 g cm^{-3}). The enforcement of organic matter in organic crop management significantly improved ($p < 0.05$) SOC, AvN, AvP, and AvK by 33.3%, 16.4%, 37.8%, and 20.3% over inorganic crop management. Similarly, integration of organic and inorganic crop management improved ($p < 0.05$) regulating ecosystem services like SOC, AvN, AvP, and AvK by 14.3%, 3.9%, 5.4%, and 9.9%, respectively, over inorganic crop management (Table 2).

3.2 Spatial and crop management amendment variability on microbial diversity

Among the different locations, the highest microbial biomass carbon was found at Pantnagar (0.52 mg g^{-1} soil), followed by Jabalpur (0.39 mg g^{-1} soil). The lowest microbial biomass carbon was found at Ludhiana (0.25 mg g^{-1} soil). The highest bacterial, fungal, and actinomycetes counts were also found to be highest at Pantnagar, followed by Jabalpur. The lowest microbial population was found in Ludhiana (Table 3). Among the different nutrient management plots of rice–wheat cropping systems, across the different locations, the highest bacterial, fungal, and actinomycetes viable cell counts were found under the pure organic plots, followed by integrated plots. The highest microbial biomass carbon was found under organic plots, followed by integrated plots. The lowest microbial biomass carbon was found in Ludhiana (Table 3).

3.3 Spatial and crop management amendment variability on yield sustainability

Averaged over the years (2004–05 to 2017–18), rice grain yield (RGY) varied from 3,543.0 kg ha^{-1} to 3,791.4 kg ha^{-1} across the location. Similarly, wheat grain yield (WGY) varied from 3,406.4 kg ha^{-1} to 4,416.1 kg ha^{-1}. The system productivity expressed in terms of rice equivalent yield (REY) varied from 7,035.6 kg ha^{-1} to 8,223.0 kg ha^{-1} across the location (Table 4). However, no significant difference was recorded between Ludhiana and Pantnagar in terms of RGY, WGY, and REY. However, both the locations had 5.2%–6.2%, 27.5%–14.3%, and 16.5%–10.7% significantly ($p < 0.05$) higher RGY, WGY, and REY over Jabalpur and Modipuram, respectively. Consequently, Ludhiana (0.82) and Pantnagar (0.83) had a significantly ($p < 0.05$) higher sustainability yield index (SYI) than Jabalpur (0.64) and Modipuram (0.72) (Figure 3). Among the crop management practices, the highest grain yield of rice (3,746.3 kg ha^{-1}) and wheat (4,190.4 kg ha^{-1}) was recorded in integrated crop management (ICM) as compared to organic and inorganic crop management. Hence, ICM had increased the system productivity (REY) by 4.7%–6.7%

TABLE 2 Effect of spatial and cop management on soil pH, bulk density, soil organic carbon, and nutrients in the rice–wheat system.

Treatment/location	**Soil pH**	**Pb (g cm^{-3})**	**SOC, g kg^{-1}**	**AvN, kg ha^{-1}**	**AvP, kg ha^{-1}**	**AvK, kg ha^{-1}**
Location						
Jabalpur	7.2	1.33	7.8	276.9	16.5	282.8
Ludhiana	7.4	1.57	5.1	338.9	46.5	154.5
Pantnagar	7.2	1.38	10.6	318.8	58.2	201.1
Modipuram	8.3	1.33	7.4	169.8	24.3	273.7
LSD ($p < 0.05$)	0.12	0.05	0.39	20.6	2.4	17.0
Crop management						
Organic crop management	7.6	1.36	8.8	293.5	40.8	249.6
Inorganic crop management	7.6	1.44	6.6	252.1	29.6	207.4
Integrated crop management	7.4	1.41	7.7	282.6	38.7	227.1
LSD ($p < 0.05$)	0.10	0.02	0.34	7.8	2.1	14.7
Interaction						
LSD ($p < 0.05$)	0.21	0.03	0.68	15.7	4.2	29.4

Pb: bulk density, SOC: soil organic carbon, AvN: available nitrogen, AvP: available phosphorus, AvK: available potassium.

TABLE 3 Effect of spatial and crop management on microbial diversity in the rice–wheat system.

Treatment/location	MBC, mg g^{-1}	Total fungi, x10^4 CFU	Total bacteria, x10^6 CFU	Total actinomycetes, x10^6 CFU
Location				
Jabalpur	0.39	39.8	30.5	12.4
Ludhiana	0.25	5.2	17.7	5.8
Pantnagar	0.52	46.2	54.2	23.0
Modipuram	0.37	32.1	22.3	11.7
LSD ($p < 0.05$)	0.02	3.8	3.7	1.9
Crop management				
Organic crop management	0.45	36.2	40.6	17.5
Inorganic crop management	0.32	25.8	25.4	12.4
Integrated crop management	0.38	30.3	27.6	9.8
LSD ($p < 0.05$)	0.02	3.3	3.2	1.7
Interaction				
LSD ($p < 0.05$)	0.04	6.6	6.4	3.4

MBC: microbial biomass carbon.

TABLE 4 Effect of spatial and crop management on grain yield and system productivity of the rice–wheat system.

Treatment/location	Rice grain yield (kg ha^{-1})	Wheat grain yield (kg ha^{-1})	Rice equivalent yield (kg ha^{-1})
Location			
Jabalpur	3,576.9	3,406.4	7,035.6
Ludhiana	3,734.5	4,416.1	8,223.0
Pantnagar	3,791.4	4,341.4	8,196.7
Modipuram	3,543.0	3,796.9	7,404.2
LSD ($p < 0.05$)	142.4	209.1	572.7
Crop management			
Organic crop management	3,740.1	3,702.0	7,499.4
Inorganic crop management	3,498.0	4,078.2	7,643.1
Integrated crop management	3,746.3	4,190.4	8,002.1
LSD ($p < 0.05$)	123.4	181.1	496.0
Interaction (location × crop management)			
LSD ($p < 0.05$)	246.7	362.1	991.9

over inorganic and organic crop management. Similarly, the highest SYI was recorded in ICM (0.77) as compared to inorganic (0.74) and organic management (0.75) (Figure 3).

3.4 Spatial and crop management amendment variability in economics

Spatial variability significantly influences the farm net returns of the long-term (15 years) rice–wheat cropping system. Among the location, net returns and B:C ratio varied from Indian rupees (INR) 7.4 × 10^4 to 12.8 × 10^4 and 2.02 to 2.95, respectively. The highest net return was obtained in Pantnagar > Ludhiana, and it was 44.1%–63.4% higher than those in Modipuram and Jabalpur. Similarly, on an average, the B:C ratio was increased by 21.0%–35.3% in Pantnagar > Ludhiana over Modipuram and Jabalpur, respectively (Figure 4). Crop management practices had significantly ($p < 0.05$) different net returns and B:C ratio. The ICM gave 22.2% and 23.5% higher net returns over organic and inorganic crop management practices.

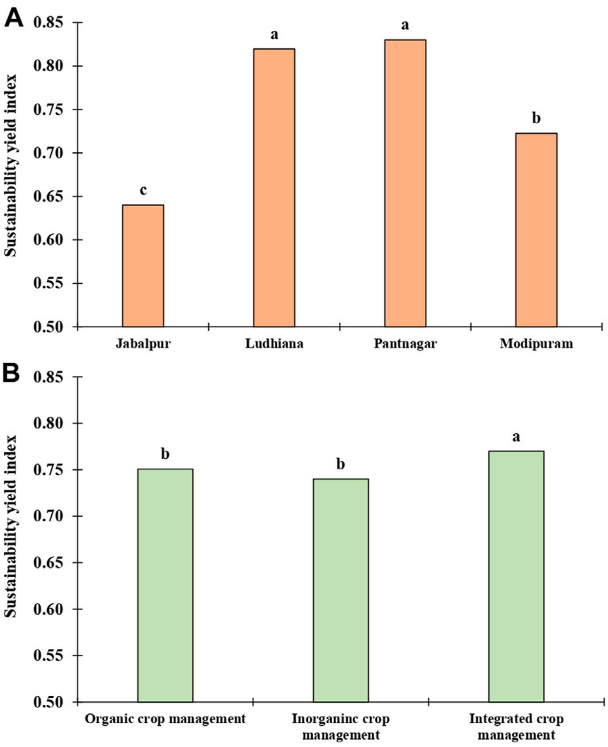

FIGURE 3
Sustainability yield index influenced by **(A)** spatial variation and **(B)** crop management in the rice–wheat system. Different lowercase letters in the same color columns (for each factor) are significantly different at $p < 0.05$.

Similarly, a higher benefit-cost ratio was recorded in ICM (2.52) as compared to organic (1.84) and inorganic (2.45) crop management practices (Figure 4).

3.5 Spatial and crop management amendment variability on the soil quality index

For deriving SQI, soil *p*H, ρb, SOC, AvN, AvP, AvK, MBC, total fungi, total bacteria, and total actinomycetes were included in the data for principal component analysis. In Table 1, the first, second, and third PCs explained 45.2%, 32.4%, and 18.5% of variability with eigenvalues of 4.52, 3.24, and 1.85, respectively. Therefore, the eigenvalues of three PCs (principal components) were ≥ 1 which explained 96.1% of the cumulative variability. The calculated weights for PC 1, PC 2, and PC 3 were 0.47, 0.34, and 0.19, respectively. Soil *p*H, ρb, AvK, fungi, and actinomycetes have the highest factor loading in the first PC1. As AvN has a strong positive correlation with other indicators, AvN was retained in PC1 as the minimum dataset (MDS). In PC2, MBC was selected with the highest loading factor. In PC3, AvP with the highest weighted factor was selected for MDS. The highly weighted factors that were taken for deriving the SQI were AvN (factor loading: 0.918), MBC (factor loading: 0.817), and AvP (factor loading: 0.778) from PC1, PC2, and PC3, respectively. Thus, AvN, MBC, and AvP were selected as MDS for deriving the SQI. Spatial variation influenced the SQI, and it varied from 0.53 to 0.61. The highest SQI was recorded in Pantnagar (0.63) as compared to other locations (0.53–0.55). Similarly, the SQI for crop management practices were estimated as 0.60, 0.53, and 0.54 in organic, inorganic, and ICM, respectively (Figure 5).

3.6 Interaction and correlation

Spatial variation (Jabalpur, Ludhiana, Pantnagar, and Modipuram) and crop management practices (organic, inorganic, and ICM) having a significant ($p < 0.05$) interaction with productivity, economics, and soil quality indicators (soil *p*H, ρb, SOC, AvN, AvP, AvK, MBC, total fungi, total bacteria, and total actinomycetes) were studied. The interaction between spatial variation and crop management practices is presented in Tables 1–4; Figure 6 revealed a strong relationship between soil quality indicators like SOC (r = +0.84, $p < 0.01$) and MBC (r = +0.72, $p < 0.01$) with SQI. Soil microbial diversity like actinomycetes was also strongly correlated with soil quality indicators like ρb (r = 0.92, $p < 0.001$), AvN (r = +0.90, $p < 0.01$), and total fungi (r = +0.77, $p < 0.01$). Similarly, MBC was strongly correlated with soil physical indicators *viz.* ρb (r = −0.88, $p < 0.01$) (Figure 6). The favorable relationship between soil quality indicators and SQI has a significant impact on soil ecosystem services.

4 Discussion

4.1 Current and future importance of organic and toward organic approaches in the IGP

Many districts in the IGPs have large tracts of chaur (waterlogged soils), tal (active flood plains), and diara (lamp-shaped depressions/shifting river course) which are flooded during monsoon, and fields get vacated very late for wheat. Furthermore, ρb of trans and upper IGPs are higher than in middle and lower areas indicating soil compaction, leading to a reduction in long-term soil productivity, especially under the rice–wheat system. However, results indicate that the addition of organic manures, especially FYM, helps improve the soil condition, especially the physical properties of soil (Patil et al., 2014). Therefore, the present investigation of organic and toward organic (integrated crop management) approaches aims to reverse the soil's physical property degradation in addition to

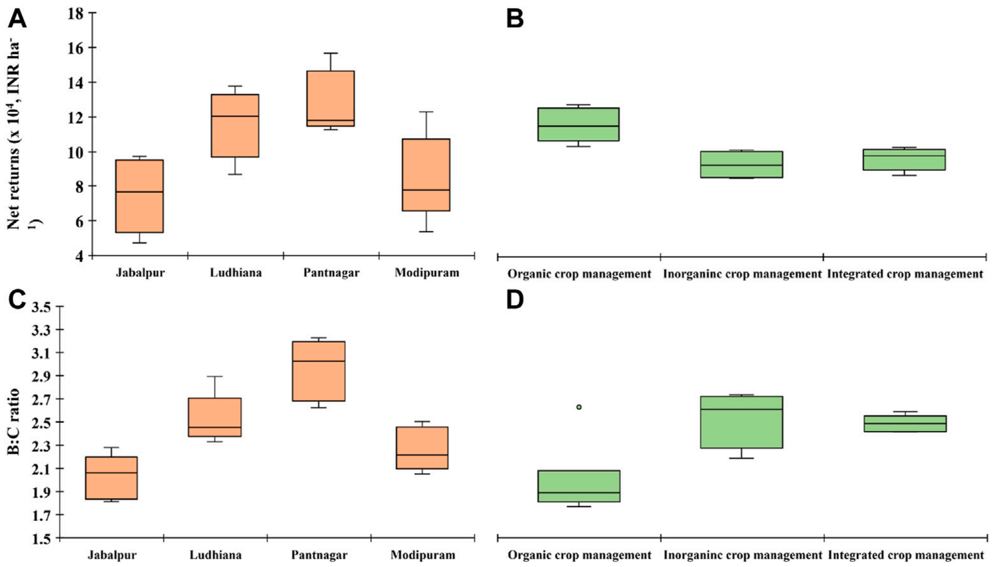

FIGURE 4
Economics **(A,B)**. Net returns **(C,D)**. Benefit: cost (B: C) ratio of the rice–wheat system influenced by spatial variation and crop management.

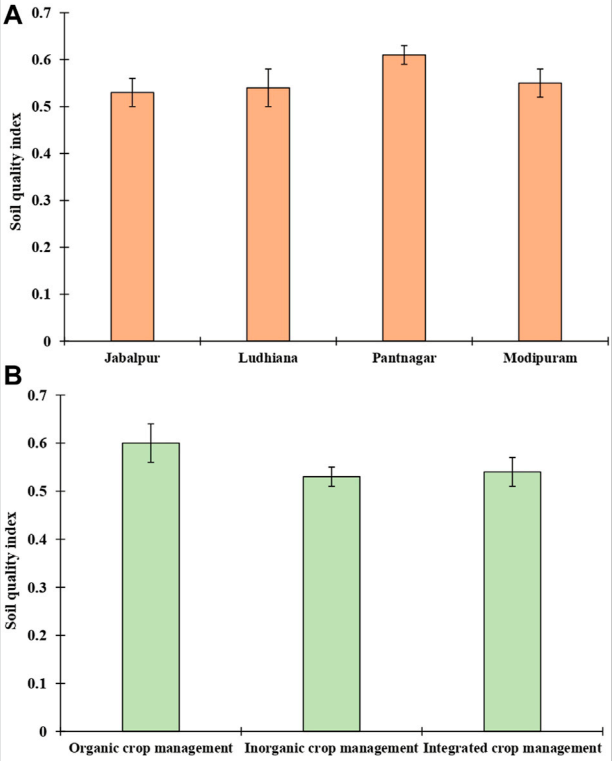

FIGURE 5
Soil quality index influenced by **(A)** spatial variation and **(B)** crop management in the rice–wheat system. Vertical bar represents a standard error (SE) of mean.

maintaining the comparable productivity of the rice–wheat system with that of synthetic-oriented conventional farming.

Crop residues (straws) are a by-product (241 million tonnes of crop residues, including 85 million tonnes from wheat and 21 million tonnes from sorghum, pearl millet, and maize in IGP) of crop production and in the majority of the IGP areas, the residues of rice, wheat and maize are not being utilized as livestock feed; rather, it is burnt, causing pollution, especially air.

Ruminant population in IGP includes 69.86 million (34%) cattle, 36.72 million (44%) buffalo, 46 million (40%) goats, and 6.80 million (13%), thereby cattle and buffalo contributing to a major manure supply for farming. However, progressive replacement of draught animals by electrical and mechanical sources of power, diminishing reliance on crop residues as ruminant fodder, large-scale burning of straw, and a progressive decline in the recycling of farmyard manure for enriching soils have all upset the traditional symbiotic interactions between crops and livestock in the small-holder, mixed farming systems in the IGP (Rao, 2002). Only a few parts of IGP, namely, the middle and lower areas continue to utilize crop residues for livestock feed. Therefore, it again provides great opportunities to utilize the crop residues in the Trans and Upper Gangetic Plains to promote organic and toward organic approaches there by which the long-term soil productivity could be maintained as evidenced from the current study.

Deteriorating water quality in the IGPs is a major concern, especially in the intensively cultivated areas with synthetic inputs. A study conducted by Sihi et al. (2020) points out that the quality parameters of water (nitrate, NO_3; total dissolved solids (TDS); electrical conductivity (EC)), *p*H, and irrigation (sodium

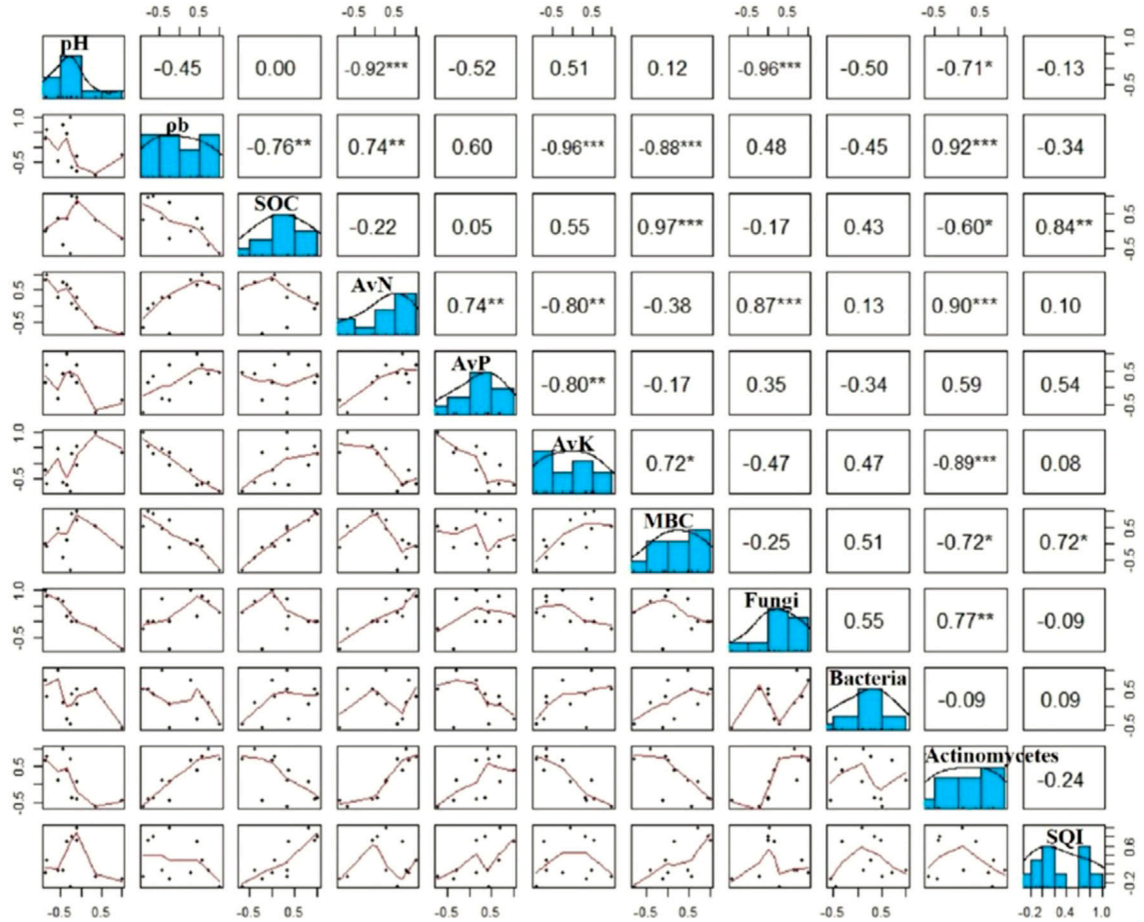

FIGURE 6
Correlations between soil quality indicators as influenced by spatial variation and crop management in the rice–wheat cropping system. pb: bulk density, SOC: soil organic carbon; AvN: available nitrogen, AvP: available phosphorus, AvK: available potassium, microbial biomass carbon, SQI: soil quality index.

adsorption ratio (SAR) and residual sodium carbonate (RSC)) used for drinking purposes were below permissible limits for all samples collected from organic fields and those from conventional fields over the long term (~15 and ~20 years). The magnitude of water NO_3 contamination in conventionally farmed fields was approximately double that of organic fields in the IGP in South-Eastern Asia. Therefore, the current study on the long-term effect of organic and toward organic approaches is more relevant in reducing the water pollution in the Gangetic areas in addition to sustaining the crop productivity and its interaction with livestock systems in the region.

Furthermore, the Government of India has been focusing on the promotion of organic and natural farming on either side of the Ganga River up to 5 km stretches in order to reduce the agriculturally induced water pollution in the river. Schemes such as Paramparagat Krishi Vikas Yojana (PKVY; Traditional Agricultural Development Plan), Namami Ganga, and Rashtriya Krishi Vikas Yojana (RKVY; National Agricultural Development Plan) are being implemented to promote organic farming practices in the IGP areas. It is aimed to bring 10% of the area under organic farming by 2030 by using available organic resources such as livestock manures, cropping system diversification including green manuring, crop residue utilization for soil health restoration, sustaining the crop-livestock interactions, and crop productivity, reducing the water and air pollution. Therefore, findings from the current study on the long-term (15 years) impact on organic and toward organic (integrated crop management) approaches will enable the policymakers to implement the eco-system restoration farming practices in the IGPs.

4.2 Spatial variability and crop management on yield sustainability and economics

In IGPs, the rice–wheat cropping system is the life-supporting and most prevalent production system, occupying about ~13.5 million ha of productive land (~10 m ha in India). The land degradation and soil fertility depletion were reported across different states, especially on account of the non-application of organic amendments to the system and without the inclusion of leguminous green manure crops/crop residue recycling. Inclusion of legumes and green manure crops like *Sesbania* increased the system productivity and stabilized the yield sustainability in saline-alkaline soils (Parihar et al., 2018) of the IGP and acidic soils of the Eastern Himalayan region (Ansari et al., 2022b). In this study, SYI varied from 0.64 to 0.73 due to spatial variability and 0.74 to 0.77 due to manipulation in crop management practices. Across the location and treatment, the SYI value is higher than 0.50 of the critical limits. This indicates long-term enforcement of organic amendments either in organic crop management or ICM, enhancing the system productivity and stabilizing the yield sustainability as compared to inorganic crop management. Therefore, this study notably suggests that enforcement of organic inputs along with the inclusion of green manuring in the system could stabilize the system's productivity and sustainability in the IGP. Due to an improvement in the physical, biological, and chemical characteristics of the soil, the addition of green manure crops and the enforcement of organic amendments have emerged as potential options to increase economic production (grain yield) (Babu et al., 2020a; Ansari et al., 2021). The nutrient availability and microbial diversity are directly related to the improvement in soil productivity. The increased grain production of rice and wheat in this study, compared to the organic and inorganic nutrient additions and crop management, led to higher net returns and the benefit-cost ratio being obtained under ICM. Due to the changes occurring in the soil health and climate as a result of the continuous and expanded use of synthetics in farming, policy planners are placing a greater emphasis on food security, safety, and sustainability. Therefore, results clearly bring out that organic amendment integration in the existing conventional system (synthetic-based) is important and needs to be promoted for the long-term sustainability of the rice–wheat system.

4.3 Spatial variability and crop management on soil quality indicators and ecosystem services

Long-term data generated in this study under the national level scheme, namely, the All India Network Programme on Organic Farming indicates that the crop productivity of selected crops in identified regions having better soil health can be sustained without an external supply of synthetic fertilizers and pesticides. However, soil quality parameters are better under organic management, which will again be helpful for improved water and nutrient use efficiency of the cropping system, leading to the long-term sustainability of the cropping system. Maintaining supporting, and regulating ecosystem services require ecologically feasible and socially acceptable agriculture management technologies (Baveye et al., 2016). Soil quality refers to a set of specific soil factors that are crucial for long-term agricultural production and ecosystem (vegetation and soil) health (Karlen et al., 2001). Organic matter enforcement, either through green manuring (leguminous) or organic nutrient amendments in the soil, is known to increase soil organic C accumulation and improve soil biological function (diversity in soil microbial population) in tropical and subtropical soils (Ansari et al., 2022a). This study revealed that enforcement of organic manure provided a large amount of C into the soil (8.21 Mg C ha^{-1} $annum^{-1}$) through FYM/oilcake/biofertilizers and (> 9.58 Mg C ha^{-1} $annum^{-1}$) through green manuring under organically crop management treatment. Similarly, the integration of organic manure provided 5.88 Mg C ha^{-1} $annum^{-1}$ and > 9.58 Mg C ha^{-1} $annum^{-1}$ through green manuring under ICM. Therefore, all these enforcements significantly ($p < 0.05$) increased the C stock in the soil under organic and ICM as compared to inorganic crop management. Several factors, such as spatial variation, land-use patterns, vegetation types, organic manure enforcement, green manuring, and soil management strategies, have a significant impact on soil nutrients (Choudhury et al., 2021). Intensive crop cultivation without sufficient nutrient application and input addition to the soil lowers soil carbon stock and nutrient concentrations and has negative consequences for soil physicochemical and biological qualities (Choudhury et al., 2021).

In this study, it is reported that organic enforcement improved by +41.4, +11.2, and +42.2 and ICM improved by +30.5, +9.1, and 19.7 kg AvN, AvP, and AvK kg ha^{-1}, respectively, as compared to inorganic crop management. Under organic crop management combined with *Sesbania* green manuring, the highest concentration of N, P, and K can be attributed to nutrient addition and recycling, which improves soil nutrient concentrations and microbial diversity (Choudhury et al., 2021). Stabilization of soil C and nutrients will help reduce CO_2 emissions into the atmosphere and can address several SDGs, including climate action (SDG–13) and life on land (SDG–15), by preserving soil microbial diversity, which is an important component of growing crops for humans and livestock on the planet. *Sesbania* is a leguminous crop with a low C:N ratio (23.5: 1.0), which aids in residue decomposition and nutrient release, as well as having potential microbial diversity (Babu et al., 2020a; Ansari et al., 2022c). In *Sesbania* integrated sites, the crop cover may have generated a conducive environment for greater microbial breakdown, resulting in faster decomposition and nutrient release. The balance between the addition of C inputs (root exudates, root biomass, and crop wastes) and C losses is critical for increasing soil C (respiration by soil biota and erosion). The amount of residue accumulated, the quality of the residue, and the rate of decomposition all play a role (Almagro et al., 2021). The inclusion of green manure biomass boosts microbial activities substantially. Under cereal-based cropping systems, including nutrient-rich leguminous crops and incorporating them as green manure biomass into the soil protects nutrients for succeeding crops, improves carrying capacity, and makes the system feasible and sustainable (Babu et al., 2020b; Ansari et al., 2021). In this study, green manure and organic manure enforcement greatly improve the soil quality by reducing the bulk density (about +5.9%) and enhancing the soil microbial population (+40%–60%). Green manuring and organic manure enforcement resulted from a significant reduction in fertilizer dependency due to increased nutrient availability and altered biomass-mediated soil ecological functions and ecosystem services (Shahid et al., 2013). Soil organic matter is the storehouse of different nutrients required for plant growth and development. It plays a crucial role in maintaining the soil health and sustainable crop production. Excessive application of agrochemicals during the last few decades for intensive agriculture has resulted in the severe degradation of different soil properties. Long-term management of soil in different ways for nutrient, insect, and disease management has a significant impact on soil physic-chemical and biological properties. Biological diversity, especially bacteria, fungi, and actinomycetes, has been crucial to understanding the structure and function of soil ecology, and diversity plays a key role in the resilience and adaptability of complex systems (Bebber and Richards, 2022). The highest number of bacterial, fungal, and actinomycetes viable counts found under organic management plots may be due to the greater availability of soil organic carbon (SOC) and nutrients due to the application of different organic inputs/practices like FYM, vermicompost, and green manuring that might have favored the growth and proliferation of microbes. Growth and colonization of soil microorganisms can be affected by the physico-chemical properties of soil. Naher et al. (2021) found a greater microbial population under the long-term PL (poultry litter)-INM and CD (cow dung)-INM (balance chemical fertilizer + decomposed poultry litter/cow dung) plots as compared to chemically managed plots. They also found higher enzymatic activities and a greater population of nitrogen-fixing and phosphate-solubilizing bacteria under PL-INM and CD-INM plots. Naher et al. (2021) also found a significant increase (18%) in soil organic matter with the application of poultry litter (at 2.0 t ha^{-1}). Similarly, Adeleye et al. (2010) reported a 37.8% increase in SOC with the application of poultry litter (at 10 t ha^{-1}). The greater microbial population is directly related to the microbial biomass carbon present in the soil.

The plant biomass and amendments of organic manure influence changes in microbial populations (Naher et al., 2021). Previous studies also affirmed that soil's physical, chemical, and biological properties influence the soil community structure and ecosystem services (Pang et al., 2017). It is also reported that the cropping system, soil fertility, and soil microbial community structure are all interrelated and can be adjusted at the same time, as confirmed experimentally (Song et al., 2018). Apart from the treatment effect, the varying population of microbes under different locations is governed by soil and environmental factors. The greater amount of microbial biomass at Pantnagar as compared to others may be due to the availability of more vegetation cover and comparatively cooler climate which might have favored the proliferation of microbes. The results of regulating and supporting ecosystem services from long-term organic and integrated crop management will further strengthen and pave way for more such studies to precisely estimate and value these benefits which can be passed on to farm households by the policymakers.

4.4 Spatial variability and crop management on the soil quality index

One of the most important and easily adopted strategies for improving, regulating, and supporting ecosystem services and fighting soil degradation is quality biomass inversion through green manuring in cropping systems (Lal, 2017). Biomass accumulation and retention, as well as organic amendment enforcement-mediated soil microclimate, generates a favorable soil environment that promotes nutrient pumping from the sub-surface to the surface for plant uptake, and improvement of the nutrient utilization efficiency leads to increased crop output (Lal, 2017). However, an intensive cropping system in IGP with unsustainable agro-techniques could result in land degradation, which leads to deterioration in the soil quality (Kumar et al., 2019). In this long-term study (15 years), we notably observed that enforcement of organic amendments in organic crop management, followed by ICM, improved the soil quality indicators like SOC, MBC, AvN, AvP, and AvK, as well as enriched the microbial diversity (fungi, actinomycetes, and bacteria). The microbial diversity improved due to the abundant energy obtained from the organic substrates and drives the biological processes like nutrient/microbial decomposition, nutrient transformation/mobilization, and physical property optimization. All the organic enforcements act as a major source of nutrients and improve resilience. Furthermore, higher SQI across the crop management and location affirmed that green manuring and organic amendments under organic crop management and ICM resulted in a substantial reduction in dependency on fertilizers through improvement in nutrient storage in soil and their availability for plant uptake in long term.

Conclusion

The essential goals for agriculture's sustainable production are to reduce gas emissions and optimize carbon, as well as nutrient management efficiency with restoring the soil quality. Organic manure enforcement along with green manuring improves the soil's biological function and ecosystem services. Continuous enforcement of green manuring and organic manure through different sources improved the soil's biological properties like soil organic carbon (14.3%–33.3%), available N (4.0%–16.4%), available P (5.4%–37.8%), and available K (9.9%–20.3%) in organic and integrated crop management, respectively, over inorganic crop management. Similarly, these practices also improve the biological diversity in soil *viz.*, microbial biomass carbon (18.4%–40.6%), fungi (19.5%–40.3%), bacteria (47.1%–59.8%), and actinomycetes (41.1%–78.6%) in organic and integrated crop management, respectively, over inorganic crop management. Hence, higher SYI was recorded in ICM (0.77) followed by organic (0.75) than in inorganic crop management (0.74). With the improvement in soil biological functions and availability of nutrients, the SQI was estimated to be higher in organic (0.60), followed by ICM (0.54) than inorganic crop management (0.53). Hence, enforcement of organic manure along with green manuring, either as fully organically managed or in integration, yield sustainability, soil quality, nutrient availability, and biological function leads to improving the ecosystem services and restoring land productive capacity in the Indo-Gangetic Plains of India.

Policy implication

Rice–wheat (RWS) is the life–supporting and pre-dominant production system spread over ~10.0 M ha in the Indian Indo-Gangetic Plains, meeting 60% of the calorie intake of the population. Contemporary soil and crop management practices are capital, energy, water, and external input-intensive upsetting the ecological balance and depleting ground water and soil organic carbon, thereby affecting the long-term sustainability of the RWS. The result of the present study indicates that integrated crop management otherwise can be referred to as the toward organic approach and organic management as National Standard for Organic Products (NSOP) standards are able to sustain the system with better soil quality and yield stability with supporting and regulating ecosystem services. Overall, our estimates suggested that the adoption of ICM in rice–wheat systems increases system farm productivity by ~5% and soil organic carbon by 2.46 Mg ha^{-1} over traditional rice–wheat systems (business as usual of the region). The Indian government is promoting organic and natural farming along both banks of the Ganges River up to 5 km lengths. To encourage the use of organic farming methods in the IGP regions, programs like the Rashtriya Krishi Vikas Yojana (RKVY; National Agricultural Development Plan), Namami Ganga, and Paramparagat Krishi Vikas Yojana (PKVY; Traditional Agricultural Development Plan) are being implemented. By utilizing readily available organic resources like livestock manures, cropping system diversification, including green manuring, crop residue utilization for soil health restoration, sustaining crop–livestock interactions and crop productivity, and lowering water and air pollution, it is intended to convert 10% of the agricultural land to organic farming by 2030. Hence, it is presumed that if a 10% area of RWS brings under integrated organic nutrient management that will add ~5% in food grain in addition to ~3.32 × 10^6 Mg C ha^{-1} storage in soil carbon over traditional production practices. Therefore, findings from the study will help the policymakers to realize the benefits of long-term organic and integrated crop management practices and devise appropriate policies for incentivization including extending carbon credit benefits *in lieu* of contributing to ecosystem services for the adoption of the toward organic approach. The findings of the present study will also reinforce India's commitments toward COP-26 and Bonn challenges.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

ASP: Visualization, supervision and project administration, MAA: conceptualization, data analysis, writing of original and first draft, and review and editing of the final draft; NR: data curation, review and editing, visualization, and supervision; SB: review and editing; AKP: statistical analysis, and review and editing; PCG: data curation and editing of materials and method: JC: data curation, and review and editing; MS: meteorological data analysis; RS: review and editing; RKJ: review and editing; DD: review and editing; ALM: review and editing; GVC: data compilation; MHA: review and editing of the first and final draft; RS: review and editing; CSA, DKS, and PBS: data curation.

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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.

The handling editor IP declared a past co-authorship with the authors SB and RS.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.972394/full#supplementary-material

References

Adeleye, E. O., Ayeni, L. S., and Ojeniyi, S. O. (2010). Effect of poultry manure on soil physico- chemical properties, leaf nutrient contents and yield of yam (*Dioscorea rotundata*) on alfisol in southwestern Nigeria. *Am. J. Sci.* 6 (10), 871–878. https://www.researchgate.net/publication/259999743.

Almagro, M., Antonio, R. N., Elvira, D. P., Juan, A., and María, M. M. (2021). Plant residue chemical quality modulates the soil microbial response related to decomposition and soil organic carbon and nitrogen stabilization in a rainfed Mediterranean agroecosystem. *Soil Biol. Biochem.* 156, 108198. doi:10.1016/j.soilbio.2021.108198

Ansari, M. A., Babu, S., Choudhury, J., Ravisankar, N., and Panwar, A. S. (2022c). Soil quality restoration and yield stabilization in acidic soils of northeastern Himalayas: Five years impact of green manuring and crop residue management. *Front. Environ. Sci.* 10 (940349), 1–18. doi:10.3389/fenvs.2022.940349

Ansari, M. A., Choudhury, B. U., Layek, J., Das, A., Lal, R., and Mishra, V. K. (2022b). Green manuring and crop residue management: Effect on soil organic carbon stock, aggregation, and system productivity in the foothills of eastern himalaya (India). *Soil Tillage Res.* 218, 105318. doi:10.1016/j.still.2022.105318

Ansari, M. A., Choudhury, B. U., MandalJat, S. S. L., and Meitei, C. (2022a). BungbungchaConverting primary forests to cultivated lands: Long-term effects on the vertical distribution of soil carbon and biological activity in the foothills of Eastern Himalaya. *J. Environ. Manage.* 301, 113886. doi:10.1016/j.jenvman.2021.113886

Ansari, M. A., Saha, S., Das, A., Lal, R., Das, B., Choudhury, B. U., et al. (2021). Energy and carbon budgeting of traditional land use change with groundnut-based cropping system for environmental quality, resilient soil health and farmers income in eastern Indian Himalayas. *J. Environ. Manage.* 293, 112892. doi:10.1016/j.jenvman.2021.112892

Aulakh, C. S., and Ravisankar, N. (2017). Organic farming in Indian context: A perspective. *Agricul. Res. Jour.* 54 (2), 149–164. doi:10.5958/2395-146x.2017.00031.x

Babu, S., Mohapatra, K. P., Das, A., Yadav, G. S., Tahasildar, M., Singh, R., et al. (2020b). Designing energy-efficient, economically sustainable and environmentally safe cropping system for the rainfed maize–fallow land of the Eastern Himalayas. *Sci. Total Environ.* 722, 137874. doi:10.1016/j.scitotenv.2020.137874

Babu, S., Singh, R., Avasthe, R. K., Yadav, G. S., Das, A., Singh, V. K., et al. (2020a). Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in Eastern Himalayas. *Sci. Rep.* 10 (1), 16129–16214. doi:10.1038/s41598-020-73072-6

Banerjee, V., Krishnan, P., Das, B., Verma, A. P. S., and Varghese, E. (2015). Crop status index as an indicator of wheat crop growth condition under abiotic stress situations. *Field Crops Res.* 18, 16–31. doi:10.1016/j.fcr.2015.06.009

Baveye, P. C., Baveye, J., and Gowdy, J. (2016). Soil ecosystem services and natural capital: Critical appraisal of research on uncertain ground. *Front. Environ. Sci.* 4, 1–49. doi:10.3389/fenvs.2016.00041

Bebber, D. P., and Richards, V. R. (2022). A meta-analysis of the effect of organic and mineral fertilizers on soil microbial diversity. *Appl. Soil Ecol.* 175, 104450. doi:10.1016/j.apsoil.2022.104450

Bhattacharyya, P., and Chakraborty, G. (2005). Current status of organic farming in India and other countries. *Indian J. Fert.* 1 (9), 11–123.

Blake, G. R., and Hartge, K. H. (1986). *Bulk density in: Methods of soil analysis, Part I: Physical and mineralogical methods*. Editor A. Klute. second ed. (Madison WI: American Society of Agronomy).

Charyulu, K., and Biswas, S. (2010). *Organic input production and marketing in India : Efficiency, issues and policies*. IIMA, Ahmedabad: CMA Publication, 239.

Choudhury, B. U., Ansari, M. A., Chakraborty, M., and Meetei, T. T. (2021). Effect of land-use change along altitudinal gradients on soil micronutrients in the mountain ecosystem of Indian (Eastern) Himalaya. *Sci. Rep.* 11, 14279. doi:10.1038/s41598-021-93788-3

Dwivedi, B. S., Singh, V. K., and Meena, M. C. (2017). Efficient nitrogen management under predominant cropping systems of India. *Indian Nitrogen Assess.* 2017, 95–115. doi:10.1016/B978-0-12-811836-8.00007-0

Gangwar, B., Singh, V. K., and Ravisankar, N. (2013). Fertilizer best management practices in important cropping systems. *Indian J. Fert.* 9 (4), 34–51. https://krishi.icar.gov.in/jspui/bitstream/123456789.

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educ. Psychol. Meas.* 20, 141–151. doi:10.1177/001316446002000116

Karlen, D. L., Andrews, S. S., and Doran, J. W. (2001). Soil quality: Current concepts and applications. *Adv. Agron.* 74, 1–40. doi:10.1016/S0065-2113(01)74029-1

Kumar, N., Nath, C. P., Hazra, K. K., Das, K., Venkatesh, M. K., Singh, S. S., et al. (2019). Impact of zero-till residue management and crop diversification with legumes on soil aggregation and carbon sequestration. *Soil Tillage Res.* 189, 158–167. doi:10.1016/j.still.2019.02.001

Lal, R. (2017). Improving soil health and human protein nutrition by pulses-based cropping systems. *Adv. Agron.* 145, 167–204. doi:10.1016/bs.agron.2017.05.003

Mahajan, A., and Gupta, R. D. (2009). *Balanced use of plant nutrients: Integrated nutrient management (INM) in a sustainable rice–wheat cropping system*. Dordrecht: Springer. doi:10.1007/978-1-4020-9875-8_8

Meena, B. L., Fagodiya, R. K., Prajapat, K., Dotaniya, M. L., Kaledhonkar, M. J., Sharma, P. C., et al. (2018). "Legume green manuring: An option for soil sustainability," in *Legumes for soil health and sustainable management* (Singapore: Springer), 387–408. doi:10.1007/978-981-13-0253-4_12

Naher, U. A., Haque, M. M., Khan, F. H., Sarkar, M. I. U., Ansari, T. H., Hossain, M. B., et al. (2021). Effect of long-term nutrient management practices on soil health and paddy yield of rice-rice-fallow cropping system in tropic humid climate. *Eur. J. Soil Biol.* 107, 103362. doi:10.1016/j.ejsobi.2021.103362

NSSO (2013). *India - situation assessment survey of agricultural households, january - december 2013, NSS 70th round*. New Delhi: National Sample Survey Organization - Ministry of Statistics and Programme Implementation (MOSPI), Government of India.

Olsen, S. R., and Sommers, L. E. (1982). "Phosphorus," in *Methods of soil analysis: Part 2. Chemical and microbiological properties*. 2nd ed (Madison, WI: ASA and SSSA), 403–430.

Pang, G., Cai, F., Li, R., Zhao, Z., Li, R., Gu, X., et al. (2017). Trichoderma-enriched organic fertilizer can mitigate microbiome degeneration of monocropped soil to maintain better plant growth. *Plant Soil* 416, 181–192. doi:10.1007/s11104-017-3178-0

Panwar, A. S., Ravisankar, N., Sharma, S. K., and Suja, G. (2020). "Organic and low input agriculture: Gandhian Way," in *Mahatma gandhi's vision of agriculture: Achievements of ICAR*. Editors H. Pathak, Suresh Pal, and T. Mohapatra (New Delhi: Indian Council of Agricultural Research), 86–96.

Panwar, A. S., Shamim, M., Ravisankar, N., Ansari, M. A., Singh, R., Prusty, A. K., et al. (2021). Influence of long-term fertilization with organic sources on crop productivity and soil quality in rice-wheat system under arid and sub humid conditions. *Indian J. Fert.* 16 (6), 544–554. https://scholar.google.com/citations.

Parihar, C. M., Parihar, M. D., Sapkota, T. B., Nanwal, R. K., Singh, A. K., Jat, S. L., et al. (2018). Long-term impact of conservation agriculture and diversified maize rotations on carbon pools and stocks, mineral nitrogen fractions and nitrous oxide fluxes in inceptisol of India. *Sci. Total Environ.* 604-641, 1382–1392. doi:10.1016/j.scitotenv.2018.05.405

Patil, N. G., Tiwary, P., Bhattacharyya, T., Chandran, P., Sarkar, D., Pal, D. K., et al. (2014). Natural resources of the indo-gangetic plains: A land-use planning perspective. *Curr. Sci.* 107 (9), 1537–1549. https://www.researchgate.net/publication/268212008.

Phillips, R. L. (2014). "Green revolution: Past, present, and future," in *Neal K. Van alfen. Encyclopedia of agriculture and food systems* (Amsterdam, Netherlands: Academic Press), 529–538. doi:10.1016/B978-0-444-52512-3.00208-4

Rao, P. P. (2002). "Role of livestock subsystem in sustaining the mixed crop-livestock farming systems in the Indo-Gangetic plains in India," in *Rice-wheat consortium regional technical coordination committee meeting. 10–13 February 2002* (New Delhi, India: Rice–Wheat Consortium for the Indo-Gangetic Plains).

Ravisankar, N., Ansari, M. A., Panwar, A. S., Aulakh, C. S., Sharma, S. K., Suganthy, M., et al. (2021). Organic farming research in India: Potential technologies and way forward. *Indian J. Agron.* 66, S142–S162. https://www.researchgate.net/publication/356000991.

Ravisankar, N., Ansari, M. A., Shamim, M., Prusty, A. K., Singh, R., Panwar, A. S., et al. (2022). Sustainable livelihood security of small farmers improved through a resilient farming system in the semiarid region of India. *Land Degrad. Dev.* 33, 2830–2842. doi:10.1002/ldr.4358

Sengupta, R. (2021). Land degradation in India hurts farmers and forest dwellers the most. Avaliable At: https://www.downtoearth.org.in/news/environment/land-degradation-in-india-hurts-farmers-and-forest-dwellers-the-most-78701.

Shahid, M., Nayak, A. K., Shukla, A. K., Tripathi, R., Kumar, A., Mohanty, S., et al. (2013). Long-term effects of fertilizer and manure applications on soil quality and yields in a sub-humid tropical rice-rice system. *Soil Use Manag.* 29, 322–332. doi:10.1111/sum.12050

Sharma, S. K., Ravisankar, N., Chander, M., Jat, G., Choudhary, R., Kumar Fagodiya, R., et al. (2021). Organic agriculture under changing climate scenario. *Indian J. Agron.* 66, S82–S94. https://www.researchgate.net/publication/362491232.

Sihi, D., Dari, B., Yan, Z., Sharma, D. K., Pathak, H., Sharma, O. P., et al. (2020). Assessment of water quality in Indo-Gangetic Plain of South-Eastern Asia under organic vs. conventional rice farming. *Water* 12, 960. doi:10.3390/w12040960

Song, X., Tao, B., Guo, J., Li, J., and Chen, G. (2018). Changes in the microbial community structure and soil chemical properties of Vertisols under different cropping systems in Northern China. *Front. Environ. Sci.* 6, 132. doi:10.3389/fenvs.2018.00132

Stagnari, F., Maggio, A., Galieni, A., and Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chem. Biol. Technol. Agric.* 4, 2. doi:10.1186/s40538-016-0085-1

Suárez, R. P., Goijman, A. P., Cappelletti, S., Solari, L. M., Cristos, D., Rojas, D., et al. (2021). Combined effects of agrochemical contamination and forest loss on anuran diversity in agroecosystems of east-central Argentina. *Sci. Total Environ.* 759, 143435. doi:10.1016/j.scitotenv.2020.143435

Subbiah, B. V., and Asija, C. L. (1956). A rapid procedure for estimation of available nitrogen in soils. *Curr. Sci.* 25, 259–260.

Tripathi, S., Srivastava, P., Devi, R. S., and Bhadouria, R. (2020). "Influence of synthetic fertilizers and pesticides on soil health and soil microbiology," in *Agrochemicals detection, treatment and remediation pesticides and chemical fertilizers* Editor M. N. V. Prasad. (Oxford, United Kingdom: Butterworth Heinemann, Elsevier Ltd), 25–54. doi:10.1016/B978-0-08-103017-2.00002-7

Vance, E. D., Brookes, P. C., and Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. *Soil Biol. Biochem.* 19 (6), 703–707. doi:10.1016/0038-0717(87)90052-6

Walkley, A., and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38. doi:10.1097/00010694-193401000-00003

Yadav, G. S., Babu, S., Das, A., Mohapatra, K. P., Singh, R., Avasthe, R. K., et al. (2020). No till and mulching enhance energy use efficiency and reduce carbon footprint of a direct-seeded upland rice production system. *J. Clean. Prod.* 271, 122700. doi:10.1016/j.jclepro.122700

Yadav, G. S., Das, A., Kandpal, B. K., Babu, S., Lal, R., Datta, M., et al. (2021). The food-energy-water-carbon nexus in a maize-maize-mustard cropping sequence of the Indian Himalayas: An impact of tillage-cum-live mulching. *Renew. Sustain. Energy Rev.* 151, 111602. doi:10.1016/j.rser.2021.111602

Yuan, B. C., and Yue, D. X. (2012). Soil microbial and enzymatic activities across a chronosequence of Chinese pine plantation development on the Loess Plateau of China. *Pedosphere* 22 (1), 1–12. doi:10.1016/S1002-0160(11)60186-0