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Soil quality and crop productivity under 34 years old long-term rainfed rice based cropping system in an Inceptisol of sub-tropical India

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Introduction: Soil quality deterioration with the introduction of modern agriculture is a major threat to agricultural sustainability and food security and the problem is more aggravated specially under rainfed agriculture. Asessment of soil quality is a tortuous task as it can not be measured directly. The objective of the present investigation was to evaluate the effect of long-term fertilization and manuring on soil quality and identify the most sensitive indicators of assessing soil quality under rainfed rice based system.

Methods: Soil samples were collected from selected six treatments viz. control, 100%NPK, 50%NPK, 50%FYM, 100%FYM and 50%NPK+FYM of 34 years old long-term fertilizer experiment with rainfed rice-lentil cropping system situated at BHU Varanasi, India.

Results and discussion: Result revealed that continuous organic manure application along with inorganic fertilizer increased soil organic carbon by 54.1% over control treatment.Principal component analysis (PCA) was done to screen out key indicators and mean weight diameter, available Fe, available N, potentially mineralizable N, available Zn, FDA hydrolase activity and Clay were selected as key indicators of soil quality. The highest soil quality index (SQI) of 0.95 was found in 50% NPK+FYM treatment. Regression analysis showed better agreement of equivalent rice yield and SQI (0.87). Therefore, the balanced fertilization with organic and inorganic fertilizers is important for sustainability of the rainfed rice-lentil cropping system and this practice may be recommended for rainfed rice based system of Indian Inceptisol.

KEYWORDS

equivalent rice yield, PCA, rainfed, rice-lentil, soil quality

1 Introduction

In the modern agricultural system, securing a sustainable source of income has arisen as the most crucial public concern. Richardson et al. (1) reported that there is need to guarantee food security without jeopardizing ecological stability and the environment has received considerable attention. The soil is a complex ecosystem that provides multiple agricultural and environmental services, as well as supplying food for most terrestrial life (2). Intensive land use practices have complex effects on the physical, chemical, and biological properties of the soil, which has resulted in a reduction in soil quality and sustainable agricultural yield (3, 4). Due to its interaction with soil physicochemical and biological features, soil quality degradation has a negative impact on the sustainability of yields (5). For agricultural production to be self sustaining, strategies that are efficient at sustaining soil quality are receiving more attention (6, 7).

Soil quality is defined as 'the continued capacity of soil to function as a living system, within the ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water environment and promote plant, animal and human health' (8). A soil quality indicator can be categorized as physical, chemical and biological attributes, and the interaction between these components makes up a complex functional state, making it necessary to define how the function of soil about each attribute (9). However, dynamic soil characteristics such as soil organic matter (SOM), aggregation, and the majority of microbiological traits are more sensitive to management techniques, disturbances, and/or changes in land use (10–13). Due to their high sensitivity, microbial and biochemical properties can serve as systematic potential indicators of soil quality for its assessment after ecological stress and perturbation (11, 14, 15). It is important to identify and determine soil quality indicators that are sensitive to changes and disturbances in the soil environment (14). Individual soil indicators cannot be used to determine soil quality because of their interdependence, which makes it difficult to assess soil conditions in a comprehensive manner (16, 17). Consequently, a combination of soil characteristics into a single overall index can make the evaluation more relevant and practical (18). Since the land capability classification system in 1961 (19), issued by United States Department of Agriculture, Soil Conservation Service, a numerous approaches have been developed to evaluate soil quality but the complexity and heterogeneity of soil systems represent a challenge to creating a universal model or method to determine soil quality (20). Among a variety of assessment methods, the approach of soil quality index has been most widely used, because of its quantitative flexibility and suitability for different types of soil (21, 22), and its integration of soil physical, chemical and biological properties. Soil quality indices have been used to assess the effect of agricultural practices (23) and crop production (24) on the soil as well as the impacts of soil management at a regional scale (25). Therefore, to achieve sustainable agricultural production, soil quality index (SQI) and soil productivity provides the key information (26). As soil parameters typically take a long time to manifest, long-term experiments are appropriate to investigate the relationship between soil characteristics and crop yield in order to develop management strategies for improved crop productivity and soil health (27–29).

Rice-based cropping systems are the backbone of India's food security, covering a total area of 38 Mha (30). Throughout the Indo-Gangetic plains (IGP), rice-based cropping pattern is most prevalent among farmers due to region's abundant water supply and fertile land but intensive cultivation, puddling induced soil structure deterioration, excessive use of agrochemicals and injudicious ground water depletion without any regard to environmental protection compromised crop yield throughout IGP region since post green revolution period at cost of soil health (31). Lentil (*Lens esculenta*) is also adapted to local harsh climate and low fertility soil conditions. Because of its adaptation to intercropping and relay cropping, lentil occupies a unique place in cropping systems in northern, eastern, and central India (32). However, limited information are available on long-term impact of chemical fertilization and integrated application of chemical and organic amendments on SQI in rice-lentil cropping systems in the Indo-Gangetic plains, particularly in the middle Indo-Gangetic plains of Varanasi, UP. The study hypothesized that the following soil parameters (physical, chemical and biological) under the influence of inorganic-organic fertilization combined with an organic amendment, such as farmyard manure (FYM), will be significant in enhancing productivity and soil quality in the study region. Thus, in the present study, we studied three aspects of soil quality: (i) To quantify the impact of long-term organic and inorganic amendments addition on soil quality and crop productivity, (ii) To screen physical, chemical and biological indicators of soil quality in a 34 years old long-term rice– lentil cropping system and (iii) to establish soil quality index based on these indicators. The novelty of the present investigation lies in the identification of the best management practices for maintaining soil quality and sustaining crop productivity under rainfed rice based system in Indo-Gangetic Plain.

2 Material and methods

2.1 Description of experimental site and treatment details

The long-term fertilizer experiment (LTFE) with a rice-lentil cropping system on an Inceptisol was initiated in the year of 1985 at Agriculture Research Farm of Banaras Hindu University, Varanasi (25°18′0′′ North latitude, 83°3′0′′ East longitude and at an altitude of 128.93 meter above the mean sea level). The soil of the study site belongs to the order of Inceptisol which is part of the middle Indo-Gangetic plains of India. The climate of the area is characterized by a dry tropical climate with strong variations in seasonal temperature and precipitation. The experimental site receives an average annual rainfall of approximately 1100 mm (80% of which is received by southwest monsoon between June to September), potential evapotranspiration of 1500 mm, and the mean annual minimum and maximum temperature of 8.9°C and 37.9°C, respectively. The mean relative humidity is about 68% which rises to 86% during the wet season and goes down to 33% during the dry season.

The initial (1985) physical and chemical properties of the surface soil (0-15cm) were: the soil pH of 6.7, total SOC content of 1.4 g kg^{-1} of soil, low available N (160 kg ha^{-1}), medium available P (21.20kg ha^{-1}) and available K (119 kg ha^{-1}), respectively. The soil of the experimental site is sandy clay loam with a textural composition consisting of 582 g kg^{-1} of sand, 140 g kg^{-1} of silt and 278 g kg^{-1} of clay. The soil is classified as fine-silty, mixed, hyperthermic Udic Ustochrepts.

The rice (NDR- 97) and lentil (HUL-57) crop sequences were followed every year for 34 years (1985–2019). Rice was grown in the Kharif season (July 1st week every year) followed by lentil (HUL-57) in the rabi season (last week of October-November 1st week). The long-term field experiment was conducted using Randomized Complete Block Design (RCBD) with the following treatments: i) T1: control (no external fertilizer application), ii) T2: 50%NPK (50%RDF (@ 40-20-15 kg/ha N:P:K), iii) T3: 100%NPK (100%RDF (@ 80-40-30 kg/ha N:P:K), iv) T4: 50%NPK + FYM (@ 40-20-15 kg/ha N:P:K + 40kg/ha N through FYM), v) T5: 50%FYM (@40kg/ha N through FYM) and vi) T6: 100%FYM (@80 kg/ha N through FYM). The fertilizer NPK was applied in the form of urea, diammonium phosphate (DAP) and muriate of potash (MOP). The whole field was divided into three blocks each representing a replication (net plot size 10m x 9m).

2.2 Collection and analysis of soil samples

The representative field moist soil samples were collected from each of the plots in each replication at 0-15cm depth after harvesting of wet season rice in October 2019. Samples for biological assays were stored in the refrigerator at 4^0C and samples for chemical assays were dried at room temperature then ground and passed through a 2mm sieve and stored in a plastic container. The physical component of soil quality was assessed by determining soil bulk density (BD) by the core sampler method (33), mean weight diameter (MWD) (34) and soil texture was determined by the Bouyoucos hydrometer method (35). Chemical parameters of soil were assessed by determining soil pH (36), soil organic carbon (SOC) (37), total soil organic carbon (TOC) (38), alkaline potassium permanganate oxidizable soil nitrogen (available N) (39), Olsen phosphorus (available P) (40), NH_4OAc extractable potassium (available K) (41), $CaCl_2$ extractable sulfur (available S) (42), $CaCl_2$ extractable boron (available B) (43) and diethylene triamine penta acetic acid (DTPA)-extractable micro-nutrients (available Zn, Cu, Fe and Mn) (44). The biological parameters of soil quality were determined by measuring microbial biomass C (MBC) (45), mineralizable C (C_{min}) (46), mineralizable N (N_{min}) (47) and enzyme activities viz., dehydrogenase (DHA) (48), acid (ACP) and alkaline phosphatase (ALKP) (49), arylsulphatase (ASP) (50), urease (URE), β-glucosidase (BGL) and fluorescein diacetate hydrolase (FDA) activity (48) of the soils.

2.3 Development of soil quality index

Soil quality index (SQI) was determined by using the steps as described by 17. Minimum data set (MDS) was prepared from the best representing variables, followed by scoring of selected indicators and finally summarizing the weighed and scored indicators into soil quality index. Most representing indicators were carefully chosen from principal component analysis (PCA) based on the eigenvalue >1 as described by (51). Highly weighed factor loadings in each PC for were retained for further analysis. Scoring of selected indicators was performed using linear function where, 'more is better', 'less is better' or 'optimum is better' approach was followed (12, 52, 53).

Weighing factors for each PC were obtained from PCA. Finally, the weighed variable scores were summarized to develop soil quality index (SQI) (53, 54).

$$\mathrm{SQI} = \sum_{i=1}^{n} WiSi$$

where, Wi is the weighting factor and Si is the score of each selected indicator

2.4 Yield and equivalent rice yield

Average yield data of rice and lentil under different treatments was taken and equivalent rice yield (ERY) was calculated for each of the treatments for expressing the yield in a common unit following the formula given below

$$ERY = \left[\frac{Lentil\ \ Yield\ \ x\ \ Unit\ \ Price\ \ of\ \ Lentil}{Unit\ \ Price\ \ of\ \ Rice}\right] + (Rice\ \ Yield)$$

Results

3.1 Effect of long-term fertilization and manuring on soil physical and chemical properties

The result showed that BD ranged from 1.36 to 1.46 Mg m^{-3} in 0-15cm soil depth. In surface soil, the highest BD was observed in the T1 (1.46 Mg m^{-3}) treatment and the lowest in the T6 (1.36 Mg m^{-3}) treatment (Table 1). Continuous combined application of NPK +FYM significantly enhanced the MWD as compared with the control. In 0-15cm depth, MWD was varied between 0.61-0.89, where the highest value was found in the treatment T6, and the lowest value was found in the control (T1) treatment. The soil pH (Table 1) value ranged from 6.1 to 7.3 with the maximum value observed under T3 treatment. It was observed that SOC varied between 3.27-5.04 g kg^{-1} in the surface layer. Results showed that 54.1% higher SOC content was found in 50%NPK+FYM treatment than in control at 0-15 cm depth (Table 1). Total organic carbon (TOC) in different treatment was in the range of 4.10-6.82 g kg^{-1} in the surface layer.

TABLE 1 Effect of long-term fertilization and manuring on soil physical and chemical properties.

Treatment	BD (Mg m^{-3})	MWD (mm)	Clay (%)	pH	SOC (g kg^{-1})	TOC (g kg^{-1})
Control	1.46¶	0.61e	25.6a	6.5ab	3.27c	4.10
100% NPK	1.42a	0.70d	26.1a	6.3ab	3.93b	4.60
50%NPK	1.43a	0.69d	26.2a	7.3a	3.84bc	4.34
50%FYM	1.40a	0.75c	26.6a	7.0ab	4.37b	5.72
100%FYM	1.39a	0.81b	27.6a	6.6ab	4.99a	6.67
50%NPK+ FYM	1.36a	0.89a	27.8a	6.1b	5.04a	6.82

(BD, bulk density; MWD, mean weight diameter; SOC, soil organic C; TOC, total organic C)

¶Values (mean) in each column (between the treatments) for particular soil parameter followed by different lower case letters are significant according to Duncan's Multiple Range Test at P = 0.05.

3.2 Effect of long-term fertilization and manuring on soil macro-nutrients

The available N content under different treatments was in the range of 117 to 184 kg ha^{-1} (Table 2). The available N was significantly higher (184 kg ha^{-1}) in T2 (100%NPK) treatment over control (117 kg ha^{-1}). The available P content in the surface layer varied from 10.2 under control to 41.8 kg ha^{-1} in the T6 treatment. The available P varied significantly among all treatments (Table 2). The available K content under different treatments was in the range of 114-82 kg ha^{-1} (Table 2). Results showed that 39% higher available K content was found in 50%NPK+FYM treatment than in control at the surface layer. It was found that available sulphur content varied between 6.11-17.8 mg kg^{-1} (Table 2). Continuous combined application of organic and inorganic fertilizer significantly increases the available S content as compared to either inorganic fertilizer or control.

3.3 Effect of long-term fertilization and manuring on soil micro-nutrients

It was found that available Zn content was significantly higher in 50%NPK + FYM (1.36 ppm) and 100%FYM (0.95 ppm) treatments as compared to others in 0-15cm depth (Table 3). The extent of available Zn varied between 0.63 ppm under the treatment of 50% NPK (T3) to 1.36 ppm under the treatment of 50% NPK +FYM (T6). It was observed that available Cu ranged between 1.67 ppm under control (T1) to 2.39 ppm in T6. The sample showed significant variation in available Cu content as compared to the control. The available Fe content under different treatments was in the range of 58.5 ppm under the treatment control (T1) to 118 ppm under the treatment of 50% NPK+FYM (Table 3). There was no significant difference in available Fe content in the surface layer. Available Mn in the surface layer varied from 23.8 ppm under T4 to 34.0 ppm in T6. There was no significant treatment effect on available Mn content. The available B content significantly higher (1.66 mg kg^{-1}) was in treatment T6 (50%NPK + FYM) over control (1.40 mg kg^{-1}) at 0-15cm depth (Table 3).

3.4 Effect of long-term fertilization and manuring on biological properties of soil

Results showed that continuous cropping of rice-lentil with 50% NPK+FYM and 100% NPK input significantly increase the acid phosphatase activity over control in surface soil (Table 4). Acid phosphatase activity varied from being lowest (126 µg p-nitrophenol g^{-1} h^{-1}) in the control treatment to highest (369 µg p-nitrophenol g^{-1} h^{-1}) in 50%NPK+FYM treatment. Alkaline phosphatase activity was varied in the range of 72.9-108 µg p-nitrophenol g^{-1} h^{-1} at surface soil. Results showed that continuous

TABLE 2 Effect of long-term fertilization and manuring on soil macro- nutrients.

Treatment	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (mg kg^{-1})
Control	117b¶	10.2d	82.0a	6.79bc
100% NPK	184a	34.2ab	101a	6.96bc
50%NPK	146ab	16.6cd	98.0a	6.11c
50%FYM	125ab	25.1bc	86.9a	14.6ab
100%FYM	159ab	30abc	89.7a	15.6a
50%NPK+FYM	134ab	41.8a	114a	17.8a

¶Values (mean) in each column (between the treatments) for particular soil parameter followed by different lower case letters are significant according to Duncan's Multiple Range Test at P = 0.05.

TABLE 3 Effect of long-term fertilization and manuring on soil micro-nutrients.

Treatment	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	B (mg kg^{-1})
Control	0.88ab¶	1.67c	58.5a	25.2a	1.40b
100% NPK	0.93ab	2.09abc	89.8a	27.5a	1.42b
50%NPK	0.63b	1.87bc	86.5a	24.8a	1.64a
50%FYM	0.81ab	2.23ab	80.2a	23.8a	1.62a
100%FYM	0.95ab	2.20ab	59.2a	28.8a	1.44b
50%NPK+FYM	1.36a	2.39a	118a	34.0a	1.66a

¶Values (mean) in each column (between the treatments) for particular soil parameter followed by different lower case letters are significant according to Duncan's Multiple Range Test at P = 0.05.

application of organic and inorganic fertilizer for 34 years significantly improved 48.1%, 17.7%, 16.3%, 6.03% and 4.8% of alkaline phosphatase activity over control in 50%NPK+FYM, 50% FYM, 100%FYM, 100%NPK and 50%NPK treatment, respectively at surface layer (Table 4). Arylsulphatase activity under different treatments was in the range of 15.6-30.08 μg p-nitrophenol g^{-1} h^{-1}. It was observed that 92.8% higher arylsuphatase activity was found in 50%NPK+FYM treatment than control (Table 4). β-glucosidase was varied in the range of 16.6-30.5 μg *p*-nitrophenol g^{-1} h^{-1} at surface soil (Table 4). Balanced fertilization with organic and inorganics contributed about 83.7% improvement in β-glucosidase over control. Fluorescein diacetate hydrolase activity varied from being lowest (7.66 μg fluorescein g^{-1} h^{-1}) in 50%FYM treatment to highest (14.6 μg fluorescein g^{-1} h^{-1}) in 100%FYM treatment (Table 4). Significantly higher dehydrogenase activity was found in sites supplemented with 50%NPK+FYM (54.89 μg TPF g^{-1} h^{-1}) treatment over control (31.78 μg TPF g^{-1} h^{-1}). The descending trend of DHA was as follows – 50%NPK+FYM > 100%FYM > 50% FYM > 100%NPK > 50%NPK > control (Table 4). Urease was varied in the range of 29.1-61.7 μg NH_4-N g^{-1} 2 h^{-1} at surface soil (Table 4). Plot with nutrient supplementation (50%NPK+FYM) exhibited the highest (61.7 μg NH_4-N g^{-1} 2 h^{-1}) enzymatic activity compared to the control plot (29.1 μg NH_4-N g^{-1} 2 h^{-1}). Results revealed that all treatments recorded significantly higher MBC than the control (Figure 1). The highest magnitude of increase was found in treatment 100%FYM (83.9%) followed by 50%NPK+FYM (82.4%), 50%FYM (62.3%), 100%NPK (44.7%) and 50%NPK (35.2%) over control. Mineralizable C (C_{min}) content under different treatments varied from 223-339 μg g^{-1} 64 d^{-1} and was in the following order: 50%NPK+FYM> 100%FYM> 100%NPK> 50% FYM > 50%NPK> control (Figure 2). Mineralizable N (N_{min}) varied from being lowest (2.13μg NH_4-N g^{-1} d^{-1}) in control treatment to highest (2.85 μg NH_4-N g^{-1} d^{-1}) in 50% NPK+ FYM treatment (Figure 2).

3.5 Formulation of minimum dataset and development of soil quality index and validation

The analytical values of soil quality parameters were run through principal component analysis (PCA) to formulate minimum data set (MDS) (Table 5). Seven principle components (PC 1 to PC 7) were selected for further analysis. Highly weighed factor loading(s) from each PC were selected for formulation of MDS namely MWD, available Fe, available N, potentially

TABLE 4 Effect of long-term fertilization and manuring on activities of various enzymes.

Treatment	ACP (μg p-nitrophenol g^{-1} h^{-1})	ALKP (μg p-nitrophenol g^{-1} h^{-1})	ASP (μg p-nitrophenol g^{-1} h^{-1})	BGL (μg p-nitrophenol g^{-1} h^{-1}	FDA (μg fluorescein g^{-1} h^{-1})	DHA (μg TPF g^{-1} h^{-1}	URE (μg NH4-N g^{-1} 2 h^{-1})
Control	126c¶	72.9b	15.60c	16.62b	10.24ab	31.78b	29.1c
100% NPK	268ab	77.3ab	23.04ab	17.49b	13.8a	40.22ab	35.3bc
50%NPK	165bc	76.4ab	21.41bc	20.93b	11.6ab	36.76ab	59.2a
50%FYM	246abc	85.5ab	25.62ab	18.50b	7.66b	48.73ab	48.6ab
100%FYM	263ab	84.8ab	26.90ab	19.41b	14.6a	49.39ab	51.2ab
50%NPK +FYM	369a	108a	30.08a	30.53a	9.21ab	54.89a	61.7a

(ACP, acid phosphatase activity; ALKP, alkaline phosphatase activity; ASP, arylsulphatase activity; BGL, β-glucosidase activity; FDA, fluorescein diacetate hydrolase activity; DHA, dehydrogenase activity; URE, urease activity)

¶Values (mean) in each column (between the treatments) for particular soil parameter followed by different lower case letters are significant according to Duncan's Multiple Range Test at P = 0.05.

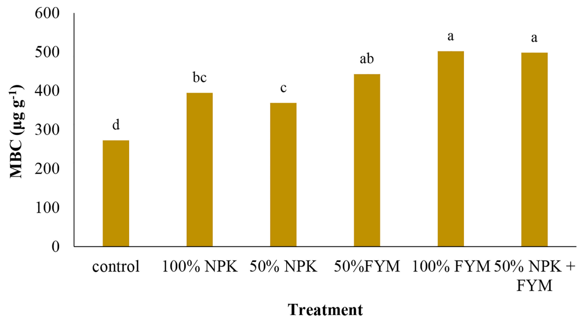

FIGURE 1
Effect of long-term fertilization and manuring on soil microbial biomass carbon.

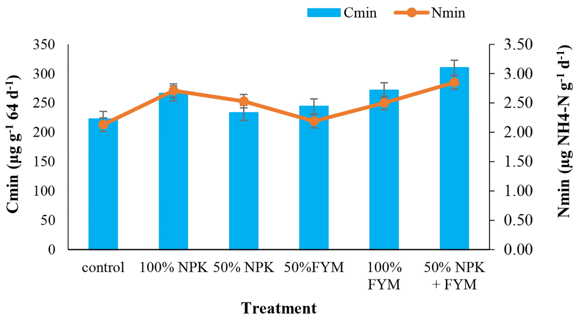

FIGURE 2
Effect of long-term fertilization and manuring on soil mineralizable carbon and mineralizable nitrogen.

mineralizable N, available Zn, FDA hydrolase activity and Clay. Although, PC1 and PC2 exhibited few absolute values greater than 10% of the highest factor loading, they were not considered for MDS as those parameters were correlated significantly (54).

Selected variables were scored using linear scoring function. Since, higher values of all the selected parameters are considered as good in relations to soil function they were grouped as *'more is better'* function. The weighed scores were integrated into soil quality index (SQI). The calculated value of SQI was ranged from 0.68 to 0.95 among the treatments. The highest SQI was observed under 50% NPK+FYM treatment whereas; the lowest SQI was contributed by control (Figure 3). The developed SQI under different management practices was validated with equivalent rice yield (ERY) as productivity was management goal of the present study (Figure 4). To validate the SQI regression analysis was done, and it was found that there was good agreement between SQI and ERY (R^2 = 0.87).

4 Discussion

4.1 Effect of long-term fertilization and manuring on physical and chemical soil properties

Physical and chemical properties varied with different agronomic practices like tillage, irrigation, manuring and fertilization. In our study, it was found that the inclusion of FYM either alone or integrated use of with NPK lowers the bulk density of soil in comparison to control or NPK treatment. The significant decrease in the bulk density resulting from higher soil organic carbon content due to the addition of root and plant biomass, improve soil aggregation and increased root growth and bio pores in the NPK+FYM treated plot (55). The decomposition of organic residues in soil encourages microbial activity which produces organic acid and polysaccharides that act as a binding agent to change micropores into macropores, resulting in a lower BD of the soil (56). Aggregate stability of soil i.e., MWD in our study found to be higher under NPK+FYM treated plots which might be due to the higher organic carbon content of these soil. The incorporation of organic matter causes an increase in soil aggregates because organic substances that are added to the soil through FYM can bind the soil particles together (57). It was reported that the improvement in soil structure is likely to be associated with better root growth and microbial activity when organic matter is added to the soil (58). Combined application of organic and inorganic fertilizers results in slightly lower soil pH due to the presence of organic acids formed after decomposition (59). Hu et al. (60) reported that integrated inorganic and organic manure use increased the microbial activity that promotes the degradation of organic matter by producing organic acids which slightly lower the soil pH. The cation exchange capacity of these organic acids may increase with manure application and accelerate the pH decrease due to the high proton release (61). Long-term manuring and fertilization significantly increased the SOC concentration in surface soil. Soil organic C was higher in the plot receiving NPK + FYM fertilizer as compared to the plot receiving NPK fertilizer alone or unfertilized plot because this can be attributed to the direct addition of organic carbon through FYM and the addition of crop residues and root biomass (62–64). The continuous addition of root biomass, root exudates and plant residues, resulted in more organic residues in the soil, which after decomposition might have increased the concentration of SOC. Liu et al. (65) also found a similar effect.

4.2 Effect of long-term fertilization and manuring on soil macro-nutrients

Different fertilization treatments significantly influenced the availability of N, P, and K in soil. In this study, it was observed that long-term use of chemical fertilizer significantly increases the available N content of the soil in comparison to the control treatment. Qin et al. (66)reported that in sites receiving recommended doses of fertilizer, good growth in root and plant biomass could have a positive influence on the nitrogen content of the soil. In this study, it was observed that the application of either balanced chemical fertilizer alone or in combination with farmyard manure led to a significantly higher content of soil available P over the control treatment. It might be because, during decomposition, organic acids are released, which then contribute to releasing phosphorus from the native phosphorus pool in the soil (67). Long-term use of NPK either alone or in combination with FYM

TABLE 5 Principal components with factor loading of soil parameters.

Statistic or Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigen value	9.96	2.836	2.279	2.041	1.453	1.314	1.049
% **of** variance	39.839	11.344	9.118	8.166	5.812	5.254	4.197
Cumulative %	39.839	51.183	60.301	68.467	74.278	79.533	83.73
Eigen vectors							
Balk density	-0.418	0.592	-0.412	0.018	-0.009	-0.130	0.324
Mean weight diameter	**0.951**	0.107	0	-0.035	0.180	0.025	0.157
Clay	0.056	-0.288	0.427	-0.379	-0.282	-0.095	**-0.443**
pH	-0.373	0.399	0.613	0.159	0.282	0.089	0.269
Available N	0.080	-0.37	**-0.692**	0.331	0.273	0.010	-0.111
Available P	0.867	0	-0.213	0.085	-0.246	-0.116	-0.090
Available K	0.441	0.483	0.11	0.337	-0.407	0.415	0.196
Available S	0.723	-0.413	0.045	-0.347	0.169	-0.027	0.316
Available B	0.367	0.649	0.198	-0.348	0.336	0.234	-0.086
Available Zn	0.533	-0.095	-0.041	-0.252	**-0.636**	0.401	0.187
Available Cu	0.822	-0.024	-0.207	-0.139	-0.167	-0.029	0.001
Available Fe	0.390	**0.722**	0.01	0.226	-0.013	-0.083	-0.403
Available Mn	0.472	-0.034	0.394	0.524	-0.309	-0.343	0.167
Total organic carbon	0.885	-0.103	0.052	0.018	0.192	0.059	0.127
Oxidisable organic C	0.832	-0.122	0.004	-0.081	0.223	0.146	0.105
Mineralizable C	0.908	0.069	-0.100	0.066	-0.121	0.054	-0.033
Mineralizable N	0.523	-0.241	0.185	**0.732**	0.095	-0.075	0.126
Microbial biomass C	0.412	-0.414	0.421	0.392	0.070	0.069	-0.229
Acid phosphatase activity	0.829	0.067	-0.441	-0.045	-0.115	-0.114	-0.152
Alkaline phosphatase activity	0.558	0.340	-0.188	-0.248	0.023	-0.420	0.144
Aryl sulphatase activity	0.807	0.308	-0.063	0.172	0.220	-0.216	-0.190
β-glucosidase activity	0.696	0.304	0.149	-0.032	0.047	0.071	-0.127
Fluorescein diacetate hydrolase activity	-0.138	-0.062	-0.427	0.322	0.171	**0.643**	-0.136
Dehydrogenase activity	0.721	-0.408	0.069	-0.197	0.216	-0.007	0.159
Urease activity	0.613	0.002	0.327	-0.232	0.188	0.243	-0.154

Bold and underlined values related to soil parameters were selected as key indicators of soil quality through PCA.

increases the available K content in the soil. The positive effect of organic manure on available K has been reported by many researchers (58, 68). Urkurkar et al. (69) reported that a significant increase in available K with the application of FYM is likely due to the reduction of K fixation and release of K due to the interaction of organic matter with clay, as well as the direct addition of K to the soil. Sulphur is an essential nutrient for plant growth, and it is considered a secondary nutrient because plants require them in smaller quantities than nitrogen, phosphorus and potassium. Sulphur can be found in soil in organic and inorganic forms. A variety of organic sources, such as farmyard manure, green manure and plant residues, can supply enough sulphur to plants (70). Sharma et al. (71) concluded that the application of inorganic and organic fertilizers together increases soil sulphur content as the decomposition and recycling of organic manures enhance sulphur content in the soil.

4.3 Effect of long-term fertilization and manuring on soil micro-nutrients

DTPA- extractable micronutrient concentration in soil may be affected by soil properties such as pH and their chemical nature (72, 73). Continuous cropping for 34 years increased DTPA extractable

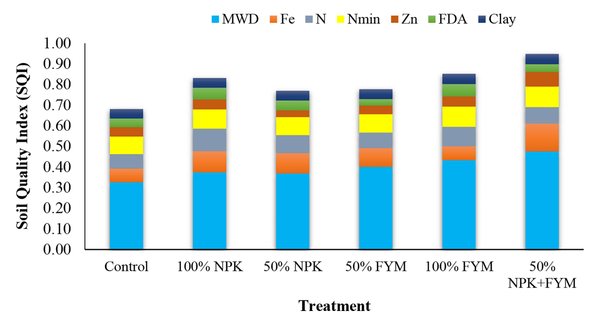

FIGURE 3
Contribution of various key indicators to PCA based SQI.

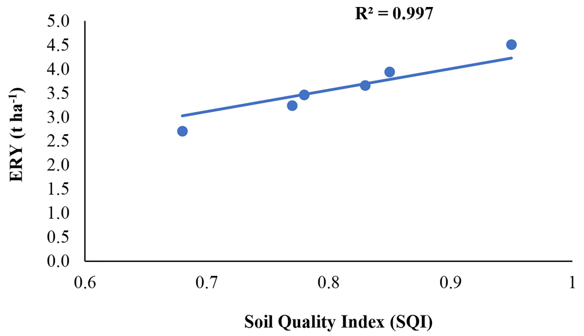

FIGURE 4
Relationship between soil quality index and equivalent rice yield as obtained through simple regression model.

Zn, Cu, Fe, and Mn content of the soil in plots that received either FYM along with NPK or FYM alone over plots that received 50% NPK and control plots. The increase in soil micronutrient levels after FYM application can be attributed to several reasons, including mineralization of organically bound forms (74), dissolution of relatively unavailable forms (75), redox-potential reduction (76), and chelating action of organic compounds released during the decomposition of organic matter (77). Katyal & Sharma (78) reported that significant correlation between DTPA-extractable micronutrients and the organic matter content of the soil. There might be an explanation for the increase in DTPA extractable micronutrients in the soil based on the presence of protons/H+ in organic manure and decreasing soil pH (as well as Eh), thereby enhancing the dissolution and reduction of micronutrients, and therefore increasing their availability. These results are consistent with the findings of Keshavarzi et al. (79) and Zhang et al. (80). According to Setia and Sharma (81), chemical fertilizers decreased soil DTPA- extractable micronutrients. According to Singh et al. (82), the integration of inorganic and organic manure significantly promotes microbial decomposition of soil organic matter released complexing agents such as organic acid and humic acid, which allowed the movement of micronutrients from the less soluble forms to more plant-available forms. According to Das et al. (83), FYM contributed to a positive effect on soil B availability by mobilizing B from soil minerals and chelating it with breakdown products of soil organic matter. The authors reported that higher decomposition rates of organic matter increase the production of various organic acids including tartaric, citric, and humic acids, all of which can solubilize relatively unavailable B and make it available for plants (84).

4.4 Effect of long-term fertilization and manuring on biological properties of soil

The phosphatases are a group of enzymes that hydrolyze esters and anhydrides of phosphoric acid. Phosphomonoesterases also include acid and alkaline phosphatases, phosphoprotein phosphatases, phytases and nucleotidases. These are typically adaptive enzymes indicating their activity increases when plant available P content decreases. Orthophosphoric monoester phosphohydrolases (acid and alkaline phosphatases) particularly catalyze the hydrolysis of P-ester bonds binding P to C (C-O-P ester bonds) in organic matter (85). Phosphatase enzymes are important because they release PO_4 from immobile organic P to improve soil phosphorus availability to plants (86). Based on our result of the present study, acid phosphatase activity in soil was higher than alkaline phosphatase activity. It is possibly due to the extensive root system of rice producing higher levels of acid phosphatase enzymes through exudation in rhizospheric soil as well as the long-term fertilization with phosphorus may have impeded the activity of alkaline phosphatase enzymes in soil (87). When farmyard manure was applied in combination with inorganic manure, significantly greater phosphatase activity has detected the reason for this may be that manure contains a higher level of microbial activity and greater diversity of phosphate-solubilizing bacteria (88).

The arylsulfatase enzyme in soil plays an essential role in releasing SO_4^{-2} so that it can be used by plants. A balanced fertilization with and without FYM applications leads to significantly higher levels of arylsulfatase in soil than an imbalanced fertilizer application. According to our results, the highest ASP was found under NPK + FYM treatment, and the lowest was measured under control. It is mostly due to the high correlation between soil organic matter and arylsulphatase activity in FYM-treated plots (89). As discussed by Knauff et al. (90), arylsulfatase enzyme activity is greatly affected by soil organic C content and is further enhanced by the long-term addition of organic manure.

β-glucosidase is an important enzyme involved in the carbon cycle in the soil and it facilitates the breakdown of cellulose and the release of glucose utilized by microorganisms for growth (91, 92). According to our results, the highest β-glucosidase activity was found under the NPK+ FYM plot, and the lowest was observed under the control plot. There might be a reason for this because FYM supplies a large amount of easily decomposable carbon e.g., carbohydrates (93).

The fluorescein diacetate (FDA) method is widely accepted as a reliable and simple method for determining the abundance of active fungi and bacteria (94). The hydrolysis of fluorescein di acetate is mediated by several enzymes in soil, including protease, esterase, and lipase (95). The increased values of fluorescein diacetate activity were observed in the organically amended plot due to a strong correlation between FDA activity and soil organic C and nutrients (96). This corroborated with the finding of Nayak et al. (97), who reported that organic matter content has significant correlations with FDA under continuous rice-growing soil.

Continuous manuring and balanced fertilization for 34 years resulted in significantly higher activities of all major enzymes than the control. The study found that DHA was an effective indicator for maintaining soil microbial activity as well as maintaining soil health. DHA activity has been widely used to measure microbial activity in soils since it represents overall metabolic status. Bhattacharyya et al. (98), reported that increase in the DHA activity in soil due to the combined application of FYM with NPK. Hence, FYM treatment resulted in a higher level of biological activity and stabilization of extracellular enzymes *via* complexation with humic substances (99). An imbalanced and inadequate fertilizer application led to a significant decline in DHA activity.

In soil, the urease enzyme hydrolyzes urea into carbon dioxide and ammonia, which plays a crucial role in N cycling. In our study, the highest mean value for urease activity was found in NPK+FYM treatment, it might be the result of continuous farming under organic manure fertilization, which stimulates heterotrophic microbes, which decompose organic manure and provide carbon and energy to heterotrophic microbes (65, 100, 101). Similarly, Chhonkar and Tarafdar (102) reported that soil enzyme activities were significantly related to organic carbon and microbial populations in the soil. Dick et al. (103) and Bandick and Dick (104), have reported significant reductions in urease activity in the soil after the addition of inorganic nitrogen. This is mostly due to the build-up of NH^+_4, which suppresses urease activity.

Microbial biomass carbon is commonly used to evaluate the effect of different farming practices on soil fertility. It was found that the microbial biomass carbon was significantly higher in plots that received organic manure along with NPK fertilizer than in plots that received only inorganic fertilizer. This may be due to the catalytic effect of FYM which stimulates microbial growth, thus increasing microbial biomass C (89). Patil and Puranik (105) found similar positive effects of using organic manures combined with chemical fertilizers together. By applying FYM, nutrients and carbon were supplied in a balanced manner, which, in turn, supported the growth of microorganisms in the soil (106).

The results of a long-term experiment showed that amendments of organic manure with chemical fertilizer enhances microbial growth and activity and provides substrates for mineralization (107). The amount of Cmin vary from treatment to treatment, because of variations in soil labile organic carbon (108). A labile pool of soil organic carbon contributes significantly to nutrient cycling in soil by accelerating C mineralization (109).

The most commonly limited nutrient in agriculture is nitrogen. Plants take up nitrogen from a various mechanism, including fertilisation, biological N fixation, and mineralization of N from soil organic matter (110). In the present study we found significantly higher mineralizable N in NPK+FYM treated plot, which could be due to the addition of nitrogen through manuring and the increased microbial activity under abundant carbon resources (111).

4.5 Soil quality indicators, indices and validation

Highly weighed factor loading(s) from each PC were selected for formulation of MDS namely mean weight diameter (MWD), available Fe, available N, potentially mineralizable N, available Zn, FDA hydrolase activity and clay. Presence of MWD in MDS is justified because destruction of soil structure in puddled transplanted rice is of great concern for sustenance of soil productivity. Iron is vital for seed development, starch and chlorophyll synthesis and in the present study available Fe contributed to soil quality index. Masto et al. (112) proposed DTPA-Fe as component of minimum dataset under an assessment of soil health across different land uses including rice-wheat system. DTPA-Fe also emerged as sensitive indicators of rice productivity at Inceptisol of upper IGP (113). Permanganate oxidizable nitrogen was not found to be in sufficient amount in soil thus it can be a potential yield limiting factor. Available N was selected as key indicator of soil quality under rice based system in Indo-Gangetic Plain (114). Potentially mineralizable N is proposed as indicators of soil quality because it forecasts plant availability of nitrogen, thus must be included in soil health assessment framework (115). Since rice is one of the crops that are most susceptible to zinc deficiency, Zn is the micronutrient that has the most impact on the growth and output of rice (116). Av-Zn was chosen because it was crucial for preserving soil quality, especially in low-land rice-based agricultural systems (117). The availability of Zn is a sensitive indicator of soil quality in Inceptisols of semi-arid subtropics, and DTPA-Zn has also emerged as a sensitive predictor of rice production (21). Fluorescein diacetate has been used to determine abundance of active fungi and bacteria. Several enzymes in soil such as protease, esterase and lipase take part in hydrolysis of fluorescein di acetate (118). Enhanced activity of FDA under integrated treatment is attributed to greater microbial biomass carbon and higher carbon resources in rhizospheric soils (119). Higher values of fluorescein diacetate activity in organic amended plot due to strong correlation between FDA activity and bioavailability of soil organic C and nutrients (96). Nayak et al. (97) also showed that organic matter content has significant correlations with FDA under continuous rice growing soil. Clay was selected as key indicators of soil quality in semi arid Decan Plateau where both inherent and dynamic properties of soil were taken into account in developing soil quality index (120).

The highest SQI of 0.95 was found in 50% NPK+FYM treatment and the lowest value of 0.68 was obtained from control. The relative contribution of MWD was highest to the SQI in all the treatments, indicating MWD as the most influential among the variables. MWD was significantly correlated with SOC, similar finding was also observed by Rahaman et al. (121). Higher weightage of MWD attributed by the higher SOC content (54.1% higher than control) in 50% NPK+FYM treatment exhibited the highest SQI; in contrast, decline in the weighted value of key indicators contributed to poor SQI in the control. The lowest contributor to SQI was FDA, followed by clay content. The weighted additive SQI gives more pertinent and accurate information concerning the actual status of the soil by representing the proportional contributions of several variables to SQI (122). Application of organic matter *via* farmyard manure and crop wastes significantly affects the soil's physical, chemical, and biological functional capability (123). As a result, farming systems, which include integrated treatment, are a fundamental strategy for enhancing soil quality. It also serves to keep soil quality at a desirable level (124). Therefore, balanced fertilization and manuring, which optimises the key indicators can be adopted to improve soil quality undere rainfed rice-lentil system of Indo-Gangetic Plain. Results of regression analysis confirmed better yield forecasting ability of PCA based SQI (R^2 = 0.87) which might be due to inclusion of more responsive and meaningful dataset of the cropping system. Such type of information is very much crucial to assess performance of present system or scope of advancing alternate ones in a particular region. Performance of weighted additive index of soil quality in relation to crop yield was reported to be best in several scientific study worldwide (125). Vasu et al. (120) observed significantly higher correlation (0.34) o weighted SQI with crop yield at semi-arid Deccan Plateau of India.

5 Conclusion

The application of FYM along with NPK fertilizer for 34 years long in rainfed rice-lentil cropping system improved the soil quality and sustain the crop productivity. The recommended doses of fertilizers along with organic manure play a vital role in improving physical, chemical, and biological properties of the soil and thereby enhancing soil quality and ensuring sustainable yield for a long period of time. Mean weight diameter (MWD), available Fe, available N, potentially mineralizable N, available Zn, FDA hydrolase activity and clay were chosen as the key indicators of soil quality out of the 25 parameters examined. Despite the possibility that these indicators could serve as a management-induced early warning system for changes in soil quality, extensive validation is required before they can be successfully used for practical purposes. The application of integrated use of chemical fertilizer and organic sources stood out among the practices as the best management method for improving soil quality of the system. Thus, this practice may be recommended for assessing management-induced changes in soil quality under rainfed rice based system in subtropical areas of many south and south-east Asian countries.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

SB: conceptualization, investigation, data analysis, supervision, project administration, funding, and manuscript writing and editing. PS: analysis of soil samples, data recording, and manuscript preparation, RR: investigation, data analysis, and manuscript preparation, KP: investigation, and manuscript preparation. ND: experimentation and manuscript editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

Publisher's note

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