Long-term impact of integrated nutrient management on sustainable yield index of rice and soil quality under acidic inceptisol

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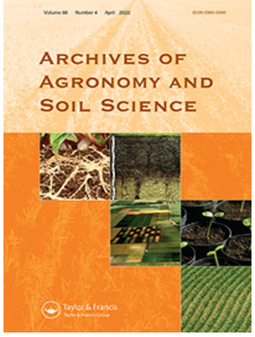

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Long-term impact of integrated nutrient management on sustainable yield index of rice and soil quality under acidic inceptisol

Abhik Patra[a,b], Vinod Kumar Sharma[a], Dhruba Jyoti Nath[c], Asik Dutta[d], Tapan Jyoti Purakayastha[a], Sarvendra Kumar[a], Mandira Barman[a], Kapil Atmaram Chobhe[a], Chaitanya Prasad Nath[d] and Chiranjeev Kumawat[e]

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ABSTRACT

An in-depth knowledge on impact of integrated nutrient management (INM) practice on yield sustainability and soil quality is important to scale INM practice across regions. Therefore, field experiment was initiated in 2006, which consisted of five treatments: absolute control, 100% recommended doses of nitrogen (N), phosphorus (P) and potassium (K) (RDF), 50% recommended doses of NP + 100% K + biofertilizers, 50% recommended doses of NP + 100% K + 1 t ha^{-1} enriched compost (ECM) and 25% recommended doses of NP + 100% K + 2 t ha^{-1} ECM (25RDF + 2ECM). The use of 25RDF + 2ECM increased soil organic carbon by 32 and 24% over control and RDF, respectively, at 0–5 cm soil layer. It also increased soil microbial biomass carbon, microbial phosphorus and phenol oxidase activity by 13.7, 20.9 and 55.7% than RDF, respectively, at 0–5 cm layer. Notably, phenol oxidase activity, pH, DTPA-extractable iron, available K, mineral N and microbial biomass phosphorus came out as the key indicators of soil quality in acidic soil after 10 years. The study recommends that INM practice comprising ECM and reduced inorganic fertilizers could enhance soil quality and yield sustainability of rice in the long-run in acidic soil ecology.

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Acidic soil; long term INM; principal component analysis; soil quality index; sustainable yield index

Introduction

A serious challenge of sustainable crop yield is emerging in a big way due to intensive cropping, imbalanced fertilization and over-exploitation of natural resources (Nath et al. 2019). Soil quality degradation adversely affects yield sustainability because of its interaction with soil physico-chemical and biological properties (Kumar et al. 2019). Thus, soil quality has direct relations with crop productivity, land degradation and food security (Drobnik et al. 2018). Therefore, restoring soil quality is critical for higher crop productivity and soil sustainability (Costantini et al. 2016). Further, it provides guidance to the government agencies for formulating agro-based land use policies for sustainable use of natural resources concurrently keeping track of its ecosystem

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services (Sharma et al. 2019). Practically, practices that are effective in maintaining soil quality are gaining extra attention for sustainability in agricultural production (Eivazi et al. 2003; Nehrani et al. 2020).

Individual soil characteristics are frequently interconnected, which respond differently under diverse land management practices, complicating their effect as well as interpretation in crop production (Griffiths et al. 2010; Raiesi and Kabiri 2016). Consequently, a combination of soil characteristics into a single overall index can make the evaluation more relevant and practical (Armenise et al. 2013). Different biological, chemical and physical indices have been developed for monitoring the ecological change (Jackson et al. 2017). Previous studies mainly highlighted the soil microbial indices and soil microbial functions such as biomass carbon/nitrogen and soil enzymes (alkaline and acid phosphatases, β-glucosidase, arylsulfatase, protease and dehydrogenase) to delineate long-term impact of chemical and organic fertilization on soil health (Borase et al. 2020a, 2020b). Assessing the long-term changes in soil physico-chemical (such as pH, EC, available nutrient, soil organic carbon) and biological parameters is crucial to identify sustainable management options (Kumar et al. 2019). These soil properties have great potential to provide a unique integrative assessment of soils and the possibility of assessing the soil health (Alkorta et al. 2003). Therefore, to achieve sustainable agricultural production, soil quality index (SQI) and soil productivity provides the key information (Khaki et al. 2017). However, limited informations are available on long-term impact of chemical fertilization and integrated application of chemical + organic amendments on SQI in rice ecologies.

A high SQI indicates the improved soil capacity, which supports soil function and helps for better crop productivity (Karlen et al. 2006; Armenise et al. 2013). Generally, soils under integrated nutrient management (INM) practices exhibit better SQI than merely fertilized soils under different climatic situations and varied ecosystems (Araya et al. 2016; Schmidt et al. 2018). In contrast, maximum productivity of rice was registered in chemical fertilization followed by INM treatment in alkaline soils of India (Ghosh et al. 2020). Borase et al. (2020a) highlighted that INM practice embedded with farmyard manure and crop residues in conjunction with chemical fertilization increased soil biological properties that had a significant impact on rice yield. It is particularly important in rice ecologies where intensive-tillage and over-fertilization-induced sustainability issues are rampant (Kumar et al. 2019; Nath et al. 2021). Therefore, sustainable yield index could be an important indicator for assessing long-term impact of management practices on yield (Das et al. 2020). Experiments have been conducted for assessing the variations in the soil quality and crop productivity caused by the application of chemical fertilizers and INM practice (mainly farmyard manure and crop residues) (Meshram et al. 2018; Dubey et al. 2019). However, very few information is available regarding the impact of chemical fertilizers and enriched compost-based INM practice on SQI and sustainable yield of rice in acidic Inceptisol.

An alteration in soil parameters usually takes a long time to appear; thus, long-term experiments are suitable to examine the association between soil properties and crop yield to formulate management strategies for higher crop productivity and soil health (Nayak et al. 2012; Shahid et al. 2016; Rakshit et al. 2018). Therefore, we postulated that INM practice consisting chemical fertilizers + enriched compost would have higher SQI and sustainable yield index of rice than chemical fertilization (RDF) in the long-run. Considering the preceding backdrop and postulate, the current investigation was carried out with the following objectives: (i) to identify the key indicators depth-wise to evaluate the SQI using data redundancy technique, and (ii) to quantify the long-term impact of various INM practices on sustainable yield index of rice.

Materials and methods

Site description

The long-term INM experiment on rice was started during the rainy season (July–October) of 2006 under the rice sole-cropping system at Instructional-cum-Research (ICR) farm. The experimental area is located on the latitude of 26 ° 43 ′ N and a longitude of 94 ° 11 ′ E, with elevation of 91 m. The soil has clay loam texture and is classified as Aeric Endoaquept (Inceptisol) according to USDA Soil Taxonomy, having a dominant clay mineral, kaolinite. The experimental location falls under subtropical climate with an annual average rainfall of 1893 mm during 2006–2015 and receives maximum rainfall of 39.4 cm in July. The highest and lowest temperature of 32.6 °C and 10.2 °C was observed in January and August, respectively during 2006–15. The initial properties included 41.7% sand, 29.7% silt, 28.6% clay, highly acidic soil (pH 4.70), high inorganic carbon (9.6 g kg^{-1}), low in available nitrogen (200 kg N ha^{-1}) and available phosphorus (21.9 kg P ha^{-1}) and medium in available potassium (146 kg K ha^{-1}).

Experimental design

The field experiment was laid down in a randomized complete block design (RCBD) containing five treatments with four replications. The treatments consisted the following: T_1, absolute control (control); T_2, 100% recommended doses of NPK (RDF); T_3, 50% recommended doses of NP + 100% K + biofertilizers (50RDF + B); T_4, 50% recommended doses of NP + 100% K + 1 t ha^{-1} enriched compost (50RDF + 1ECM) and T_5, 25% recommended doses of NP + 100% K + 1 t ha^{-1} enriched compost (25RDF + 2ECM). The details of biofertilizers and enriched compost (ECM) preparation have been already explained in Patra et al. (2021). There were 20 plots with 8×5 m^2 area and buffer region of 1 m between the plots. The ECM was applied in the selected plots during puddling (wet tillage) of rice for proper mixing with the soil. Seedling root dipping was implemented for biofertilizer consortium *viz., Azospirillum* and phosphate solubilizing bacteria application. The recommended dose of $N:P_2O_5:K_2O$ consisted 40:20:20 kg ha^{-1} for rice in RDF treatment based on the existing recommendation for North-Eastern regions of India. Urea, single superphosphate and muriate of potash were used to fulfill the nutrient requirement of the crop. Half dose of N and a full dose of P and K were applied at the time of transplanting in rice irrespective of treatments. The remaining half dose of N was supplied during maximum tillering stage of the crop (approximately 45 days after transplanting). The experiment was carried out in a rice mono-cropping system, and weed infestation occurred during the fallow period. Weeds were managed properly from the field through manual weeding before transplanting of rice. The rice seeds (cv. *Ranjit*) were sown in a nursery bed in the month of May and thereafter transplanted in the experimental plots under the puddled condition in the first fortnight of June with 20 cm (row to row) × 20 cm (hill to hill) row geometry. Essential weeding and pest control strategies were implemented to maintain healthy and uniform plant growth. After maturity, harvesting was done during the first week of December 2015 using a sickle with a cut of 5 cm above the ground.

Soil sample collection and analysis

For analysis of soil properties, soil samples were collected from three different soil depths such as D_1 (0–5 cm), D_2 (5–15 cm) and D_3 (15–30 cm) after harvesting of rice in December 2015. The soil samples were stored in polyethene zipper bags and promptly sealed to avoid changes. The half of soil samples were instantly passed through a 2 mm sieve, homogenized and preserved at 4 °C for microbial study. The remaining portions of the samples were passed through a 2 mm sieve after drying at room temperature and stored in polyethene zipper bags for the analysis of physico-chemical characteristics.

Soil pH and electrical conductivity (EC) were estimated in 1:2 soil:water suspension (Sparks et al. 2020); organic carbon by the methods of Walkley and Black (1934); mineral nitrogen by 2 M potassium chloride (KCl) (Keeney and Nelson 1982); ammonium fluoride (NH_4F) extractable-P (Bray and Kurtz 1945) by spectrophotometer; barium chloride ($BaCl_2$) extractable K (Knudsen et al. 1982) by ICP-MS; DTPA-extractable zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn) by ICP-MS (Lindsay and Norvell 1978); and salicylic acid extractable boron (B) by Datta et al. (1998). Different forms of aluminium (Al) were extracted from the post-harvest soil (PHS) samples by non-sequential extraction method with different reagents as described by Walna et al. (2005). For soil enzymatic activity, dehydrogenase activity (DHA) was determined as per the procedure outlined by Benefield et al. (1977); fluorescein diacetate activity (FDA) by Green et al. (2006); and acid phosphomonoesterase activity (PMA) by Tabatabai and Bremner (1969). Moreover, β-glucosidase (BDGLU), β-galactosidases (BDGTO) and β-glucosaminidase (BDGMI) activity were estimated by the method of Dick (2011). The method given by Perucci et al. (2000) was implemented to measure the activities of phenol oxidase (PHO), whereas the peroxidase (PEO) enzyme was estimated using the method given by Johnsen and Jacobsen (2008). Microbial biomass carbon (MBC) and nitrogen (MBN) estimation in collected samples were assessed using the fumigation followed by extraction method (Jenkinson and Powlson 1976); however, a modified fumigation method (Brookes et al. 1984) was used to assess the soil microbial biomass phosphorus (MBP).

Sustainable yield index

The sustainable yield index (SYI) was estimated using following formula (Nayak et al. 2012):

$$\mathrm{SYI} = (\mathrm{Y} - \sigma)/\mathrm{Y}_{\max}$$

where Y is the mean rice yield of over 10 years, σ is the standard deviation and $\mathrm{Y}_{\max}$ is the maximum yield documented in the experiment throughout the years of cultivation.

Assessment of soil quality index

The principal component analysis (PCA) is the mostly used technique to determine SQI (Shukla et al. 2006; Imaz et al. 2010), which was applied with physico-chemical and biological properties to evaluate the extent of soil functioning (Karlen et al. 2003; Ivezić et al. 2015). The selection of indicators during the assessment of soil quality is highly specific, as the soil system is highly heterogeneous and dynamic (Shukla et al. 2006), and the following points should be considered: (i) indicators should go with that particular niche under study and (ii) soil biological and physico-chemical properties must be included for calculating soil quality (Dutta et al. 2015). Soil quality evaluation is a three-step procedure (Raiesi and Kabiri 2016), and these steps are (i) identifying the minimum data set (MDS) from the indicators using PCA, (ii) using linear scoring methods to assign scores to the selected MDS and (iii) developing a comparative indicator index using the weighted simple additive approach by amalgamating the individual indicator score. The principal components (PCs) with high Eigen values better reflect the variance in the system; thus, PCs with eigen values ≥1 were selected (Andrews et al. 2002). The indicators that fell within 10% of the highest weighted indicator were kept for the MDS for each PC. Simple correlations among the screened variables were conducted to minimize variability within each PC, and the variables were selected based upon the correlation sum. For the computation of the SQI, each MDS indicator observation was normalized (Tesfahunegn 2014). This normalized value of the indicator is called the ‘indicator score’ (S). The scoring was done by the linear scoring functions (LS) (Andrews et al. 2002) and critical limit method (Dadhwal et al. 2011). The assigning of scores was done by arranging the indicators in proper order, and higher values were evaluated ‘good or bad’ based on their influence on soil functions. There are mostly two kinds of indicators, namely ‘more is better’ and ‘less is better’. For ‘more is batter’ category, individual observations are divided by the highest observed value such as one and vice-versa for the latter (Singh et al. 2013). When each indicator has been assigned a score, weight is determined for them using the PCA data. Every PC described definite amount of variation (%) to the overall variation (%). The weighted factor (W) of each selected indicator from the PCA was analyzed by dividing the specific amount of variation by the total variation (%) (Singh et al. 2013). The SQI was determined by the score and weight factor of every variable (Romaniuk et al. 2011)

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

where S represents the score of the indicator, W represents the weighted factor derived from the PCA and n and i represent the parameters. The higher index score suggests improved quality of soil, and measures of soil quality perform well.

Statistical analysis

The data were analyzed for randomized complete block design (RCBD) using analysis of variance (ANOVA) technique. The statistical analyses of the data were done using SAS 9.1 software (SAS Institute Inc 2013). Microsoft Office Excel 2010 was used for drawing all the figures. Cluster analysis was developed using the Ward-algorithmic method, and the Euclidean squared distance was used to calculate the distance between clusters with identical treatments.

Results

Minimum data set (MDS) and soil quality indicators

In the surface soil (0–5 cm), 81.8% of the variance among the variables can be explained using the first three PCs (Table 1). The data revealed that highly weighted variables under PC1 were EC, available P, DTPA extractable Zn, salicylic acid extractable B, weakly organically bound Al, amorphous Al, free Al, dehydrogenase activity, acid phospho-monoesterase activity, microbial biomass nitrogen, microbial biomass phosphorus, β-glucosidase activity, β-galactosidases activity and β-glucosaminidase activity, which correlated significantly with phenol oxidase activity (Table 2). However, the phenol oxidase activity having a maximum correlation sum was selected from PC1. From PC2 and PC3, pH and DTPA extractable Fe were selected, respectively, because of their highest factor loadings (Table 1). At 0–5 cm depth, the respective weighted factors for PC1, PC2 and PC3 were 0.87, 0.07 and 0.06, respectively.

Moreover, in the subsequent depth (5–15 cm), PCA illustrated 84.6% of the variation in the data by the initial four PCs, and there was a significant difference among the variables (Table 1). In PC1, the soil parameters such as EC, available P, weakly organically bound Al, amorphous Al, strongly organically bound and interlayer Al, free Al, dehydrogenase activity, β-glucosidase activity, β-galactosidases activity and phenol oxidase activity were considered. From PC1, phenol oxidase activity was selected due to its maximum weighted value and highest correlation sum. Likewise, pH from PC2, available K from PC3 and mineral N from PC4 were selected (Table 1). All of these PCA indicators were significantly correlated with phenol oxidase activity, available K and N (Table 2).

At the bottom soil layer (D_3), the PCA of variables having significant differences revealed that 83.5% of the variance in the data was described by the first five PCs (Table 1). The highly weighted variables that emerged from PC1 were EC, available P, weakly organically bound Al, amorphous Al, strongly organically bound and interlayer Al, free Al, acid phospho-monoesterase activity, β-glucosidase activity, β-galactosidases activity and phenol oxidase activity, which significantly correlated with phenol oxidase activity (Table 2). Although based on the highest correlation sums, phenol oxidase activity from PC1, DTPA extractable Zn from PC2, DTPA extractable Fe from PC3, microbial biomass phosphorus from PC4 and pH from PC5 were chosen and used for MDS and SQI development (Table 1).

Soil quality index and interpretation

At the surface soil layer (D_1), the contribution of phenol oxidase activity towards SQI value was the highest followed by pH and DTPA extractable Fe (Figure 1). The SQI was determined using the following equation

Table 1. Results from the principal component analysis of statistically significant variables at different soil depths after harvest of rice ($p \leq 0.05$). Please format the table properly especially the rows of Cumulative percentage and Weightage.

Statistic or variable	PC1	PC2	PC3	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4	PC5
	0–5 cm			5–15 cm				15–30 cm				
Eigen value	19.2	1.63	1.30	18.5	1.95	1.33	1.03	15.9	2.32	1.94	1.29	1.09
% Variance	70.9	6.05	4.82	68.6	7.21	4.94	3.82	58.9	8.61	7.18	4.79	4.03
Cumulative percentage	70.9	76.9	81.8	68.6	75.8	80.8	84.6	58.9	67.5	74.7	79.5	83.5
Weightage	0.87	0.07	0.06	0.81	0.09	0.06	0.05	0.71	0.10	0.09	0.06	0.05
Factor loading												
pH	0.32	**0.70**	−0.24	0.42	**−0.72**	−0.19	0.01	0.34	0.30	0.38	−0.22	**0.59**
EC	**0.89**	0.06	−0.16	**0.88**	−0.10	−0.11	−0.24	**0.93**	0.12	−0.01	0.23	−0.09
Organic carbon (OC)	0.76	−0.22	−0.24	0.84	0.10	−0.06	−0.01	0.73	−0.38	0.15	0.37	−0.05
Mineral nitrogen (N)	0.70	0.39	**0.48**	0.67	0.08	**0.40**	**0.37**	0.84	0.15	−0.15	−0.14	−0.05
Available phosphorus (P)	**0.92**	0.07	0.27	**0.90**	0.03	0.25	0.25	**0.92**	−0.03	−0.17	−0.19	0.07
Available potassium (K)	0.77	0.41	0.12	0.82	−0.02	**0.47**	0.14	0.74	0.23	−0.29	−0.35	0.22
DTPA extractable zinc (Zn)	**0.90**	0.18	0.21	0.86	−0.28	0.15	0.04	0.43	**0.68**	−0.35	0.27	−0.01
DTPA extractable copper (Cu)	0.86	0.03	0.01	0.74	−0.34	−0.34	0.30	0.61	**−0.67**	0.05	−0.13	−0.21
DTPA extractable iron (Fe)	0.48	−0.42	**0.48**	0.37	**0.66**	−0.35	**0.36**	0.39	0.17	**0.82**	−0.12	−0.24
DTPA extractable manganese (Mn)	0.79	−0.22	0.39	0.78	0.27	0.38	−0.17	0.78	0.01	−0.20	−0.41	−0.24
Salicylic acid extractable boron (B)	**0.90**	−0.03	−0.03	0.83	0.22	0.04	−0.32	0.51	**−0.62**	0.08	−0.09	0.28
Exchangeable aluminium (Al)	−0.85	0.11	0.35	−0.77	0.40	0.04	0.10	−0.73	−0.40	0.14	0.17	0.19
Weakly organically bound Al	**0.95**	−0.09	−0.10	**0.94**	−0.02	0.02	−0.18	**0.92**	−0.09	−0.12	0.10	−0.07
Strongly organically bound and interlayer Al	−0.87	−0.11	0.19	**−0.89**	−0.06	−0.05	**0.34**	**−0.88**	0.26	0.10	−0.08	−0.13
Amorphous Al	**0.88**	0.21	0.19	**0.89**	−0.11	0.28	0.02	**0.86**	−0.27	−0.17	−0.16	0.11
Free Al	**0.88**	0.19	0.16	**0.92**	0.03	0.05	−0.08	**0.87**	−0.14	−0.04	0.052	−0.10
Dehydrogenase activity	**0.93**	0.02	−0.20	**0.90**	−0.06	−0.22	−0.08	0.85	0.06	0.11	0.33	0.07
Fluorescein diacetate activity	0.83	−0.25	−0.05	0.80	−0.14	−0.29	0.26	0.70	0.32	0.37	0.11	0.01
Acid phospho-monoesterase activity	**0.90**	−0.12	0.11	0.86	0.13	−0.02	0.16	**0.88**	−0.02	0.17	−0.09	−0.02
Microbial biomass carbon	0.79	0.31	−0.14	0.83	0.08	−0.26	0.09	0.62	−0.08	−0.44	0.24	−0.23
Microbial biomass nitrogen	**0.88**	−0.07	−0.11	0.86	−0.28	0.11	0.05	0.79	−0.09	0.30	0.15	0.29
Microbial biomass phosphorus	**0.89**	0.06	−0.23	0.84	−0.11	−0.24	−0.25	0.76	0.09	0.01	**0.52**	0.14
β-glucosidase activity	**0.95**	−0.10	−0.03	**0.93**	0.04	−0.03	0.18	**0.86**	0.04	−0.30	−0.12	0.25
β-galactosidases activity	**0.94**	−0.10	0.06	**0.95**	0.05	0.11	−0.03	**0.89**	0.04	−0.07	−0.03	−0.02
β-glucosaminidase activity	**0.88**	−0.16	0.01	0.86	0.15	−0.12	0.04	0.72	−0.17	0.29	−0.12	−0.29
Phenol oxidase activity	**0.96**	−0.15	−0.11	**0.97**	0.18	−0.12	0.01	**0.95**	0.09	0.13	−0.06	0.01
Peroxidase activity	0.78	−0.39	−0.18	0.75	0.52	−0.19	−0.19	0.75	0.41	0.26	−0.11	−0.24

Bold values indicate the factor loading within 10% of the highest factor.
Bold-underlined soil attributes correspond to the indicators included in the minimum data set (MDS).

$$\mathrm{SQIat0-5cm\ soil\ depth} = \sum \begin{array}{c}(\mathrm{Phenol\ oxidase\ activity\ score} \times 0.867) + (\mathrm{pHscore} \times 0.074) + \\ (\mathrm{DTPA\ extractable\ Fe\ score} \times 0.059)\end{array}$$

Notably, the nutrient management practices followed the order of 25RDF + 2ECM > 50RDF + 1ECM > 50RDF + B > RDF > control ($p \leq 0.05$) for SQI values. At middle soil depth (D_2), phenol oxidase activity contributed the maximum to SQI value, whereas the contributions of mineral N was low while pH and available K were in between the above two soil parameters towards SQI contribution (Figure 1). The SQI was determined using the following equation:

$$\mathrm{SQIat5-15\,cm\ soildepth} = \sum \begin{array}{c}(\mathrm{Phenol\ oxidase\ activity\ score} \times 0.811) + (\mathrm{pH\ score} \times 0.085) + \\ (\mathrm{Available\ Kscore} \times 0.058) + (\mathrm{Mineral\ Nscore} \times 0.045)\end{array}$$

Table 2. Pearson's correlation matrix between highly weighted soil variables and soil properties in post-harvest soil at different soil depths.

Parameters	Phenol oxidase activity	pH	Iron (Fe)	Phenol oxidase activity	pH	Available potassium (K)	Mineral nitrogen (N)	Phenol oxidase activity	Zinc (Zn)	Iron (Fe)	Microbial biomass phosphorus	pH
	0–5 cm			5–15 cm				15–30 cm				
pH	0.21	1.00	−0.01	0.28	1.00	0.25	0.21	0.37	0.25	0.32*	0.21	1.00
EC	0.84***	0.41**	0.40*	0.85***	0.49*	0.61***	0.46*	0.86***	0.53**	0.35**	0.79***	0.28
Organic carbon (OC)	0.77***	0.15	0.46*	0.80***	0.34	0.70***	0.56**	0.66***	0.08	0.29*	0.69***	0.05
Mineral nitrogen (N)	0.58**	0.36	0.37	0.64***	0.21	0.71***	1.00	0.84***	0.45*	0.30*	0.59**	0.22
Available phosphorus (P)	0.84***	0.19	0.42*	0.85***	0.36	0.86***	0.85***	0.85***	0.39*	0.25*	0.62***	0.28
Available potassium (K)	0.68***	0.40*	0.23	0.72***	0.25	1.00	0.71***	0.74***	0.47*	0.10	0.45*	0.31
DTPA extractable zinc (Zn)	0.81***	0.38*	0.46*	0.76***	0.50**	0.74***	0.65***	0.39*	1.00	−0.03	0.52*	0.25
DTPA extractable copper (Cu)	0.84***	0.41*	0.52**	0.71***	0.61***	0.43*	0.52**	0.52**	−0.16	0.21	0.32	0.04
DTPA extractable iron (Fe)	0.46*	−0.01	1.00	0.49*	−0.20	0.17	0.24	0.49**	−0.03	1.00	0.20	0.32
DTPA extractable manganese (Mn)	0.73***	−0.04	0.64***	0.75***	0.15	0.75***	0.59**	0.73***	0.28	0.25*	0.34	0.14
Salicylic acid extractable boron (B)	0.87***	0.17	0.34	0.83***	0.19	0.65***	0.56**	0.41*	−0.22	0.09	0.31	0.28
Exchangeable aluminium (Al)	−0.87***	−0.22	−0.22	−0.68***	−0.49**	−0.65***	−0.40*	−0.66***	−0.53**	−0.23	−0.49*	−0.35
Weakly organically bound Al	0.94***	0.19	0.40*	0.90***	0.34	0.76***	0.61***	0.81***	0.39*	0.26*	0.69***	0.20
Strongly organically bound and interlayer Al	−0.84***	−0.31	−0.21	−0.84***	−0.33	−0.68***	−0.49**	−0.74***	−0.22	−0.16	−0.66***	−0.26
Amorphous Al	0.77***	0.30	0.31	0.80***	0.41*	0.86***	0.62***	0.78***	0.24	0.15	0.56**	0.25
Free Al	0.82***	0.36	0.40*	0.90***	0.39*	0.74***	0.62***	0.80***	0.39*	0.34**	0.63**	0.17
Dehydrogenase activity	0.93***	0.37	0.36	0.88***	0.44*	0.66***	0.45*	0.83***	0.43*	0.35**	0.84***	0.27
Fluorescein diacetate activity	0.79***	0.21	0.50**	0.80***	0.38	0.56**	0.44*	0.67***	0.36	0.63***	0.58**	0.42*
Acid phospho-monoesterase activity	0.89***	0.17	0.48*	0.89***	0.24	0.78***	0.59**	0.93***	0.17	0.47***	0.66***	0.26
Microbial biomass carbon	0.75***	0.41*	0.22	0.85***	0.33	0.56**	0.50**	0.47*	0.44	−0.09	0.47*	0.02
Microbial biomass nitrogen	0.83***	0.27	0.39*	0.76***	0.46*	0.79***	0.47*	0.80***	0.19	0.50***	0.67***	0.48*
Microbial biomass phosphorus	0.85***	0.40*	0.37	0.82***	0.48*	0.51**	0.45*	0.74***	0.52**	0.20	1.00	0.21
β-glucosidase activity	0.94***	0.26	0.46*	0.92***	0.38*	0.80***	0.66***	0.83***	0.40*	0.05	0.66***	0.28
β-galactosidases activity	0.89***	0.24	0.49**	0.91***	0.27	0.82***	0.66***	0.88***	0.42*	0.34**	0.67***	0.27
β-glucosaminidase activity	0.88***	0.27	0.47*	0.85***	0.31	0.68***	0.53**	0.71***	0.13	0.49***	0.52**	0.25
Phenol oxidase activity	1.00	0.21	0.46*	1.00	0.28	0.72***	0.64***	1.00	0.39*	0.49***	0.74***	0.37
Peroxidase activity	0.88***	0.04	0.42*	0.86***	0.01	0.45*	0.44*	0.81***	0.53**	0.60***	0.48*	0.44*

*significance at $p < 0.05$ level, **significance at $p < 0.01$ level and ***significance at $p < 0.001$ level.

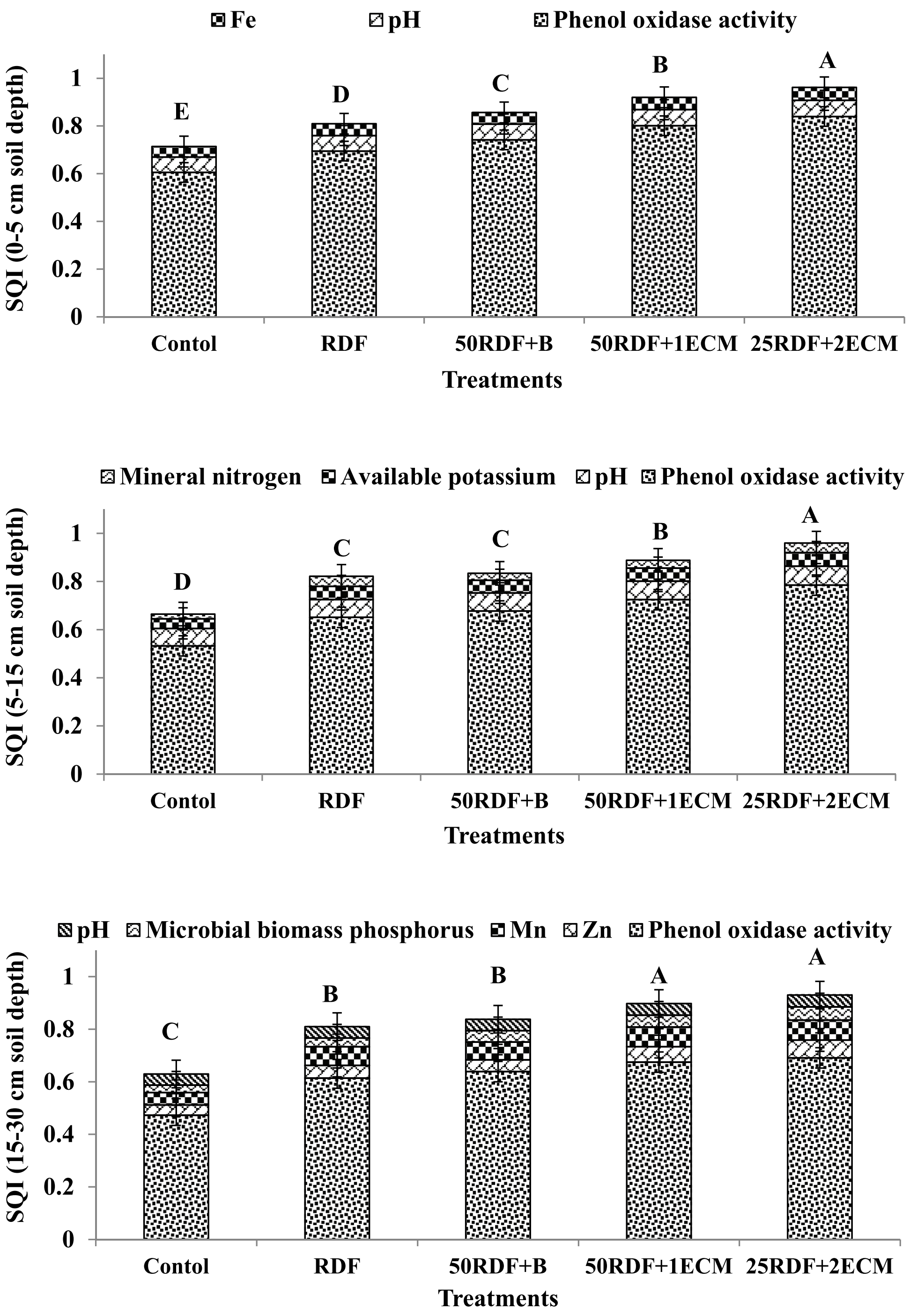

Figure 1. Effect of manuring and fertilization on soil quality index (SQI) at different soil depths in post-harvest soil of rice (Different letters for each parameter show significant difference at $p \leq 0.05$ by Duncan's multiple range test). See Materials and Methods section for treatment details.

The INM practices such as 25RDF + 2ECM and 50RDF + 1ECM recorded 10–41% higher SQI values for phenol oxidase activity compared to the 50 RDF + B, RDF and control treatments. At the lowest soil depth (D_3), phenol oxidase activity contributed the maximum towards SQI value followed by DTPA extractable Zn, DTPA extractable Fe, soil microbial phosphorus and pH (Figure 1). The SQI was determined as per the equation given below:

$$\begin{aligned}&\text{SQIat15} - \text{30cmsoildepth} =\\&\sum(\text{Phenoloxidaseactivityscore} \times 0.705) +\\&(\text{DTPAextractableZnscore} \times 0.103) +\\&(\text{DTPAextractableFescore} \times 0.086) +\\&(\text{Microbialbiomassphosphorusscore} \times 0.057) + (\text{pHscore} \times 0.048)\end{aligned}$$

The nutrient management practices followed the sequence of 25RDF + 2ECM = 50RDF + 1ECM > 50RDF + B = RDF > control ($p \leq 0.05$), which were observed for SQI values at D_3. Overall, the phenol oxidase activity had the highest SQI values (0.53 to 0.85) across the depth. Integrated nutrient management practices comprising ECM and biofertilizers (25RDF + 2ECM and 50RDF + 1ECM) recorded the higher SQI values ($p \leq 0.05$) over RDF and control after 10 years of agricultural practices at all depths.

Sustainable yield index and interrelation between yield and soil quality index

In the long-run, the SYI varied for different nutrient management techniques in rice. All the nutrient management practices resulted in 31–47% higher SYI of rice compared with control ($p \leq 0.05$) after 10 years of rice mono-cropping (Figure 2). Although nutrient management practices (from T_2 to T_5) did not differ significantly for SYI of rice, however, INM practices *viz.*, 50RDF + 1ECM and 25RDF + 2ECM had higher values (0.72–0.75) for SYI than that of RDF (0.67). There was a significant correlation of SQI with the yield of rice grain and straw across the depths (Figure 3). The relationship in SQI and yield (grain and straw of rice) followed a quadratic function at all soil depths.

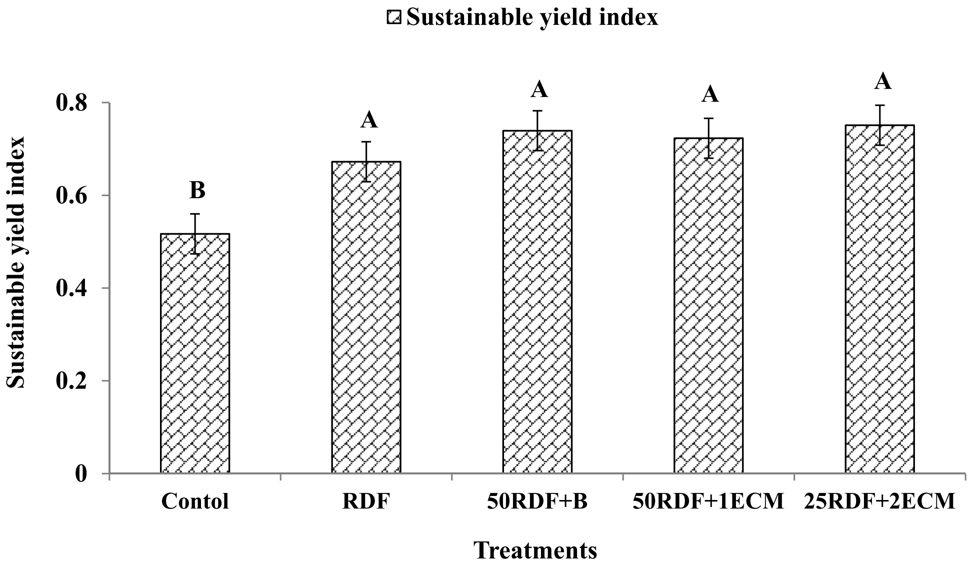

Figure 2. Effect of manuring and fertilization on sustainable yield index (SYI) of rice over a period of 10 years (2006–2015) (Different letters for each parameter show significant difference at $p \leq 0.05$ by Duncan's multiple range test). See Materials and Methods section for treatment details.

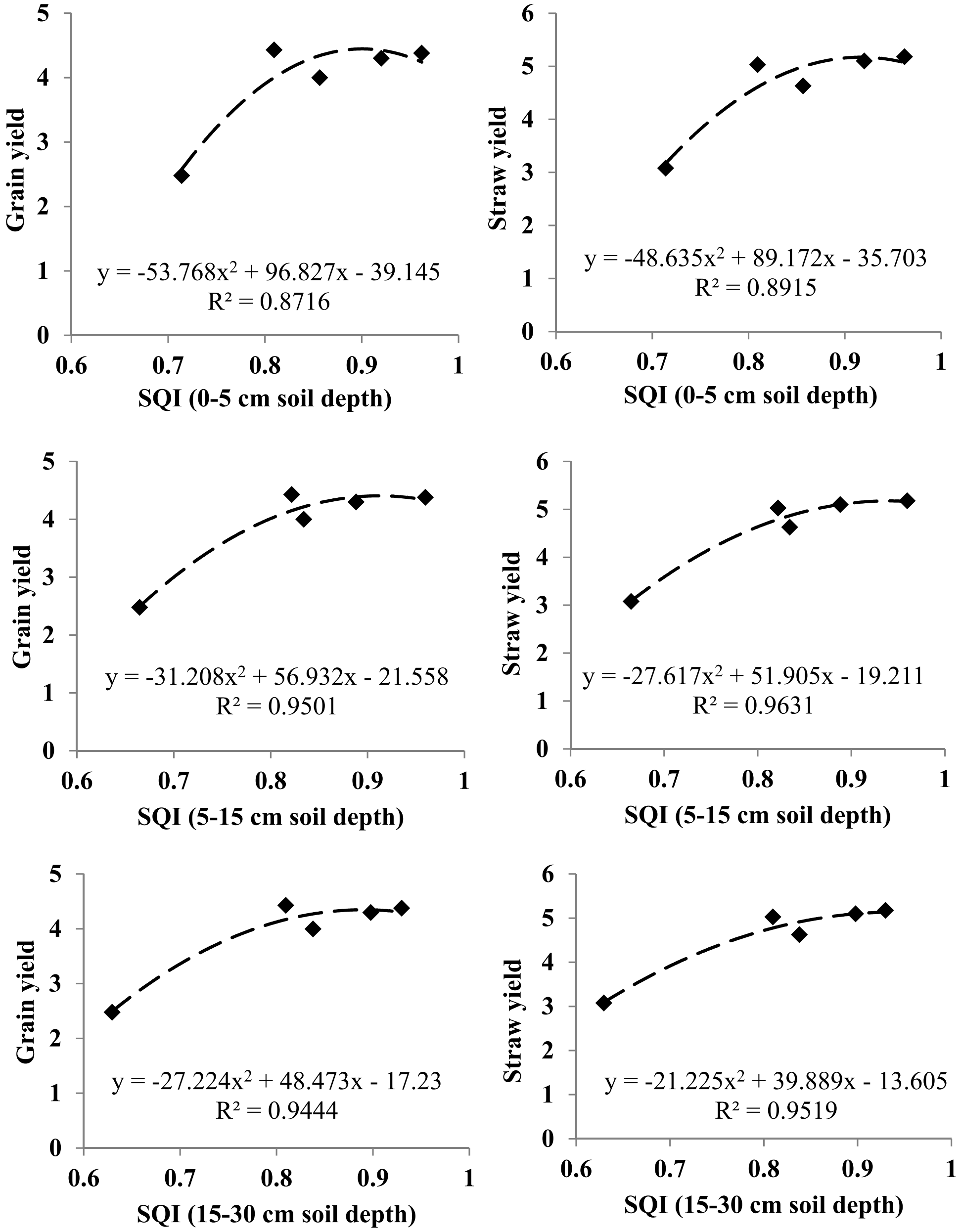

Figure 3. Relationship between soil quality index (SQI) at different soil depths with grain and straw yield (t ha^{-1}) of rice. See Materials and Methods section for treatment details.

Correlation and multivariate analysis

The first two ordinations of PCA explained >75% of the total variance at D_1 and D_2, whereas at D_3, it explained >65%. The PCA revealed that pH, DTPA extractable Fe, Zn and Cu, salicylic acid extractable B, phenol oxidase activity, strongly organically bound and interlayer Al and exchangeable Al were strongly influenced by the adoption of different nutrient management practices for 10 consecutive years (Figure 4 and 5) and (Figure 6). The remaining parameters are situated as a cluster in the PCA scattergram. At all soil depths, strongly organically bound and interlayer Al and exchangeable Al

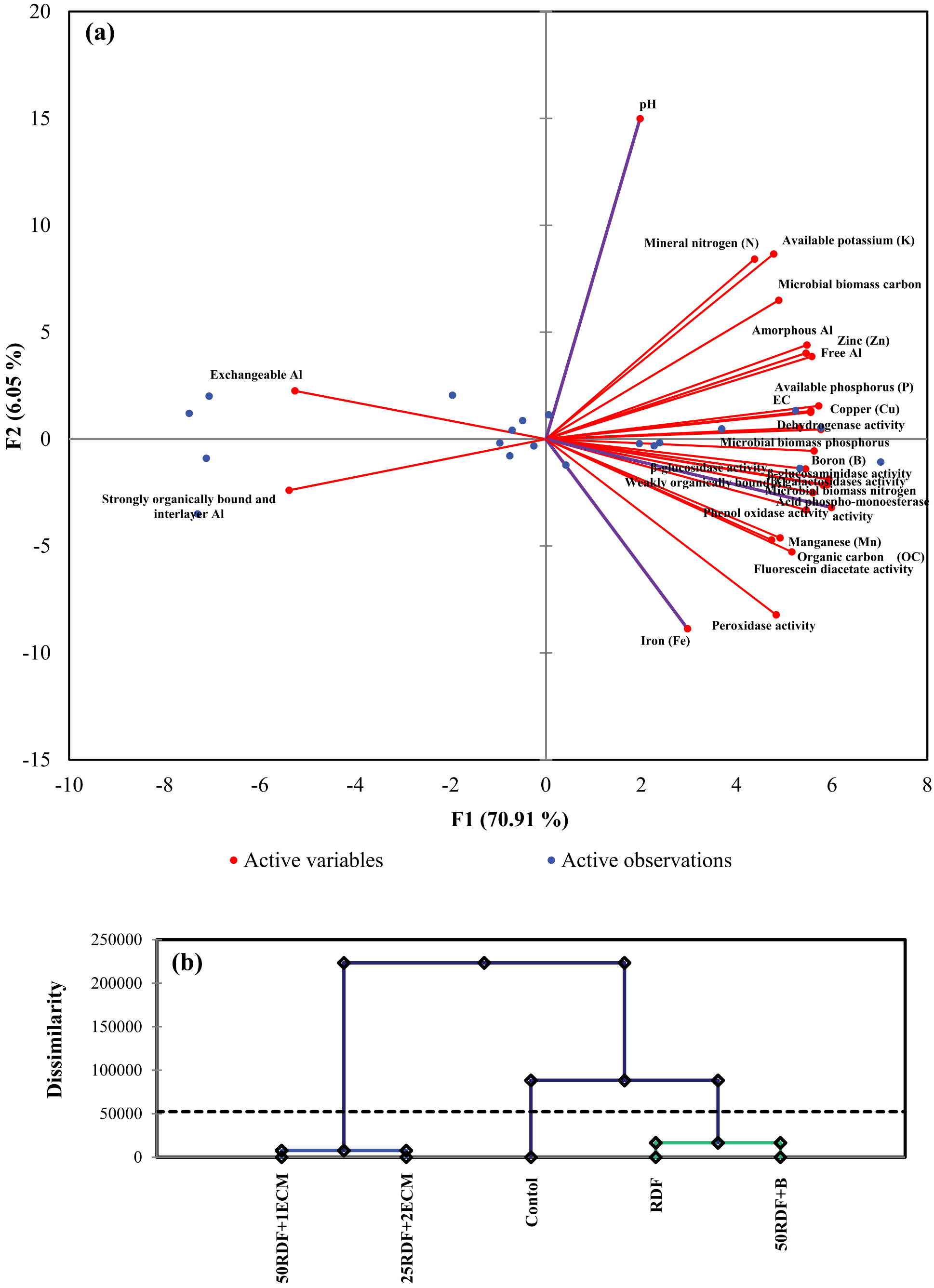

Figure 4. Ordination diagram of principal component analysis showing effects of manuring and fertilization on various soil parameters at 0–5 cm soil depth (a) and dendrogram obtained by hierarchical clustering analysis for different soil parameters at 0–5 cm soil depth (b). See Materials and Methods section for treatment details.

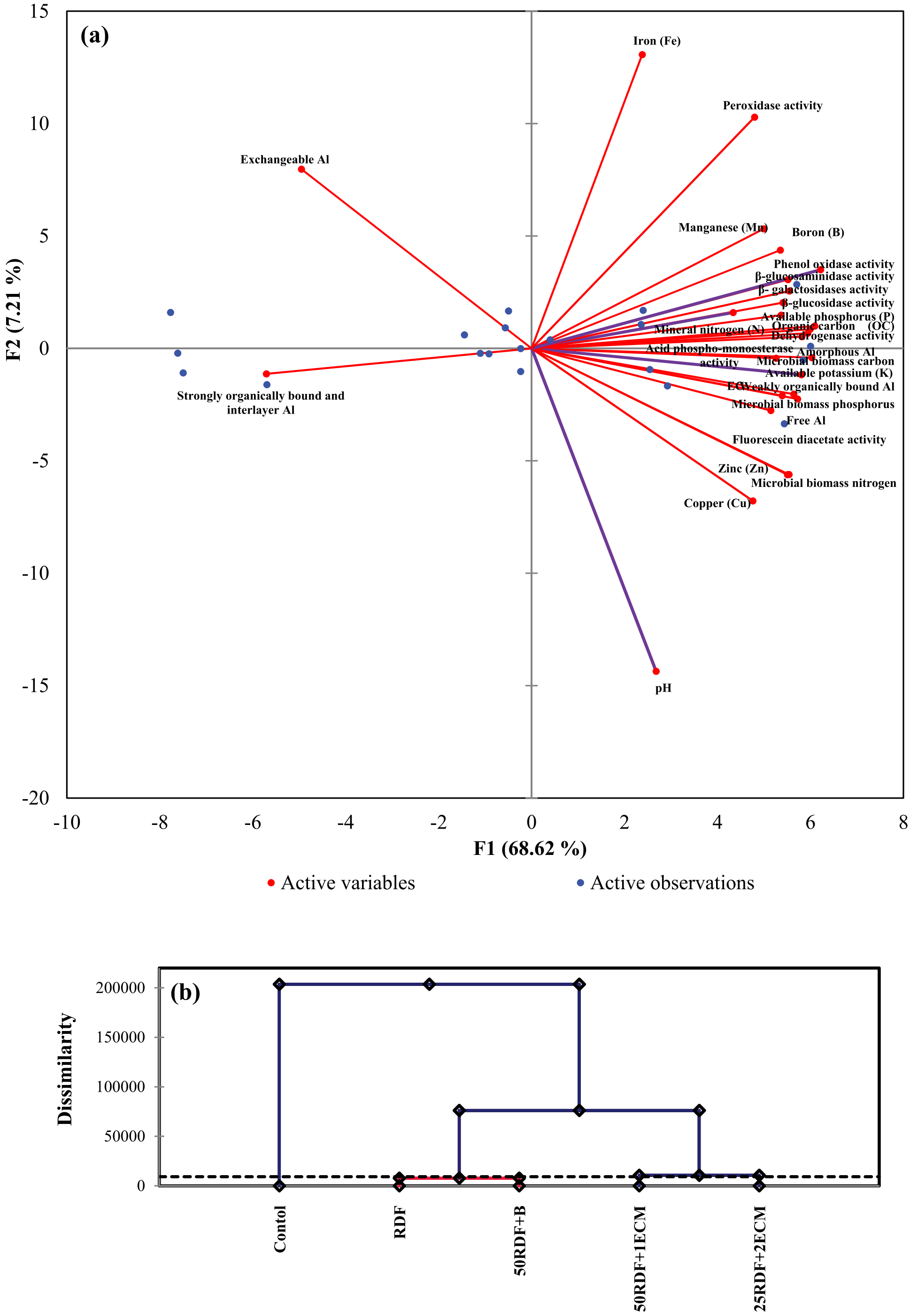

Figure 5. Ordination diagram of principal component analysis showing effects of manuring and fertilization on various soil parameters at 5–15 cm soil depth (a) and dendrogram obtained by hierarchical clustering analysis for different soil parameters at 5–15 cm soil depth (b). See Materials and Methods section for treatment details.

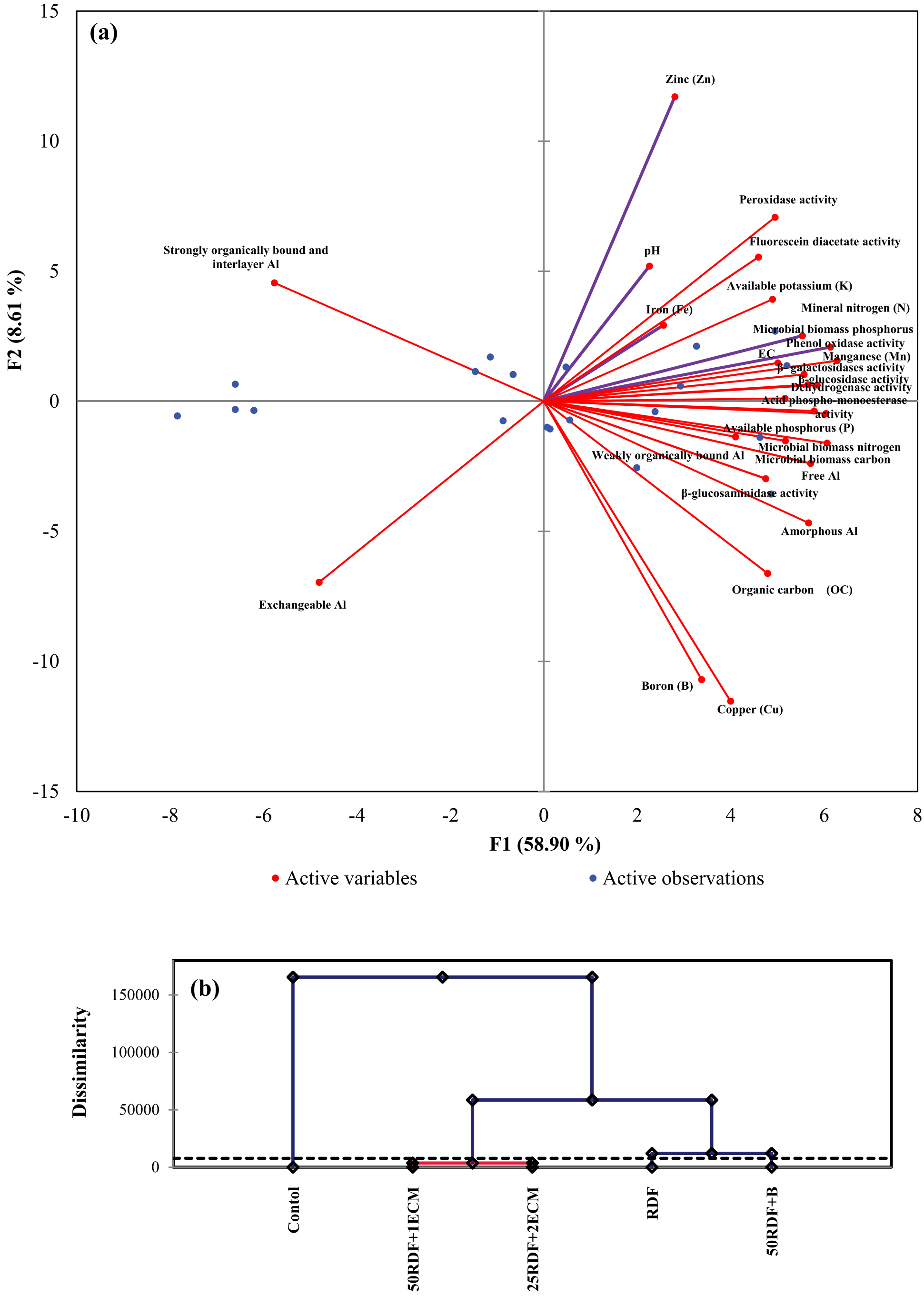

Figure 6. Ordination diagram of principal component analysis showing effects of manuring and fertilization on various soil parameters at 15–30 cm soil depth (a) and dendrogram obtained by hierarchical clustering analysis for different soil parameters at 15–30 cm soil depth (b). See Materials and Methods section for treatment details.

were negatively correlated with all the remaining indicators selected in MDS for SQI determination. Notably, 50RDF + 1ECM and 25RDF + 2ECM treatments are distinctly situated from control RDF and 50RDF + B practices in the PCA coordinate. Furthermore, treatments formed three distinctive clusters such as (i) 50RDF + 1ECM and 5RDF + 2ECM, (ii) RDF and 50RDF + B and (iii) control as evident from the dendrogram.

Discussion

Minimum data set (MDS) and soil quality indicators

The indicators with the maximum correlation sum were chosen as MDS indicators because they best represented the group; however, the selection of indicators might also be based on their feasibility, implacability, simplicity to estimation, etc (Andrews et al. 2002). In this experiment, uni- and multivariate statistical analysis (SAS software) were used for concentrating data into MDS, and to determine the variables with substantial treatment differences, non-parametric statistics such as Kruskal–Wallis χ^2 test were used (Andrews and Carroll 2001). To eliminate redundancy and biasness while grouping the variables, higher weighted factor multivariate correlation matrices was used for taking final MDS and desired output (Andrews et al. 2002; Romaniuk et al. 2011). In the MDS, soil pH was included in all depths because the study was conducted in highly acidic soil; thus, soil acidity was considered as important indicator of SQI estimation by altering other soil properties such as nutrient availability and microbial activity (Patra et al. 2021). Soil enzyme activity is a crucial contributor towards overall soil microbial function (Dick 1994), as well as soil quality; therefore, phenol oxidase activity and microbial biomass phosphorus were incorporated in MSD. Among the various nutrients, mineral N, available K and DTPA extractable Zn, Fe and Mn were selected for MDS formulation for different soil layers.

Soil quality index and interpretation

For computing SQI, 27 soil parameters were assessed and 8 of these soil parameters gave high indicator scores selected to the MDS, based on their soil functional performance for SQI. Each of these soil quality parameters such as phenol oxidase activity, pH, DTPA extractable Fe, available K, mineral N, DTPA extractable Zn, DTPA extractable Mn and microbial biomass phosphorus were found to be significant at the level $p \leq 0.05$ and used for computing the SQI. The SQI measured after 10 years of experimentation revealed that ECM at 2 t ha^{-1} in combination with a 75% reduction in recommended inorganic NP fertilizers achieved the highest SQI at all soil layers. However, application of inorganic NPK along (T_2) significantly declined the SQI by 19, 17 and 15% at D_1, D_2 and D_3 over T_5 (25RDF + 2ECM), respectively, which highlights that inclusion of organic manures was necessary for long-term sustaining and elevating soil quality under rice mono-cropping system on acidic Inceptisol. Previous researchers (Buragohain et al. 2018; Saha et al. 2020) have also reported a decline in the SQI under inorganic NPK applied plots as compared to inorganic fertilizers + manures treated plots under long-term rice trials. Besides, its direct impact on OM addition, organic amendments helps in improving soil bio-physico-chemical attributes, soil aggregate formation, nutrients supply to plants and microbes and carbon sequestration (Patra et al. 2017, 2021). Integration of ECM reduces harmful Al fractions (exchangeable Al and strongly organically bound and interlayer Al), thereby, neutralizing various types of soil acidity in the soil (Patra et al. 2020a, 2020b, 2021). It resulted in antagonistic interaction among cationic micronutrients with Al^{3+} besides promoting microbial activity in the soil. Due to INM practices, the toxic Al fractions and carbon mineralization rate have altered to varying degrees under different soil layers that affect soil fertility status, acidity and microbial activity to varying degrees under different depths of soil (Patra et al. 2020a, 2020c, 2021) and influences the SQI depth-wise. Rice straw and rock phosphate were used to produce the enriched compost in this research, and the rock phosphate contains secondary nutrients such as calcium (Ca) ~24% and magnesium (Mg) ~0.85%. Enriched compost, a low-cost substitute of lime, was mainly applied to neutralize soil acidity due to the presence of basic cations. Moreover, it recycles crop residues and offers an alternative to crop residue burning. Besides its direct influence on soil acidity, ECM provides carbon and other vital nutrients to crops and microorganisms depending on its characteristics, quantity and soil conditions. In the experimental site, heavy rainfall facilitates rapid leaching of basic cations in lower soil layers, and the rate of organic matter (OM) degradation varies substantially across the soil depths (Patra et al. 2020b). Therefore, the long-term application of organic and inorganic fertilizers in integration is the most rational approach for maintaining as well as sustaining SQI under rice sole-cropping system on highly acidic soil, and the findings of the present study are in line with the findings of Meshram et al. (2018), Buragohain et al. (2018) and Saha et al. (2020).

Sustainable yield index and interrelation between yield and soil quality index

The sustainable yield index is an empirical methodology that estimates the actual yield of a crop with a long-term duration through the implementation of various INM practices (Meena et al. 2019). It was used for determining the lowest assured yield, which might be attained in comparison to the highest measured yield. The maximum SYI was documented under conjoint use of ECM along with curtailing doses of inorganic fertilizers to the extent of three-fourth, which enhances grain production by enabling nutrient transport to the grain (Patra et al. 2018) besides improving soil fertility (Patra et al. 2020a). Among all the treatments, highest SYI value was observed in T_5 (25RDF + 2ECM) and lies close to 1, whereas others deviate from 1, indicating ineffectual in sustaining the yield in the long run (Araya et al. 2016; Meena et al. 2019). Organic amendments explicitly supplied a substantial quantity of vital nutrients to the soil and enhanced soil physical characteristics, creating a favorable soil micro-environment for root development and increased nutrient absorption, which leads to increased crop production (Meshram et al. 2018; Meena et al. 2019). Patra et al. (2021) reported that the use of ECM stimulated soil microbial function in soil by neutralizing different forms of soil acidity, which was advantageous not only because microorganisms engage in nutrient cycling but also they promote the synchronization of crop nutrients need with soil. This emphasizes the concomitant and prudent use of inorganic fertilizer, and manure was essential to safeguard the grain productivity for long term under rice sole-cropping system on acidic Inceptisol, which was corroborated with numerous experimental outcomes viz. Bhattacharyya et al. (2016), Buragohain et al. (2018) and Saha et al. (2020). This improvement in SQI and SYI as a consequence of integrated use of ECM with a substantial reduction in NP doses ensured increased crop productivity that ascribed to the cumulative effect of nutrient release and enhancements in soil physico-chemical and biological characteristics. As a result, under long-term INM practices, grain and straw yield demonstrated a strong positive correlation with SQI at various soil depths. Meshram et al. (2018), Meena et al. (2019) and Saha et al. (2020) also observed that crop yield improved under various balanced fertilization (organic manure + inorganic fertilizer) treatments with higher SQI.

Conclusions

A sound nutrient management approach should aim towards a balance between increased crop yields besides maintaining soil quality for a longer duration. In this context, the findings from the present study indicated that the INM practice with ECM for 10 consecutive years improved not only the SYI of rice but also soil quality in acidic Inceptisol. Moreover, the study revealed that phenol oxidase activity, pH, DTPA extractable Fe, available K, mineral N, DTPA extractable Zn and microbial biomass phosphorus were the conceivable soil parameters that exhibit the beneficial impact of the conjoint use of ECM along with the reduction in inorganic NP fertilizer doses on highly acidic soils. Furthermore, these specified indicators made a substantial contribution to the depth-wise SQI evaluation for maintaining and sustaining soil quality over long-term as well as higher crop productivity. Thus, to resolve the challenge of conserving and sustaining soil quality for long-term besides higher crop production in acidic Inceptisol, it was advocated to apply ECM at 2 t ha^{-1} conjoint with 25% recommended inorganic NP fertilizers.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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