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Effect of integrated nutrient management (INM) practices on soil quality indicators and indices under sorghum (*Sorghum bicolor*(L.) Moench) + pigeon pea (*Cajanus cajan* (L.) Millsp.) (4:2) and soybean (*Glycine max* (L) Merr) + pigeon pea (*Cajanus cajan* (L.) Millsp.) in rainfed Vertisols of Western India

K.L. SHARMA[1#], K. SAMMI REDDY[1], G. RAVINDRA CHARY[1], VINOD KUMAR SINGH[1], MUNNA LAL[1], K. GOPI NATH, CH. CHANDRA SEKHAR[1], A.K. INDORIA[1], B.V. ASEWAR[2], A.K. GORE[2], G.K. GAIKWAD[2], G.R. HANWATE[2], AND D.L.A. GAYATRI[1]

[1]ICAR-Central Research Institute for Dryland Agriculture, Hyderabad-500 059, Telangana

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ABSTRACT

A field experiment was conducted at the research farm of the All-India Coordinated Research Project for Dryland Agriculture, Parbhani Center, located in Central and Western Maharashtra, India, to study the effect of 7 predominant integrated nutrient management (INM) practices viz., F1: FYM @ 5 t ha^{-1}; F2: Gliricidia @ 3t ha^{-1} (semi dried); F3: Recommended dose of fertilizer (RDF); F4: 25% RDF + FYM @ 2.5 t ha^{-1}; F5: 25% RDF + Gliricidia @ 1.5 t ha^{-1}; F6: Control with rotation and F7: Absolute control without rotation, on soil quality indicators and indices under two inter-cropping systems viz.,i) sorghum + pigeon pea (4:2), and ii) soybean + pigeon pea (4:2). The effect of INM treatments on soil quality indicators and indices under these cropping systems was studied individually, and the common indicators were also identified among the two cropping systems and mean SQI (Soil Quality Index) and RSQI(Relative Soil Quality Indices) were computed. The common indicators among the two cropping systems emerged for these Vertisol soils were: available S, dehydrogenase assay (DHA), labile carbon (LC) and mean weight diameter (MWD) of soil aggregates. These indicators assume great significance in managing these Vertisol soils. The methodology followed and the results of the present study will be immensely useful to different stakeholders such as researchers, students, farmers, land managers and NGOs in managing and improving soil quality under different inter-cropping systems in Vertisols.

Keywords: Integrated nutrient management, soil quality indicators and indices, inter-cropping systems, Vertisols, FYM and glyricidia

INTRODUCTION

In Inida, Vertisols (Black soils) are predominant in the states of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu. These soils are developed on base-rich rocks (basalt) or the related colluvium or alluvium parent materials (Rajput *etal.*2009), which are generally alkaline and heavy in texture (clay, clay loam, or silty clay loam), dominated by smectitic clay minerals, with expansion and shrinkage characteristics on wetting and drying. These Vertisols, in general, have low infiltration rate, high plasticity and stickiness, high bulk density, high CEC, and have some calcareousness nature. Low organic matter is a major constraint in Vertisols beside low plant-available nutrients, particularly available N, P and Zn, thus limiting their productivity (Blaise *et al.* 2005). Other productivity limiting constraints include limited soil moisture availability and poor drainage. Further, the Vertisols are highly prone to sheet erosion (Rajput *et al.* 2009); especially where the soil cover is sparse and where concentrated flow of water occurs through unprotected channels. In addition, poor management of these soils lead to their further degradation.

The predominant cropping pattern followed in medium to deep Vertisols in India is cotton and cotton-based systems (Mandal *et al.* 2005). When cotton is grown continuously, there is a probability of soil structural degradation due to shearing and compaction during tillage and harvesting operations under wet conditions, and decline in fertility because of the wider nutrient removal use gap (Hullugalle *et al.* 2007). Owing to all these causes, Vertisols, especially in rainfed semi-arid tropical (SAT) regions, encounter many problems on account of physical, chemical, and biological soil quality and consequently result in poor crop yields. Several reports indicate that the quality and productivity of black soils can be enhanced by adopting

[#]*Corresponding author: klsharma9999@yahoo.co.in*
[2]*AICRP for Dryland Agriculture, MAU, Parbhani 431 402, Maharashtra*

suitable practices such as inclusion of legumes as intercrops or in rotation with cotton and other main crops, integrated use of organic and inorganic sources of nutrients, and balanced fertilization (Rajput *et al.* 2009). Appropriate soil and nutrient-management practices are needed to mitigate the effects of soil degradation or restore soil quality to a desirable level in rainfed regions. Supplementing the nutrient requirement of crops through organic manures, especially the farm-based organics, play an important role in sustaining soil fertility and crop productivity and restoring overall soil quality. Conjunctive use of organic and inorganic sources of nutrients ensures environmental safety besides sustainable productivity. In order to study the impact of these management practices on soil quality and related indicators, long-term experiments are of great significance. While conducting soil quality assessment studies in rainfed SAT Alfisols, significant influence of long-term use of soil restorative practices such as conservation tillage, farm-based residue application and conjunctive nutrient management on predominant physical, chemical and biological soil quality indicators and soil quality indices (SQIs) was reported (Sharma *et al.* 2005; Sharma *et al.* 2008). Such information was found lacking in predominant inter-cropping systems such as sorghum + pigeon pea and soybean + pigeon pea when grown under rainfed Vertisols and related soils. Much of the published research on soil quality changes caused by crop rotations in Vertisols is available for irrigated regions, but the information for rainfed regions is very scanty (Hullugalle *et al.* 2007).

In recent times, the term soil quality has been comprehensively elaborated by including several aspects. A committee for the Soil Science Society of America defined soil quality as 'the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation' (Karlen *et al.* 1997). Soil quality cannot be measured directly, but could be inferred by measuring soil attributes or properties that serve as soil quality indicators. The changes in these indicators are used to determine whether soil quality is improving, stable, or declining with changes in management, land use, or conservation practices (Brejda and Moorman 2001). There are potentially many soil properties that might serve as indicators of soil quality, and research is required to identify the most suitable indicators (Nortcliff 2002). To evaluate changes in soil quality resulting from various management systems, a minimum number of soil quality indicators (minimum data set, MDS) need to be identified from a large data set for which various techniques and procedures exist (Grace and Sharma 2010). Further, the integration of these indicators into a single index may help in assessing the soil quality more precisely, which is used to measure the level of an improving or declining soil condition (Wienhold *et al.* 2004).

Considering the above facts, it was felt essential to assess the effect of integrated use of organic and inorganic sources of nutrients on soil quality indicators and indices under different predominant inter-cropping systems in Vertisol regions of Parbhani, located in Central and Western Maharashtra Plateau in India. The present study was conducted with the objectives: (i) to quantify the impact of integrated nutrient management (INM) practices on physical, chemical and biological soil quality indicators; (ii)To identify the key indicators and to compute soil quality indices and (iii)To identify the best INM practices from the view point of soil quality.

MATERIALS AND METHODS

Along term experiment on the effect of integrated nutrient management (INM) practices on soil quality indicators and indices comprising of seven treatments under two legume based cropping systems was conducted at Parbhani center, located at Central and Western Maharashtra Plateau in India. The two inter-cropping systems adopted under this study were i) sorghum (*Sorghum bicolor* (L.) Moench) + pigeon pea (*Cajanus cajan* (L.) Millsp.) (4:2) and ii) soybean (*Glycine max* (L) Merr) + pigeon pea (*Cajanus cajan* (L.) Millsp.) (4:2) and the seven nutrient management treatments tested under these cropping systems were F1: FYM@ 5 t ha^{-1}; F2: Gliricidia @ 3t ha^{-1} (semi dried); F3: Recommended dose of fertilizer (RDF); F4: 25% RDF + FYM @ 2.5 t ha^{-1}; F5: 25% RDF + Gliricidia @ 1.5 t ha^{-1}; F6: Control with rotation and F7: Absolute control without rotation. The experiment was conducted in a Randomized Block Design (RBD) with three replications.

The experimental region represents hot moist semiarid ecological sub-region with mean annual rainfall of 961 mm, shallow and medium loamy to clayey black soils (70-100 cm) with representative pH of 8.2, having bulk density about 1.29 $gcm^{-3}$and medium to high AWC (32-33%) with length of growing period (LGP) ranging from 120-150 days. The frequency of occurrence of drought in this region is 8 out of 18 years. The experimental soils represent Typic Chromusterts. Soil quality assessment studies were taken up after five years of experimentation.

Soil sampling and analysis

After 5 years of the experimentation (2000-2005), surface soil samples were collected from plough layer (0-15 cm depth) and were ground, partitioned and passed through standard prescribed sieves for further use in different analyses. Soil samples passed through 8 mm sieve and retained on the 4.75 mm sieve were used for aggregate analysis, while the samples passed through 0.2 mm sieve were used for estimating organic carbon (OC) as well as labile carbon (LC). For the rest of the soil quality parameters viz., chemical and biological parameters, soil samples passed through 2 mm sieves were used. Soil pH and electrical conductivity were measured in 1:2 soil water suspension using pH meter and conductivity meter, respectively. OC was determined by the modified Walkley-Black wet digestion method and available nitrogen (N) by alkaline-$KMnO_4$ method. Available P was extracted with 0.5 M sodium bicarbonate (pH of 8.5) and was determined colorimetrically. Available K was extracted with neutral normal ammonium acetate and was analyzed using inductively coupled plasma spectrophotometer (ICP-OES, GBC, Australian Model). Exchangeable Ca and Mg were also extracted by 1N ammonium acetate and were determined using atomic absorption spectrophotometer (GBC906, Australian Model). Sulphur was extracted with 0.15% $CaCl_2$ reagent and was estimated turbidimetrically with a colorimeter using blue filter in spectrophotometer at 340 nm. The micronutrients viz., Zn, Fe, Cu, and Mn were estimated using the method suggested by Lindsay and Norvell, 1978 with Inductively Coupled Plasma Spectrophotometer (ICP), (ICP-OES, GBC, Australian Model) while, boron was estimated using DTPA-Sorbitol extraction method (Miller *et al.* 2001).

Bulk density was measured by Keen's box method. The distribution of water stable aggregates was determined by wet sieving technique using sieves of 4750 μm, 2000 μm, 1000 μm, 500 μm, 250 μm and 100 μm sizes (Yoder 1936) and mean weight diameter (MWD) was computed after oven drying (Van Bevel 1949). Dehydrogenase activity in the soils was measured by triphenyltetrazolium chloride method (TTC) (Lenhard 1956) and the results were expressed as mg TPF formed per hour per gm soil. Soil microbial biomass carbon (MBC) was determined using the chloroform fumigation incubation technique (Jenkinson and Powlson1976). Immediately after the collection, the portion of the 2 mm sieved samples was preserved in a horizontal refrigerator at 4-5^o C. Before analyzing MBC, these samples were taken out of the refrigerator and primed in BOD incubator at field capacity (15% w/w) moisture regime for 10 days at 25^0C ± 1^0C temperature. MBC was calculated using the following relationship:

$$\text{MBC } (\mu g\ g^{-1} \text{ of soil}) = (EC_F - EC_{UF}) / K_{EC}$$

where, EC_F is the total weight of extractable carbon in fumigated sample, EC_{UF} is the total weight of the extractable carbon in unfumigated samples and K_{EC} = 0.25 ± 0.05 represents the efficiency of extraction of MBC. Labile carbon was estimated using the Weil *et al.* method (Weil *et al.* 2003) with slight modification. In this method, moist fresh air dried soil was equilibrated with 20 ml 0.01 M $KMnO_4$ solution for 15 minutes. The soil-solution suspension was centrifuged at 3000 rpm for 5 min. The absorbance was measured at 550 nm using Mini Spectrophotometer (Model SL 171 of Elico Ltd.).

Computation of soil quality indices

The data set obtained for all the 19 soil quality parameters was statistically analyzed for their level of significance using randomized block design. After the statistical analysis, the parameters which were found significant were subjected to principal component analysis (PCA) using SPSS software (Version 12.0). The principal components (PCs) which received eigen values ≥ 1 (Brejda *et al.* 2000a; Brejda *et* *al.* 2000b) and explained at least 5% of the variation in the data (Wander and Bollero 1999) and variables which had high factor loading were considered as the best representative of system attributes. Within each PC, only highly weighted factors (having absolute values within 10% of the highest factor loading) were retained for the minimum data set (MDS). The final MDS variables were regressed with the yield as management goals. The variables qualified under these series of steps were termed as the "key indicators" and were considered for computation of soil quality index (SQI) after suitable transformation and scoring.

All the observations of each identified key MDS indicators were transformed using linear scoring technique (Andrews *et al.*2002). To assign the scores, indicators were arranged in order depending on whether a higher value was considered "good" or "bad" in terms of soil function. In case of "more is better" indicators, each observation was divided by the highest observed value such that the highest observed value received a score of 1. For "less is better" indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1. After the transformation using linear scoring method, the MDS indicators for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage when divided by the total percentage of variation explained by all PCs with eigenvectors >1, gave the weighted factors for indicators chosen under a given PC. After performing these steps, to obtain SQI, the weighted MDS indicator scores for each observation were summed up using the following function:

$$SQI = \sum_{i=1}^{n} (Wi \times Si),$$

Where, Si is the score for the subscripted variable and Wi is the weighing factor obtained from the PCA. Here the assumption was that, higher index scores meant better soil quality or greater performance of soil function. For better understanding and relative comparison of the long-term performance of the conjunctive nutrient use treatments, the SQI values were reduced to a scale of 0-1 by dividing all the SQI values with the highest SQI value. The numerical values thus obtained, clearly reflect the relative performance of the management treatments, and hence were termed as the "relative soil quality indices" (RSQI). Further, the percent contributions of each final key indicator towards SQI were also calculated.

Statistical Analyses

Analysis of variance (ANOVA) was performed using "Drysoft" design package. The randomized block design (RBD) was used for the experiment and the differences were compared by Least Significant Difference (LSD) test at a significance level of $p < 0.05$ (Snedecor *et al.*1989). Principal component analysis (PCA) was performed using SPSS version 12.

RESULTS AND DISCUSSION

Soil quality under sorghum + pigeon pea (4:2) system

The pH in this system varied from 7.78 to 8.18 and the EC from 0.14 to 0.22 dSm^{-1}, respectively across the treatments. OC was found highest under 25% RDF + FYM @ 2.5 t ha^{-1} (F4) followed by RDF (F3) while the lowest content was observed under control with rotation (F6). Available N varied from 180.1 to 203.6 kg ha^{-1} with no significant difference among treatments. The available P and K in soils were significantly influenced by the treatments. The treatment F3 recorded the highest available P (16.5 kg ha^{-1}) which was at par with that with F2 (13.2 kg ha^{-1}), while the lowest amount was recorded with F6 (8.5 kg ha^{-1}); whereas the F2 has recorded highest available K (702.4 kg ha^{-1}) which was at par with F1 (665.7 kg ha^{-1}) with the lowest amount observed under F7 treatment (500.9 kg ha^{-1}). Exchangeable Ca and Mg were not significantly influenced by the treatments; however, their contents ranged between 6.02 to 6.84 and 4.51 to 5.23 c mol kg^{-1}, respectively. Available S was significantly influenced by the treatments and the highest available S of 28.3 kg ha^{-1} was recorded F1 treatment followed by F2 (19.5 kg ha^{-}1), with the lowest amount observed under F7 treatment (13.0 kg ha^{-1}) (Table 1).

Table 1: Effect of different INM treatments on physico-chemical and chemical soil quality parameters under sorghum + pigeon pea (4:2) system

Treatments	pH	EC (dSm^{-1})	OC ($g\ kg^{-1}$)	N	P	K	Ca	Mg	S ($kg\ ha^{-1}$)
				$kg\ ha^{-1}$			C mol kg^{-1}		
F_1	7.80	0.17	5.99	195.8	10.9	665.7	6.04	5.23	28.3
F_2	7.78	0.22	5.69	203.6	13.2	702.4	6.12	5.09	19.5
F_3	8.16	0.17	6.17	193.5	16.5	572.6	6.02	4.66	18.2
F_4	7.94	0.17	6.72	198.3	12.7	573.1	6.07	4.70	15.2
F_5	7.95	0.17	5.93	196.2	10.3	608.3	6.21	5.19	15.6
F_6	8.18	0.15	5.00	185.9	8.5	525.0	6.46	4.59	16.6
F_7	7.84	0.14	5.69	180.1	9.6	500.9	6.84	4.51	13.0
CD (P = 0.05)	NS	0.02	0.51	NS	3.9	100.8	NS	NS	3.05

Soil micronutrient contents viz., Zn, Fe, Cu, Mn and B were found to be not significantly influenced by the INM treatments. However, available Zn, Fe, Cu, Mn and B in soil ranged between 0.22 to 0.30, 9.4 to 11.5, 1.26 to 1.47, 18.5 to 22.1 and 1.09 to 1.25 μg g^{-1} of soil, respectively. The biological soil quality indicators viz., dehydrogenase assay (DHA), microbial biomass carbon (MBC) and labile carbon (LC) were significantly influenced by the INM treatments. Among all the treatments, the application of F4 recorded the highest DHA (2.41 μg TPF g^{-1} of soil hr^{-1}), MBC (232.6 μg g^{-1} of soil) and LC (271.8 μg g^{-1} of soil), while F7 has recorded the lowest values. Among the physical indicators, bulk density varied from 1.19 to 1.36 Mg m^{-3} and was not conspicuously influenced by the treatments. The mean weight diameter ranged from 0.26 to 0.36 mm, the highest being under F1 (0.36 mm) (Table 2).

Table 2: Effect of different INM treatments on chemical (micronutrients), biological and physical soil quality parameters under sorghum + pigeon pea (4:2) system

Treatments	Zn	Fe	Cu	Mn	B	DHA (μg TPF g^{-1} soil hr^{-1})	MBC	LC	BD (Mg m^{-3})	MWD (mm)
	μg g^{-1} of soil						(μg g^{-1} soil)			
F_1	0.29	11.5	1.40	21.8	1.24	2.15	203.0	260.7	1.19	0.36
F_2	0.27	11.3	1.34	21.5	1.24	2.07	209.8	263.2	1.23	0.33
F_3	0.30	10.8	1.44	21.2	1.25	2.30	197.4	244.9	1.29	0.30
F_4	0.28	10.9	1.44	22.1	1.18	2.41	232.6	271.8	1.21	0.33
F_5	0.29	10.7	1.47	21.5	1.16	2.38	231.6	259.2	1.26	0.30
F_6	0.22	9.9	1.29	19.9	1.13	1.15	190.5	207.3	1.36	0.28
F_7	0.23	9.4	1.26	18.5	1.09	1.14	163.6	199.1	1.32	0.26
CD (P = 0.05)	NS	NS	NS	NS	NS	0.14	26.4	34.8	NS	0.04

Key indicators and soil quality assessment

The data on the long-term influence of INM treatments practiced under sorghum + pigeon pea system on 19 soil quality indicators has been statistically analyzed and it was observed that ten out of the nineteen variables were not significant and hence were dropped. Hence, the PCA was carried out with only nine variables. In the PCA of 9 variables, only two PCs had eigen values >1 and explained 68.9% variance in the data set (Table 3). In PC1 the highly weighted variables were DHA, LC and MWD; while in PC2, only OC and available S were the highly weighted variables. Correlation analysis was run for the variables qualified under PC1 (Table 4). Though, DHA as well as LC had significant and good correlations, both were retained for the final MDS. Though MWD also had significant correlation, the 'r' value was below 0.70; hence it was retained for the MDS. The highly weighted variables under PC2 revealed no significant correlation and hence were considered for final MDS. On the whole, surprisingly very few indicators viz., OC, available S, DHA, LC and MWD were retained for the final MDS and termed as the key indicators for sorghum + pigeon pea system and these indicators were used for computing the SQIs.

Table 3: Principal component analysis of soil quality parameters as influenced by different INM treatments under sorghum + pigeon pea (4:2) system

	PC1	PC2
Total Eigen values	4.678	1.524
% of Variance	51.975	16.934
Cumulative %	51.975	68.909
Eigen Vectors		
EC	0.743	0.248
OC	0.597	**-0.615**
P	0.539	-0.282
K	0.700	0.500
S	0.512	**0.641**
DHA	**0.890**	-0.297
MBC	0.705	-0.396
LC	**0.887**	-0.055
MWD	**0.807**	0.309

Soil quality indices were computed using five key soil quality indicators viz., OC, available S, DHA, LC and MWD. SQIs varied from 1.68 to 2.47 across the INM treatments. Among all the INM treatments, significantly highest SQI was observed under F1 treatment (2.47) which was at par with F4 (2.43). The treatments which received FYM showed the higher SQIs followed by the treatments with Gliricidia component. Irrespective of their statistical significance, the order of performance of treatments in terms of influencing soil quality were: F1 (2.47) > F4: (2.43) > F5: (2.31) > F2: (2.30) > F3: (2.27) >F6: (1.75) >F7: (1.68) (Table 9). The SQIs when reduced to a scale of 1.00 varied from 0.66 to 0.97 across the INM treatments. The percent contributions of key indicators towards SQIs were: MWD (29%), LC (28%), DHA (26%), OC (10%) and available S (7%) (Table 10).

Soybean + Pigeon pea (4:2) system

In this system, soil pH was significantly influenced by the treatments which varied from 7.60 to 8.05, while the influence on EC and OC was non-significant which varied from 0.14 to 0.18 dSm^{-1} and 5.99 to 6.90 g kg^{-1}, respectively. Available N was significantly influenced by the INM treatments and the highest content was recorded under F5 (217.3 kg ha^{-1}) which was at par with F3 (205.3 kg ha^{-1}) and F2 (203.5), while the lowest (180.7 kg ha^{-1}) was observed under F7.

Table 4: Pearson's correlation matrix for highly weighted variables under PCs with high factor loading

Variables under PCs			
PC1	DHA	LC	MWD
DHA	1.00	0.805**	0.573**
LC	0.805**	1.00	0.696**
MWD	0.573**	0.696**	1.00
Correlation sum	2.378	2.501	2.269
PC2	OC	S	
OC	1.00	0.092	
S	0.092	1.00	
Correlation sum	1.092	1.092	

The available P varied between 12.4 to 15.3 kg ha^{-1} across the treatments and was not significantly influenced by the INM treatments.

Table 5: Effect of different INM treatments on physic-chemical and chemical soil quality parameters under soybean + pigeon pea (4:2) system

Treatments	pH	EC (dSm^{-1})	OC (g kg^{-1})	N	P	K	Ca	Mg	S
				kg ha^{-1}			C mol kg^{-1}		(kg ha^{-1})
F_1	7.90	0.17	6.90	194.4	14.23	660.2	6.34	4.94	13.5
F_2	7.65	0.16	6.75	203.5	13.77	735.9	6.67	4.96	12.3
F_3	7.85	0.17	6.13	205.3	15.28	539.4	6.26	5.25	17.4
F_4	7.70	0.16	6.39	193.5	15.03	562.3	6.34	5.60	20.2
F_5	8.05	0.18	6.65	217.3	13.60	650.4	6.28	5.26	12.0
F_6	7.65	0.14	6.04	184.1	12.81	520.9	6.26	4.58	17.2
F_7	7.60	0.15	5.99	180.7	12.43	482.8	6.26	4.72	12.6
CD (P = 0.05)	0.24	NS	NS	22.2	NS	107.7	NS	NS	2.2

Available K content was significantly influenced by the INM treatments with the highest value under F2 (735.9 kg ha^{-1}) which was at par with F1 (660.2 kg ha^{-1}), while the F7 treatment recorded lowest content (482.8 kg ha^{-1}). Exchangeable Ca and Mg varied from

6.26 to 6.67 and 4.58 to 5.60 c mol kg^{-1}, respectively, with no conspicuous influence of the INM treatments. Available S was also significantly influenced by the treatments and treatment F4 recorded highest available S content (20.2 kg ha^{-1}) followed by F3 treatment (17.4 kg ha^{-1}), while lowest content (12.0 kg ha^{-1}) was recorded under the F5 treatment (Table 5). The contents of all the micronutrients contents (except Mn) were not significantly influenced by the INM treatments under this system. The available Zn, Fe, Cu and B ranged between 0.25 to 0.30, 9.6 to 11.5, 1.32 to 1.48, and 0.99 to 1.20µg g^{-1} of soil. Available Mn was significantly highest under F4 treatment (23.2 µg g^{-1} of soil) which was at par with many other treatments, while the lowest content (18.3 µg g^{-1} soil) was recorded under the treatment F7.

Table 6: Effect of different INM treatments on chemical (micronutrients), physical and biological soil quality parameters under soybean + pigeon pea (4:2) system

Treatments	Zn	Fe	Cu	Mn	B	DHA (µg TPF g^{-1} soil hr^{-1})	MBC	LC	BD (Mg m^{-3})	MWD (mm)
	µg g^{-1} of soil						µg g^{-1} soil			
F_1	0.28	11.4	1.42	22.7	1.13	2.44	242.5	271.4	1.12	0.48
F_2	0.27	11.5	1.47	22.7	0.99	2.16	237.6	277.9	1.12	0.41
F_3	0.30	10.1	1.48	22.1	1.20	1.92	226.6	259.5	1.14	0.30
F_4	0.29	10.4	1.42	23.2	1.07	2.00	243.5	266.4	1.14	0.33
F_5	0.27	11.1	1.46	21.2	1.18	2.18	252.9	260.6	1.13	0.42
F_6	0.26	9.7	1.39	19.7	1.08	1.70	211.5	220.3	1.18	0.27
F_7	0.25	9.6	1.32	18.3	1.08	1.51	182.5	219.5	1.22	0.25
CD (P = 0.05)	NS	NS	NS	2.6	NS	0.24	22.2	26.9	0.06	0.04

All the biological soil quality parameters viz., DHA, MBC and LC were significantly influenced by the INM treatments under this system. The DHA and LC were found to be highest under F1(2.44 µg TPF g^{-1} soil hr^{-1}) followed by the treatment F5(2.18 µg TPF g^{-1} soil hr^{-1}), while the lowest DHA (1.51 µg TPF g^{-1} soil hr^{-1}) was recorded under F7. The highest MBC was recorded under the treatment F5 (252.9 µg g^{-1} soil) and was at par with treatments F4, F1 and F2, while the lowest MBC (182.5 µg g^{-1} soil) was recorded under F7 treatment. Significantly highest LC was recorded under F2 (277.9 µg g^{-1} soil) which was at par with F1 treatment (271.4 µg g^{-1} soil).The physical soil quality indicators viz., BD and MWD were also significantly influenced by the INM treatments. It was quite interesting to note that, sole organic treatments of F1 and F2 recorded significantly lowest bulk density of 1.12 Mg m^{-3}. The highest MWD of 0.48 mm was recorded under F1 treatment.

Key indicators and soil quality assessment

Statistical analysis of data revealed that out of the 19 soil quality parameters, nine variables were insignificant and were dropped. Hence, the PCA was carried out with the remaining ten variables in which only three PCs had eigen values >1 and explained 78.6% variance in the data set (Table 7). In PC1, the highly weighted variables were DHA, MBC, LC and mean weight diameter MWD. All the three biological parameters included in the study were highly weighted in this PC. Hence, a correlation analysis was carried out between the variables qualified under PC1, which revealed a significant correlation between the variables (Table 8). DHA had the highest correlation sum and the correlation value for DHA and LC was below the set criteria of significance (0.70), hence both were retained for the final MDS. As MBC has good significance with both DHA and LC, it was not retained. MWD having the second highest correlation sum and because of its importance as a physical soil quality indicator for these Vertisols, it was retained. In both PC2 and PC3, only variable each viz., available S and soil pH, respectively were highly weighted, respectively and retained for the MDS. Hence, the final indicators retained for the MDS included pH, available S, DHA, LC and MWD and were termed as the key indicators for soybean + pigeon pea (4:2) system.

Table 7: Principal component analysis of soil quality parameters as influenced by different INM treatments under soybean + pigeon pea (4:2) system

	PC1	PC2	PC3
Total Eigen values	5.257	1.594	1.006
% of Variance	52.573	15.938	10.062
Cumulative %	52.573	68.511	78.573
Eigen Vectors			
pH	0.554	0.022	-0.787
N	0.559	-0.346	0.169
K	0.745	-0.286	0.358
S	-0.187	0.912	0.068
Mn	0.675	0.511	0.254
DHA	0.888	-0.096	-0.121
MBC	0.861	0.266	-0.178
LC	0.828	0.037	0.328
BD	-0.775	-0.374	0.032
MWD	0.882	-0.277	-0.080

Soil quality indices were computed using five key soil quality indicators viz., pH, available S, DHA, LC and MWD, which varied from 1.48 to 2.16 across the INM treatments. The treatment F1 maintained significantly highest SQI (2.16) followed by F2 (2.00). Irrespective of their statistical significance, the order of performance of treatments on soil quality were: F1: (2.16) > F2: (2.00) > F5: (1.97) > F4: (1.90) > F3: (1.79) > F6: (1.60) >F7: (1.48). The SQIs when reduced to a scale of 1.00 varied from 0.68 to 0.99 (RSQI) across the INM treatments. The percent contributions of key indicators towards SQIs were: LC (31%), DHA (29%), MWD (25%), available S (8%) and pH (7%) (Table 10).

Table 8: Pearson's Correlation matrix for highly weighted variables under PCs with high factor loading

Variables under PCs				
PC1	DHA	MBC	LC	MWD
DHA	1.00	0.739**	0.662**	0.902**
LC	0.739**	1.00	0.710**	0.655**
MBC	0.662**	0.710**	1.00	0.646**
MWD	0.902**	0.655**	0.646**	1.00
Correlation sum	3.30	3.10	3.02	3.20

The summarised values of SQIs and RSQIs and the ranking of the INM treatments from the view point of their performance in terms of soil quality have been presented in Tables 9 and 10. The overall performance of the INM treatments across the cropping systems studied was in the order of: F1(SQI 2.32) > F4 (SQI 2.17)> F2 (SQI 2.15) >F5 (SQI 2.14) > F3 (2.03) >F6 (SQI 1.68) >F7(SQI 1.58). Further, the common key indicators of soil quality for both the inter-cropping systems were: available S, DHA, LC and MWD which assume great significance in managing these Vertisol soils. The percent contributions of the identified key indicators towards SQI values are given in the table 10. The results revealed that the INM practices played an important role in influencing key indicators of soil quality and in improving the SQIs under these two cropping systems.

Table 9: Summary table of soil quality indices and relative soil quality indices as influenced by different INM practices under two cropping systems

Treatments	Sorghum+Pigeon pea (4:2) system		Soybean+Pigeon pea (4:2) system		Mean SQI	Mean RSQI	Ranking
	SQI	RSQI	SQI	RSQI			
F_1	2.47	0.97	2.16	0.99	2.32	0.98	I
F_2	2.30	0.90	2.00	0.92	2.15	0.91	III
F_3	2.27	0.89	1.79	0.82	2.03	0.86	V
F_4	2.43	0.96	1.90	0.87	2.17	0.92	II
F_5	2.31	0.90	1.97	0.90	2.14	0.90	IV
F_6	1.75	0.69	1.60	0.74	1.68	0.72	VI
F_7	1.68	0.66	1.48	0.68	1.58	0.67	VII
CD (P = 0.05)	0.15	0.06	0.08	0.05	-	-	

In the earlier studies , researchers reported that the conjunctive nutrient-management practices significantly and positively enhanced various soil physico-chemical, chemical, physical and biological properties under different cropping systems viz. sorghum-mung bean (Sharma *et al.* 2008; Sharma *et al.* 2015; Sharma, *et al.* 2016),maize-blackgram system (Sharma *et al.* 2019), andrainfed pigeon pea-rice system (Behera *et al.* 2012). In most of these studies, higher SQIs were obtained with conjunctive nutrient management practices. The results of the present study are in close conformity with these findings.

Table 10: Summary table of key soil quality indicators, soil quality indices and the best soil nutrient management practices identified from the view point of soil quality improvement under two cropping systems

Key soil quality indicators and their % contribution	SQI	RSQI	Ranking of INM management with higher SQIs
Sorghum + Pigeon pea (4:2) system • Mean weight diameter (29%) • Labile carbon (28%) • Dehydrogenase assay (26%) • Organic carbon (10%) • Available S (7%)	1.68-2.47	0.66 – 0.97	1. Application of FYM@ 5 t ha^{-1} (2.47) 2. Application of 25% RDF + FYM@ 2.5 t ha^{-1} (2.43) 3. Application of 25% RDF + Gliricidia @ 1.5 t ha^{-1} (2.31)
Soybean + Pigeon pea (4:2) system • Labile carbon (31%) • Dehydrogenase assay (29%) • Mean weight diameter (25%) • Available S (8%) • pH (7%)	1.48-2.16	0.68 - 0.99	1. Application of FYM@ 5 t ha^{-1} (2.16) 2. Application of Gliricidia @ 3 t ha^{-1} (semi dried) (2.00) 3. Application of 25% RDF + Gliricidia @ 1.5 t ha^{-1} (1.97)

The addition of organic matter through farmyard manure and crop residues was found to play an important role in determining soil physical (Indoria *et al.* 2016) ,chemical and biological functional capacity of soil (Sharma *et al.* 2017; Indoria *et al.* 2018).The SOC was found to significantly improve the physical soil quality parameters by supplying the organic matter, carbon and energy to various microbes, which secrete various enzymes and enhance soil aggregation and helped in improving soil physical properties. Increasing the SOM levels by using organic sources of nutrients, reducing the extent of soil disturbance and minimizing the compaction and soil erosion were reported to enhance soil porosity and improve soil structure (Indoria *et al.* 2017). Similarly, the enhanced microbial activity increased the nutrients transformation process including mineralisation and thus their availability to plants. The magnitude of influence of addition of different organic sources on nutrient availability in soil is predominantly determined by their C: N ratios. Therefore, in the present study, the variable results obtained with the application of farmyard manure and Gliricidia loppings might be associated with the C: N ratio of the added materials. It is also worthwhile to mention here that in low nutrient status soil, the sole application of the limited amount of organic sources could not maintain the soil quality parameters up to the desired levels. Thus, the organic farming comprising of integrated nutrient management sources of nutrients is very crucial strategy to improve soil quality key indicators and indices for maintaining soil quality to a desirable level in rainfed Vertisol soils. The methodology followed and the results of the present study will be immensely useful to different stakeholder such as researchers, students, farmers, NGOs and land managers etc. in managing and improving soil quality under different inter-cropping systems in Vertisols and associated black soils.

CONCLUSION

From the present study, it can be concluded that in Vertisol soils, which suffer on account of several physical, chemical and biological soil quality constraints, integrated use of organic and inorganic sources of nutrients is very crucial under inter cropping systems to maintain the desirable status of key soil quality indicators and soil quality Indices.

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