



RESEARCH ARTICLE

Soil quality and carbon sequestration potential in response to long term nutrient management practices under finger millet-maize cropping system in an Alfisol

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Abstract

Understanding the effects of long-term manuring and fertilisation is vital for sustaining soil quality in continuous cropping system particularly in low-fertile Alfisols for developing suitable soil management practices. The research evaluated the impact of long-term manuring and fertilisation on soil quality index (SQI) under finger millet-maize system in Alfisols at the University of Agricultural Sciences, Bengaluru during 2020–22 using a LTFE experiment since 1986. The experiment consists of 11 treatments viz., 50 % nitrogen, phosphorus and potassium (NPK), 100 % NPK, 150 % NPK, 100 % NPK + hand weeding, 100 % NPK + lime, 100 % NP, 100 % N, 100 % NPK + farmyard manure (FYM), 100 % NPK (-S), 100 % NPK + FYM + lime and control in a randomised block design with 3 replications. Soils (Typic Kandic Paleustalfs) were sampled at 0–15 cm after harvest of maize and analysed for various soil indicators. Application of FYM and lime with recommended NPK improved soil quality (e.g., organic carbon, dehydrogenase activity), while unfertilised or imbalanced treatments (N or NP) showed decline. The SQI ranged from 0.64 to 0.99 in surface soils, with organic carbon and pH as key contributors to soil quality. The NPK + FYM + lime treatment showed higher carbon sequestration rate from the initial compared to alone fertiliser application. Integrated application of FYM, lime and recommended NPK significantly improved soil quality, while imbalanced fertilisation led to soil degradation in the long-term finger millet-maize system on Alfisols.

Keywords: farmyard manure; finger millet-maize cropping system; long-term fertilisation; soil carbon sequestration; soil quality index; soil quality indicators

Introduction

In the modern agricultural system, securing a sustainable source of income has arisen as the most crucial concern for farmers and society. Food security must be ensured without jeopardising the environment and ecological stability has drawn a lot of attention. Furthermore, discussed how soils contribute to habitat creation and maintenance, emphasising their role in supporting biodiversity, regulating carbon and nutrient cycles and influencing water dynamics (1). Soil quality degradation adversely affects sustainable agricultural productivity by altering its physicochemical and biological properties (2). Consequently, increasing attention is being given to strategies that effectively sustain soil quality for long-term agricultural production.

Soil is a key natural resource and soil quality is defined as "the capacity of a soil to function within ecosystem and land-use constraints to sustain biological productivity, maintain environmental quality and promote plant and animal health". A soil quality indicator can be categorised into physical, chemical and biological attributes (3). However, most of the microbiological

features, soil aggregation and soil organic matter (SOM) are dynamic soil properties that are more susceptible to disturbances, management practices and/or changes in land use. Microbial and biochemical characteristics are sensitive indicators of soil quality, useful for evaluating ecological stress and disturbances.

Identifying soil quality indicators responsive to environmental changes are essential. Due to their interdependence, individual indicators alone cannot fully assess soil quality, making a comprehensive evaluation challenging (4). Therefore, combining soil properties into a single index may improve the evaluation's applicability. The soil quality index (SQI) approach is widely used for assessing soil due to its flexibility, applicability to various soil types and ability to integrate physical, chemical and biological properties. It involves normalising measurements to create a quantitative value through principal component analysis. The assessment of soil quality helps to guide the long-term sustainability of soil and crop management practices. Long-term fertiliser experiments (LTFEs) are recommended to explore the relationship between soil characteristics and crop yield for improved management strategies (5).

In many parts of southern India, particularly in the Alfisols of Karnataka, the finger millet-maize cropping system is widely practiced. These soils are inherently low in fertility and organic carbon and are highly susceptible to nutrient depletion under continuous cultivation. The continuous cropping system, along with application of imbalanced nutrients nitrogen (N) or nitrogen and phosphorus (NP) from chemical fertilisers without organic manuring, has resulted in reduced crop productivity. Under continuous intensive cropping systems, the recommended dose of nitrogen, phosphorus and potassium (NPK) fertilisers alone does not sustain crop productivity and soil fertility, whereas organic manures improve physical properties as well as the biological status of soil (6). In this context, it is critical to implement suitable soil and crop management strategies that reduce soil degradation and preserve soil quality at an acceptable level. As a result, identifying a set of sensitive soil attributes that reflect a soil's capacity to function and may be utilised as indicators of soil quality is an important part of soil quality evaluation. Thus, the present study, examined three aspects of soil quality in a long term fertiliser experiment: (i) Evaluating the impact of long-term organic and inorganic nutrient management practices on soil quality and carbon sequestration potential; (ii) To find out the physical, chemical and biological indicators of soil quality in long-term established finger millet-maize cropping system; (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 finger millet-maize cropping system in Alfisols.

Materials and Methods

Location of the field experiment

A long-term field experiment has been in progress since 1986 at the Zonal Agricultural Research Station, University of Agricultural Sciences, GKVK, Bengaluru. The study site is situated in the Eastern Dry Zone of Karnataka at an altitude of 930 m above mean sea level,

with a latitude of 13° N and a longitude of 77°33' E. The experiment follows a finger millet-maize cropping system.

The soil at the experimental site is lateritic with a sandy clay loam texture in the surface and sandy clay in subsurface depth. It is classified under the Isohyperthermic family of the Typic Kandic Paleustalfs subgroup. The soil is slightly acidic (pH 6.17) and has a low organic carbon (OC) content (4.60 g kg⁻¹). Available N (256.70 kg ha⁻¹) and K (123.10 kg ha⁻¹) were low, while available P (34.30 kg ha⁻¹) was in the medium range. The initial physico-chemical properties of the soil (1986) are presented in Table 1.

Treatment details

The long-term fertiliser experiment was carried at Gandhi Krishi Vignana Kendra (GKVK), University of Agricultural Sciences, Bengaluru. The experiment consists of 11 treatments which are replicated 4 times in a randomised block design having individual plot size of 16 m × 9 m (144 m²). However, for the present study only 3 replications were considered.

Description of the field experiment

Finger millet and hybrid maize crops were grown in sequence during kharif and rabi-summer seasons, respectively. The recommended dose of NPK for finger millet was 100 : 22 : 42 kg ha⁻¹ and maize was 100 : 33 : 82 kg ha⁻¹. Chemical weed control using appropriate weedicides was implemented in all ten treatments, except for the 100% NPK + hand weeding (HW) treatment. In treatments T₅ and T₁₀, lime was applied 15 days before sowing the finger millet crop, based on lime requirements determined using the method described earlier (7). However, when the soil pH exceeds 6.00 then lime was applied at the rate of 500 kg ha⁻¹. Well decomposed FYM at the rate of 15 t ha⁻¹ on dry weight basis has been incorporated into the soil 10–15 days prior to transplanting of finger millet crop in treatments T₈ and T₁₀. Half of the recommended dose of N, along with full dose of P and K have been applied as basal and remaining half of N dose is applied in two equal splits after 25 to 30 days of sowing/transplanting of crops as top dress. Diammonium phosphate (DAP)

Table 1. Initial soil characteristics of experimental site (1986)

Subgroup	:	Kandic Paleustalfs		
Series	:	Vijayapura		
Taxonomy	:	Fine, mixed Isohyperthermic Kandic Paleustalfs		
Mechanical composition				
Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class
0–20	62.0	8.6	29.4	Sandy clay loam
20–36	52.1	11.7	36.2	Sandy clay
36–55	35.6	12.6	54.8	Clay
Physical properties				
Bulk density (Mg m ⁻³)	:	1.51		
Maximum water holding capacity (%)	:	30.00		
Field capacity moisture (%)	:	22.70		
Pore space (%)	:	40.10		
Water stable aggregates (%) (2 mm)	:	23.70		
Chemical properties				
pH (1 : 2.5, soil : water suspension)	:	6.17		
Electrical conductivity (dS m ⁻¹)	:	0.059		
CEC [c mol (p ⁺) kg ⁻¹]	:	12.20		
Organic carbon (g kg ⁻¹)	:	0.46		
Available nitrogen (kg ha ⁻¹)	:	256.7		
Available phosphorus (kg ha ⁻¹)	:	34.3		
Available potassium (kg ha ⁻¹)	:	123.1		
Exchangeable calcium (kg ha ⁻¹)	:	1456.00		
Exchangeable magnesium (kg ha ⁻¹)	:	415.20		
Available sulphur (mg kg ⁻¹)	:	20.34		
Diethylenetriaminepentaacetic acid (DTPA) extractable micronutrients (mg kg ⁻¹)				
Zinc	:	2.34		
Copper	:	2.30		
Manganese	:	48.40		
Iron	:	5.22		

is used as a source of P and N along with urea and muriate of potash (MOP) in 100 % NPK without sulphur (-S). In rest of the treatments (except T₈) urea, single super phosphate (SSP) and MOP are used as sources of NPK, respectively. Neither chemical fertiliser nor organic manure was used in absolute control treatment (T₁₁).

Collection, processing and analysis of soil sample

Composite soil samples were collected from each plot using a soil tube auger at surface soil following the harvest of the maize crop during 2020 and 2021. Soil samples for biological assays were stored fresh in aluminum moisture cans and kept in the refrigerator at 4 °C. The samples for chemical assays were dried at room temperature then grounded and passed through a 2 mm sieve and stored in a glass bottles. The collected soil samples were analysed for physico-chemical and biological properties. The water holding capacity, porosity and bulk density were determined by Keen Raczowski cup method, whereas, soil texture by International pipette method as described previously (8). Soil chemical analyses viz., pH (potentiometric), electrical conductivity (EC) (conductometric), cation exchange capacity (CEC) (ammonium acetate leaching method), available P using Bray's extractant; available K using neutral normal ammonium acetate extractant; available S by turbidometric method as described by previous researchers (9), OC was measured by wet digestion method (10). Soil available N was determined by alkaline-KMnO₄ (11). Micronutrients were determined using diethylenetriaminepentaacetic acid (DTPA) extractant (12). Available B was determined using the azomethane-H reagent (13). Microbial biomass carbon (MBC) was measured using the chloroform fumigation technique (14), dehydrogenase activity (DHA) by triphenyl tetrazolium chloride reduction (15), acid phosphatase (ACP) activity by the modified universal buffer method (16) and urease activity by the colorimetric method (17).

Computation of soil quality index

According to previous researchers, the soil quality assessment tool was created in three steps, beginning with the selection of a minimal dataset (MDS) and concluding with the integration of indicator scores to produce a soil quality index (18). Noteworthy, the variables with significant differences ($p < 0.05$) between treatments were chosen for MDS formation and subjected to principal component analysis (PCA). Each pivotal indicator was subjected to PCA using the SPSS software and varimax rotation for relational assessment. The variables that best characterise system qualities were believed to be principal components with components with eigen values > 1 (19) and accounting for at least 5 % of the variance in the data. For the MDS, inside each main component only highly weighted components (those with absolute values within 10 % of the largest weight), whether positive or negative, were scored. Multivariate correlation matrixes (> 0.60) are used to decrease redundancy and rule out spurious groupings among highly weighted variables inside PCs. After determining the MDS indicators, each MDS variable was graded based on soil function performance, considering soil type and variation in values among treatments. Each variable was transformed or standardised to a value between 0 (least favourable soil function) and 1 (most favourable soil function) scoring functions refers to the term "indicator score" (S). The MDS variables for each observation were weighted using the PCA results after they were converted. Each PC accounted for a given percentage of the variance in the whole data set. The weighted factor for variables chosen under a given PC was calculated by dividing this percentage by the total percentage of variance explained by all PCs with eigenvectors

greater than 1. The SQI was computed by integrating the score and weight factor of each indicator. This can be explained by the following equation:

$$SQI = \sum_{i=1}^n (W_i \times S_i) \quad \text{Eq. 1}$$

Where, W is the PC weighting factor and S is the indicator score. Here, the assumption is that higher index scores meant better soil quality or greater performance of soil functions.

Statistical analysis

The data generated from the laboratory studies were subjected to statistical analysis using the technique of analysis of variance for randomised block design for the interpretation of results as described (20). The level of significance used in F and t test was $p = 0.05$. Critical difference (CD) values were calculated for the $p = 0.05$ whenever F test was found significant. The MDS was also carried out using PCA for SQI selection in the SPSS 29.0 software. To find a small number of new components that primarily explain the variation in the original variables, PCA was applied to the correlation matrix of the soil variables.

Results and Discussion

Soil physical attributes as influenced by long term manuring and fertilisation

Long term application of inorganic and organic fertilisers significantly influenced the soil physical properties (Table 2 and Supplementary Table 1). Bulk density (BD) varied from 1.37 Mg m⁻³ (100 % NPK + FYM + lime) to 1.58 Mg m⁻³ (100 % N). The highest maximum water holding capacity and porosity were recorded in treatment 100 % NPK + FYM + lime followed by 100 % NPK + FYM. The soil texture of the experimental site remained unaffected after long term cultivation of finger millet and maize cropping and it was identified to be sandy clay loam in surface soil and sandy clay in sub-surface soil. The percentage of soil particles were non-significant within the treatments over the years from initial (Supplementary Table 2).

Soil chemical attributes as influenced by long term manuring and fertilisation

There were significant changes in soil chemical properties due to different nutrient management practices was observed (Tables 3 and 4, Supplementary Tables 3 and 4). Continuous application of inorganic fertilisers alone for a longer period has resulted in decline in soil pH significantly compared to control, especially with 100 % N (1.57 times) and application of 150 % recommended dose of NPK (1.39 times). The soil pH was not differed significantly in the NPK + FYM + lime treatment (6.47) and NPK + lime (5.66) from the initial value of 6.17. Electrical conductivity and CEC were observed higher in the 100 % NPK + FYM + lime (0.15 dS m⁻¹ and 13.04 c mol (p⁺) kg⁻¹, respectively) compared to control (0.13 dS m⁻¹ and 8.74 c mol (p⁺) kg⁻¹, respectively).

It was observed that soil organic carbon (SOC) varied between 4.06–6.70 g kg⁻¹ in the soil between the treatments. The results indicated that SOC content was 65.02 % higher in application of 100 % NPK + FYM + lime treatment compared to the control. The application of FYM and lime together with 100 % NPK significantly enhanced SOC by 41.64, 28.59 and 14.72 % over suboptimal (50 % NPK), recommended (100 % NPK) and super optimal (150 % NPK) fertiliser applications, respectively. The lowest organic carbon was observed in the control and 100 % N treatment. The 100 % NPK + lime treatment also showed lower OC than 100 % NPK alone.

Table 2. Effect of long-term manuring and fertiliser application on physical properties of soil under finger millet-maize cropping sequence (average of two years)

Treatments	Bulk density (Mg m ⁻³)	Maximum water holding capacity (%)	Porosity (%)
T ₁ : 50 % NPK	1.56	33.63	41.67
T ₂ : 100 % NPK	1.53	37.46	40.80
T ₃ : 150 % NPK	1.55	34.37	43.10
T ₄ : 100 % NPK + HW	1.53	33.81	43.33
T ₅ : 100 % NPK + lime	1.49	40.68	45.12
T ₆ : 100 % NP	1.54	31.83	39.65
T ₇ : 100 % N	1.58	32.13	40.15
T ₈ : 100 % NPK + FYM	1.38	42.77	44.15
T ₉ : 100 % NPK (S-free)	1.53	34.25	39.51
T ₁₀ : 100 % NPK + FYM + lime	1.37	43.73	46.31
T ₁₁ : Control	1.55	30.95	37.45
Initial value	1.51	30	40.10
SEm ±	0.07	1.68	1.97
CD at 5 %	0.22	4.96	5.82

NPK: nitrogen, phosphorus and potassium; FYM: farmyard manure; HW: hand weeding; SEm±: standard error of mean; CD: critical difference at 5 % probability level.

Table 3. Effect of long-term manuring and fertiliser application on primary and secondary nutrients of soil under finger millet-maize cropping sequence (average of two years)

Treatments	pH (1: 2.5 soil-water ratio)	EC	OC	CEC	Available N	Available P ₂ O ₅	Available K ₂ O	Exch. Ca	Exch. Mg	Available S
		(dS m ⁻¹)	(g kg ⁻¹)	[c mol (p ⁺) kg ⁻¹]		(kg ha ⁻¹)		[c mol (p ⁺) kg ⁻¹]		(mg kg ⁻¹)
T ₁ : 50 % NPK	5.67	0.11	4.73	9.54	156.80	68.96	135.30	4.95	2.48	11.05
T ₂ : 100 % NPK	5.30	0.12	5.21	10.47	179.80	93.34	155.98	4.69	2.18	13.37
T ₃ : 150 % NPK	4.83	0.14	5.84	11.17	204.89	221.21	223.42	4.83	1.86	16.93
T ₄ : 100 % NPK+ HW	5.25	0.11	4.75	10.42	175.10	101.19	155.73	4.33	2.01	14.76
T ₅ : 100 % NPK + lime	5.66	0.12	4.91	11.85	173.58	91.79	188.04	5.33	2.30	15.42
T ₆ : 100 % NP	5.06	0.13	4.40	9.25	174.75	179.92	85.39	4.17	1.52	15.19
T ₇ : 100 % N	4.65	0.09	4.23	7.00	198.86	49.97	91.45	3.67	1.35	10.75
T ₈ : 100 % NPK + FYM	5.77	0.14	6.16	12.34	212.57	179.12	221.92	5.18	2.60	14.21
T ₉ : 100 % NPK (S-free)	5.15	0.10	4.35	9.66	181.27	161.68	164.77	3.87	1.70	8.79
T ₁₀ : 100 % NPK + FYM + lime	6.47	0.15	6.70	13.04	244.82	201.64	228.53	5.81	2.81	16.57
T ₁₁ : Control	6.22	0.13	4.06	8.74	153.45	34.78	120.68	3.98	2.15	11.68
Initial value	6.17	0.059	4.60	12.20	257	34	123	3.25	1.55	20
SEm ±	0.27	0.01	0.24	0.48	8.70	5.48	7.37	0.22	0.11	0.62
CD at 5 %	0.80	0.02	0.70	1.41	25.67	16.17	21.73	0.65	0.31	1.82

NPK: nitrogen, phosphorus and potassium; FYM: farmyard manure; HW: hand weeding; EC: electrical conductivity; OC: organic carbon; CEC: cation exchange capacity; SEm±: standard error of mean; CD: critical difference at 5 % probability level.

Table 4. Effect of long-term manuring and fertiliser application on micronutrients of soil under finger millet-maize cropping sequence (average of two years)

Treatments	DTPA extractable micronutrients				Available boron
	Iron	Manganese	Zinc	Copper	
	(mg kg ⁻¹)				
T ₁ : 50 % NPK	11.16	16.31	3.11	1.20	0.54
T ₂ : 100 % NPK	14.34	19.57	3.30	1.52	0.59
T ₃ : 150 % NPK	15.74	23.74	2.84	1.30	0.51
T ₄ : 100 % NPK + HW	14.42	17.06	2.70	1.39	0.54
T ₅ : 100 % NPK + lime	10.67	18.33	4.16	1.30	0.59
T ₆ : 100 % NP	11.96	21.79	3.42	1.20	0.57
T ₇ : 100 % N	13.19	14.78	2.71	1.15	0.52
T ₈ : 100 % NPK + FYM	17.43	24.66	4.92	1.94	0.69
T ₉ : 100 % NPK (S-free)	12.52	19.06	2.35	1.59	0.49
T ₁₀ : 100 % NPK + FYM+ lime	16.54	24.53	5.04	1.62	0.69
T ₁₁ : Control	8.33	13.30	2.28	1.13	0.56
Initial value	5.22	108.40	2.34	2.30	-
SEm ±	0.61	0.88	0.16	0.06	0.03
CD at 5 %	1.79	2.60	0.46	0.19	0.08

NPK: nitrogen, phosphorus and potassium; FYM: farmyard manure; HW: hand weeding; DTPA: diethylenetriaminepentaacetic acid; SEm±: standard error of mean; CD: critical difference at 5 % probability level.

Soil carbon sequestration

The treatments with NPK + FYM + lime and NPK + FYM improved C stock (32.00 and 22.90 %) from initial value over the years. Negative values for control as well as treatments such as 100 % NPK (-S), 100 % N and 100 % NP resulting in reduction in C stock (-9.27, -8.32, -3.82 and -2.75 %) after long term application of fertilisers and manures in finger millet-maize cropping sequence (Fig. 1 and Supplementary Table 5). A negative carbon sequestration rate was observed in treatments with control and imbalanced fertiliser application (100 % NPK (-S), 100 % N, 100 % NP i.e. -29.27, -26.28, -12.05 and -8.68 kg ha⁻¹ yr⁻¹). On the other hand, treatment with combination of 100 % NPK + FYM + lime, 150 % NPK and 100 % NPK + FYM showed a positive higher sequestration rate (101.03, 95.44 and 72.29 kg ha⁻¹ yr⁻¹) compare to alone fertiliser application (Fig. 2 and Supplementary Table 5).

The available N was significantly higher in 100 % NPK + FYM + lime (244.82 kg ha⁻¹) followed by 100 % NPK + FYM treated plot and 150 % dose of NPK fertilisers, whereas lower available N was observed in control treatment. The results show that long-term application of 150 % dose of P fertiliser maintains the higher P levels (221.21 kg ha⁻¹), which are higher than the values obtained through integrated nutrient management practices (201.64 kg ha⁻¹). Tremendous build-up of P was recorded in plots treated with 100 % P and 150 % of P. Application of N alone leads to accelerated depletion of available P. Results also revealed that decrease in soil K levels from initial value of 123.00 kg ha⁻¹ to 91.45 and 85.39 kg ha⁻¹ in treatments without application of potassic fertilisers (100 % N and 100 % NP). However, application of FYM along with 100 % NPK fertilisers can significantly enhance the available K in soil over the NPK fertilisers alone. The available K in the control was significantly higher compared to 100 % NP and 100 % N and a remarkable reduction from the initial level from 30.57–25.65 % was recorded in these treatments.

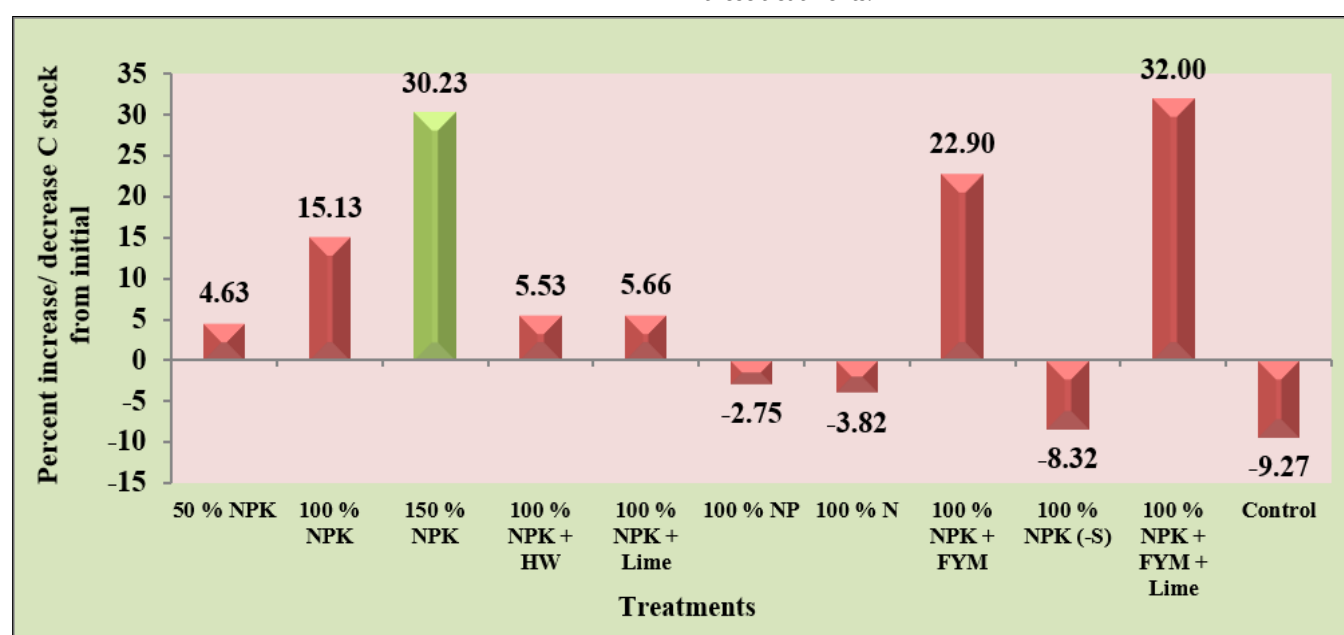


Fig. 1. Percentage change in carbon stock from the initial value due to the application of manure and fertilisers in a finger millet-maize cropping system (average of two years).

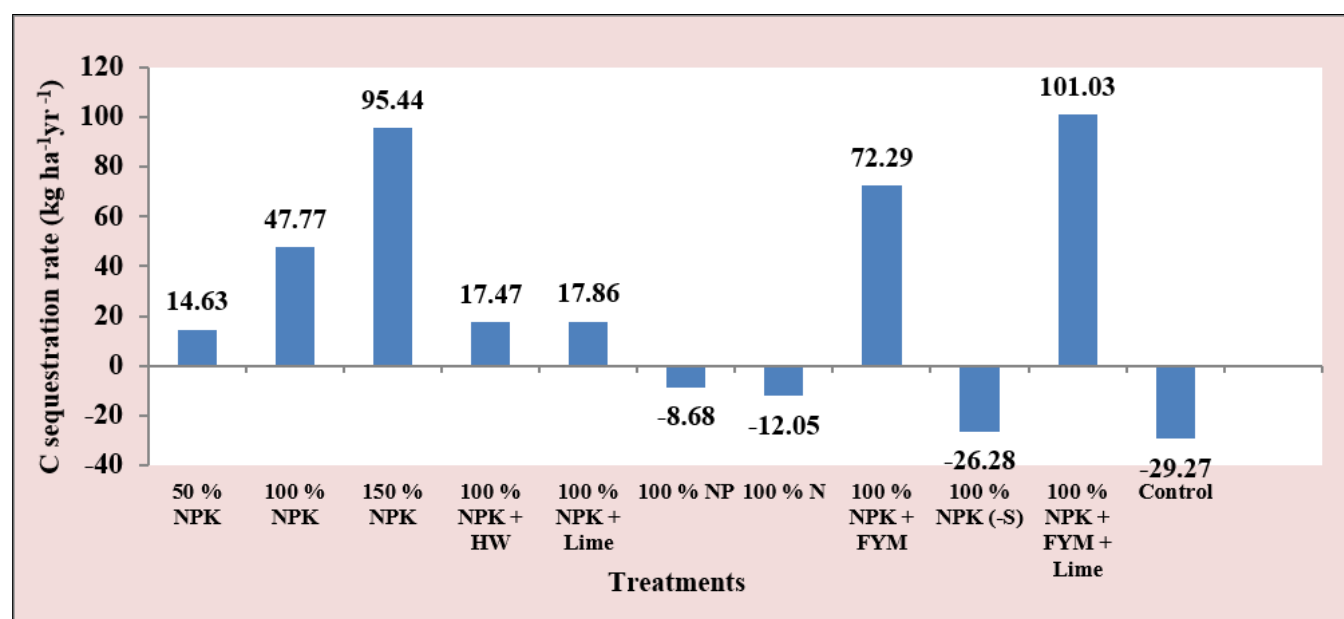


Fig. 2. Changes in carbon sequestration rate from the initial level due to the application of manure and fertilisers in a finger millet-maize cropping system (average of two years).

The application of inorganic fertilisers along with FYM and lime resulted in significantly higher exchangeable calcium (Ca) and magnesium (Mg) levels, while the lowest was observed in the 100 % N treatment. The available sulphur (S) was significantly lower in treatment that received a sulphur-free phosphatic fertiliser (DAP) than in other treatments that got a single superphosphate as a phosphatic source. Whereas highest available S was with application of 150 % NPK (16.93 mg kg⁻¹) and with application of 100 % NPK along with FYM and lime (16.57 mg kg⁻¹).

The combined application of FYM and lime along with inorganic fertilisers significantly increases the DTPA extractable micronutrients. Lower DTPA extractable Zn, Cu, Fe and Mn were observed in control treatment. Among the treatments with exclusive fertilisation (150 % NPK), B availability was lowest and higher for treatments applied with FYM and lime along with fertiliser (Table 4).

Soil biological attributes as influenced by long term manuring and fertilisation

The influence of continuous application of manure and fertilisers on soil biological properties are represented in Table 5 and Supplementary Table 6. The soil biological properties like dehydrogenase activity, ACP, urease activity, microbial biomass carbon (MBC) and microbial biomass N (MBN) were significantly increased in the inorganic fertilisers along with FYM treated plots compared to control. In the 100 % N treatment, dehydrogenase activity decreased by 19.81 %, ACP by 6.36 %, urease activity by 4.38 %, microbial biomass carbon by 4.87 % and microbial biomass nitrogen by 4.88 % compared to the control. The significant reduction in urease activity in the soil was observed after the application of N alone (4.38 %) compared to control.

Table 5. Effect of long-term manuring and fertiliser application on the soil biological properties of soil under finger millet-maize cropping sequence (average of two years)

Treatments	Dehydrogenase	Acid phosphatase	Urease	Microbial biomass carbon	Microbial biomass nitrogen
	µg of TPFg ⁻¹ of soil 24 hr ⁻¹	µg of PNP g ⁻¹ of soil hr ⁻¹	µg of NH ₄ ⁺ -N g ⁻¹ of soil hr ⁻¹	(mg kg ⁻¹ soil)	
T ₁ : 50 % NPK	49.47	89.29	28.78	243.92	28.46
T ₂ : 100 % NPK	60.09	93.11	29.46	267.07	31.16
T ₃ : 150 % NPK	61.53	95.54	30.56	256.97	30.19
T ₄ : 100 % NPK + HW	56.96	93.51	28.62	254.17	29.65
T ₅ : 100 % NPK + lime	62.48	91.18	31.80	249.81	29.15
T ₆ : 100 % NP	43.75	88.40	27.57	212.90	24.84
T ₇ : 100 % N	33.34	87.96	26.79	208.13	24.28
T ₈ : 100 % NPK + FYM	68.96	105.76	34.90	270.30	32.96
T ₉ : 100 % NPK(S-free)	50.00	90.88	30.67	247.43	28.87
T ₁₀ : 100 % NPK + FYM+ lime	71.82	107.56	38.47	297.11	35.01
T ₁₁ : Control	41.58	82.70	28.02	198.45	23.15
SEm ±	2.50	4.40	1.68	11.54	1.35
CD at 5 %	7.38	12.98	4.96	34.04	3.99

NPK: nitrogen, phosphorus and potassium; FYM: farmyard manure; HW: hand weeding; TPF: triphenyl formazan; PNP: p-nitrophenol; NH₄⁺-N: ammonium nitrogen; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; SEm±: standard error of mean; CD: critical difference at 5 % probability level.

Table 6. Eigenvalues from principal component analysis (PCA) of soil quality parameters in surface soil from long-term fertiliser experiment plots in Bengaluru

Component	Initial eigen values			
	Total	Variance (%)	Cumulative (%)	Weightage factor
1	16.074	69.887	69.887	0.766
2	2.415	10.499	80.386	0.115
3	1.403	6.098	86.484	0.066
4	1.089	4.736	91.220	0.049

Minimum data set formulation for selection of soil quality indicators

The data on soil quality parameters was statistically evaluated for their level of significance. The soil properties (23 soil properties) that showed significant treatment differences ($p < 0.05$) in this study, were selected for a representative MDS. The PCA scree plot identifying four principal components (PCs) with eigenvalues > 1, explaining 91.22 % of variability-PC1 (69.88 %), PC2 (10.49 %), PC3 (6.09 %) and PC4 (4.73 %) (Table 6 and Fig. 3).

The PCA biplot shows the relationships between soil variables and treatments (T₁ to T₁₁) in a 2D space defined by the first two principal components (PC1 and PC2) (Fig. 4 and 5). The x-axis represents PC1 and the y-axis represents PC2. Soil variables such as BD, available P₂O₅, Fe, Mn, available N, available S, ACP, Cu, available K₂O, MBC, MBN, porosity, DHA, CEC, EC, urease, MWHC, Zn, exchangeable Ca, available B, exchangeable Mg and pH are represented by blue arrows, indicating the direction and magnitude of their contribution to the principal components. Longer arrows, such as those for available P₂O₅, pH, OC, exchangeable Mg, Fe, Mn and available N, indicate a stronger influence on the variation explained by the principal components. Arrows pointing in the same direction indicate positive correlations, whereas those pointing in opposite directions indicate negative correlations. Smaller angles between arrows represent stronger positive correlations, as observed among available P₂O₅, MBN, OC, DHA, ACP and MWHC, while larger angles (approaching 180°) indicate negative correlations, such as those between BD, pH and exchangeable Mg. Perpendicular arrows indicate little or no correlation. Treatments (T₁ to T₁₁) are plotted as points in the PCA space and their positions

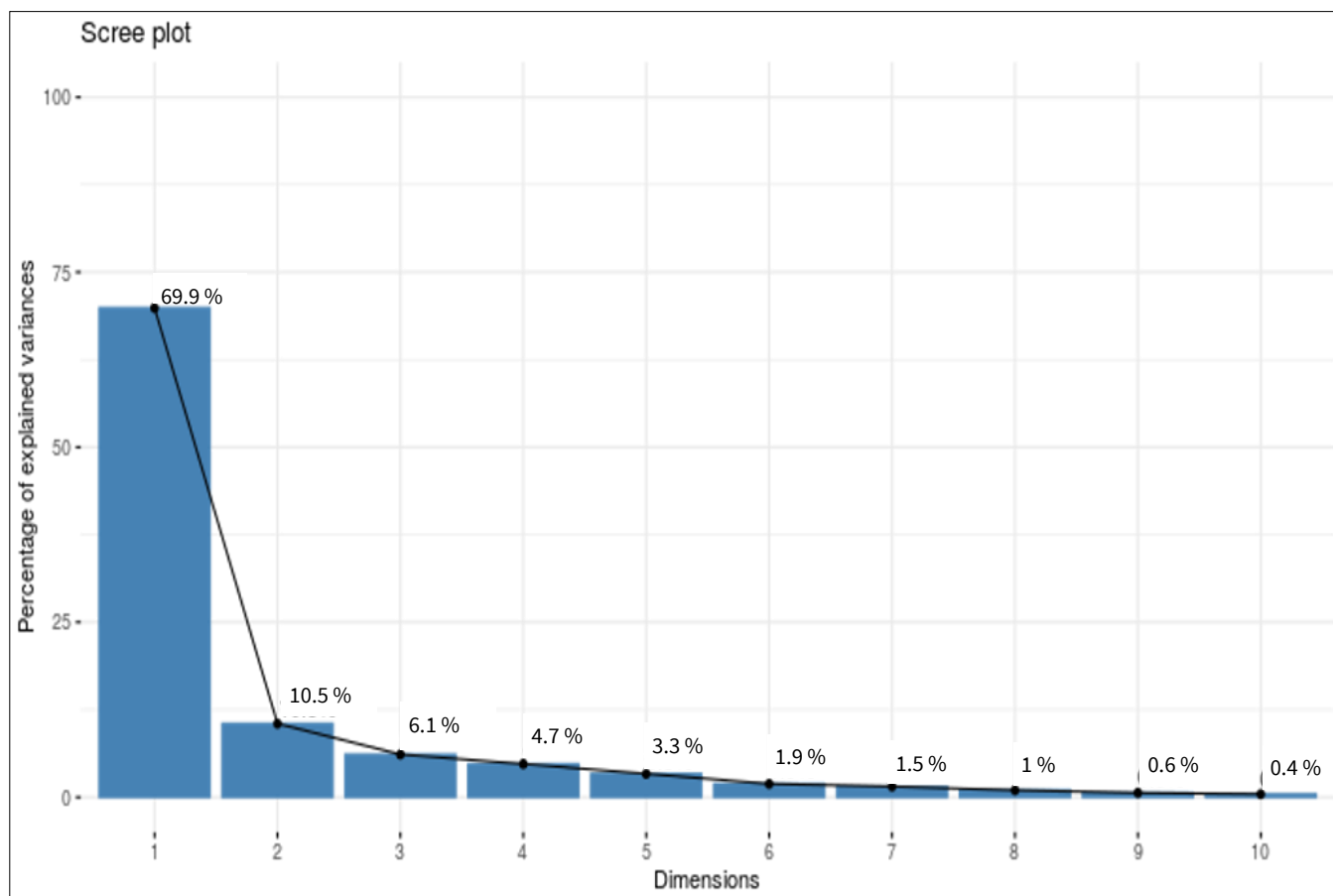


Fig. 3. Scree plot explaining the relationship of the eigenvalues and the principal components.

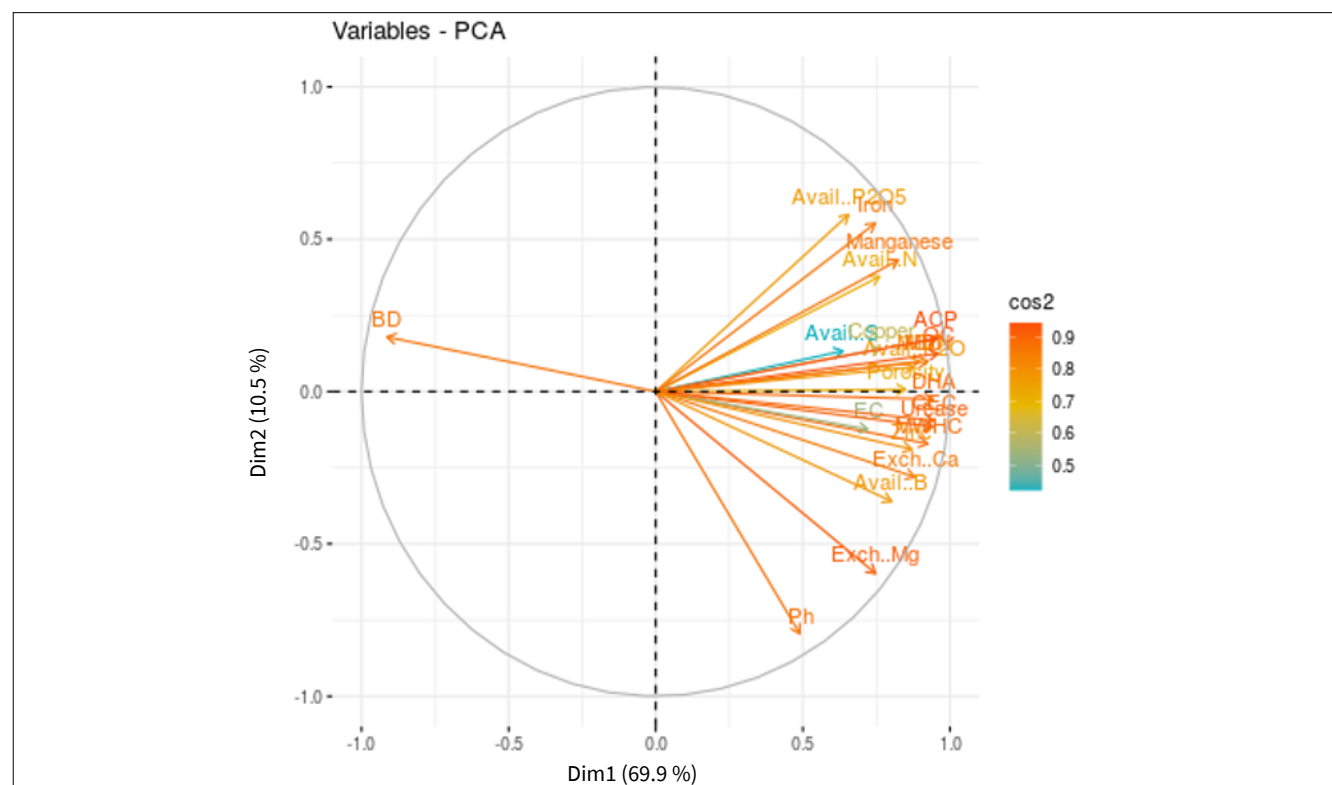


Fig. 4. Variables of principal component analysis (PCA).

PCA: principal component analysis; Dim 1: first principal component; Dim 2: second principal component; BD: bulk density; SOC: soil organic carbon; EC: electrical conductivity; CEC: cation exchange capacity; Avail. N: available nitrogen; Avail. P₂O₅: available phosphorus; Avail. K₂O: available potassium; Exch. Ca: exchangeable calcium; Exch. Mg: exchangeable magnesium; Avail. S: available sulphur; Avail. B: available boron; BD: bulk density; MWHC: maximum water holding capacity; DHA: dehydrogenase activity; ACP: acid phosphatase; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

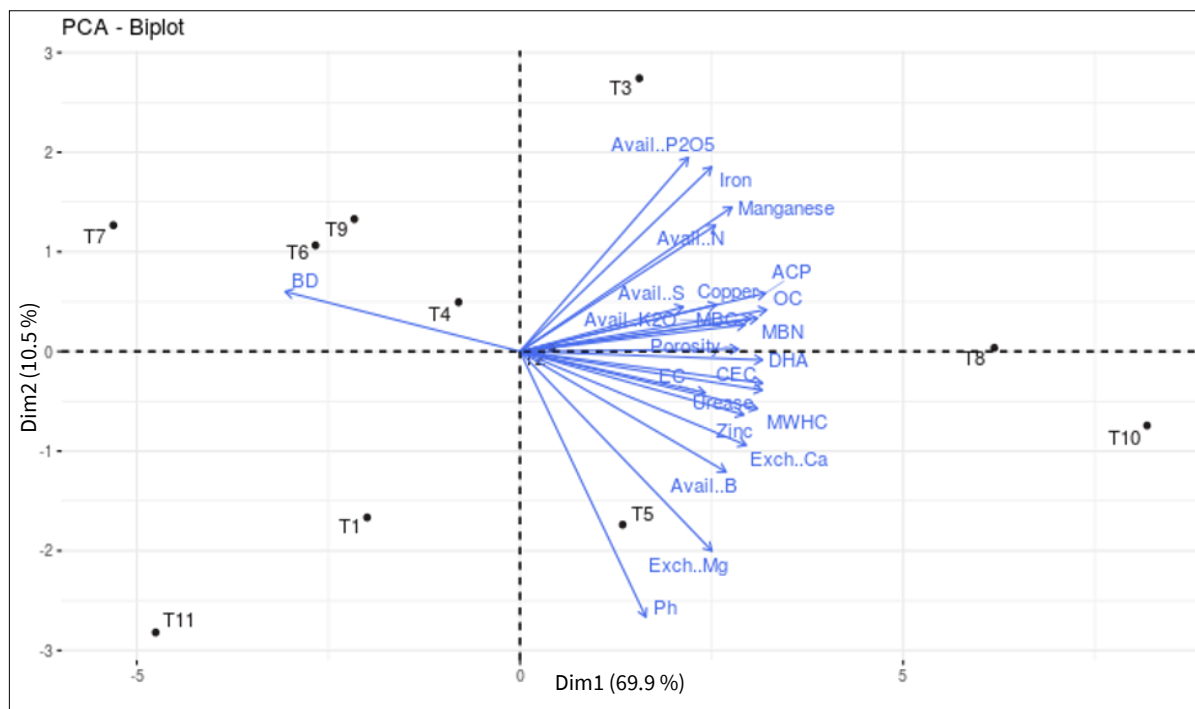


Fig. 5. Principal component analysis (PCA) biplot of various variables.

PCA: Principal component analysis; Dim 1: first principal component; Dim 2: second principal component; BD: bulk density; SOC: soil organic carbon; EC: electrical conductivity; CEC: cation exchange capacity; Avail. N: available nitrogen; Avail. P₂O₅: available phosphorus; Avail. K₂O: available potassium; Exch. Ca: exchangeable calcium; Exch. Mg: exchangeable magnesium; Avail. S: available sulphur; Avail. B: available boron; BD: bulk density; MWHC: maximum water holding capacity; DHA: dehydrogenase activity; ACP: acid phosphatase; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

relative to the arrows reflect the values of the corresponding variables. For instance, T₈, T₉ and T₁₀ are located on the positive side of PC1, indicating higher values for the contributing variables, whereas T₁, T₅ and T₁₁ are positioned on the negative sides of both PC1 and PC2, suggesting lower values for those variables (Fig. 5). Factors such as BD, MWHC, porosity, OC, CEC, available K₂O, zinc, DHA, ACP, MBC and MBN showed the highest loadings in PC1 (Table 7). These variables were also strongly correlation with each other (Fig. 6 and 7). Therefore, only the weighted variable i.e. organic carbon was retained for the final MDS. Soil pH had higher factor loading in PC2. Available S had higher factor loading in PC3. Under PC4 only available boron (B) could get highest factor loading. The final MDS consisted of OC, pH, available S and available B were termed as the key indicators for SQI (Table 7).

Soil quality index interpretation

Minimum dataset indicators were scored based on soil function performance, using linear transformation to convert values into unitless scores (0–1). The weighted factor for variables chosen under a given PC was calculated by dividing this percentage by the total percentage of variance explained by all PCs with eigen vectors greater than 1. Weighted factors for PCs with eigenvalues > 1 were 0.76, 0.11, 0.06 and 0.04 (Table 6). After scoring and weighting, SQI was calculated using an additive model, with results presented in Table 8.

$$SQI = 0.76 \times OC \text{ score} + 0.11 \times \text{soil pH} + 0.06 \times \text{Avail. S} + 0.04 \times \text{Avail. B}$$

The organic manures along with chemical fertiliser and lime received the highest SQI value (0.99) in comparison with other treatments (Table 8). The different nutrient management practices were ranked based on their impact on SQI as follows: 100 % NPK + FYM + lime > 100 % NPK + FYM > 150 % NPK > 100 % NPK > 100 % NPK + lime > 100 % NPK + HW > 50 % NPK > 100 % NP > 100 % NPK (S-free) = Control > 100 % N.

Plots treated with 100 % NPK + FYM with and without lime in the study showed SQI values that were 50.00 and 37.87 % higher compared to control and 26.92 and 16.66 % higher respectively, compared to recommended dose of fertiliser application (T₂). Plots receiving imbalanced fertiliser application (100 % N) showed SQI values 3.03 and 17.94 % lower than the control and recommended fertiliser dose, respectively (Table 8). Percentage contribution of each soil quality indicators towards SQI was soil dehydrogenase activity (74.93 %) followed by soil pH (12.83 %), available S (6.89 %) and available B (5.35 %) (Fig. 8).

Relationship between yield and soil quality indicators

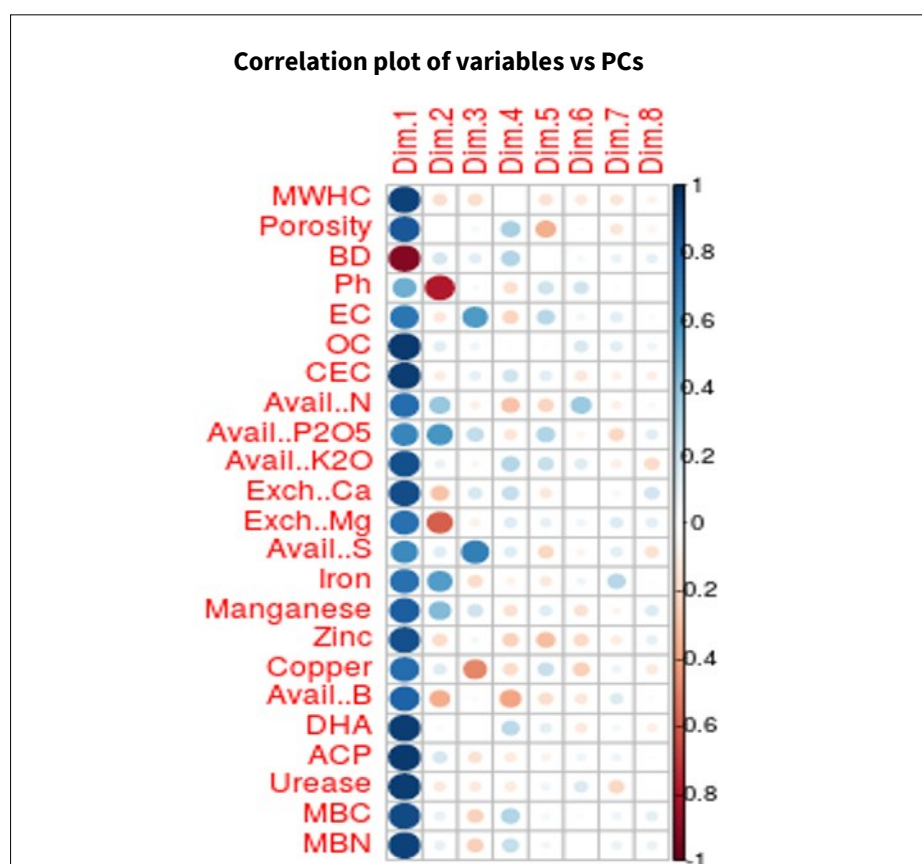
Among the soil quality indicators, microbial biomass carbon and dehydrogenase activity were exhibited the strongest positive correlation with finger millet yield ($R^2 = 0.73$ and 0.72) and maize yield ($R^2 = 0.80$ and 0.75). Similarly, cation exchange capacity was moderately correlated with finger millet and maize yield ($R^2 = 0.60$ and 0.72) followed by organic carbon ($R^2 = 0.58$ and 0.61) and ACP activity ($R^2 = 0.52$ and 0.58). Available P ($R^2 = 0.23$ and 0.25) and available sulphur ($R^2 = 0.12$ and 0.20) were weak positively correlated with finger millet and maize yield. In contrast, soil pH showed weak negative correlation with finger millet and maize yield ($R^2 = 0.02$ and 0.07) (Supplementary Table 7) (Fig. 9 and 10).

The application of imbalanced inorganic fertilisers increased soil bulk density possibly due to deterioration of soil structure (21). Maximum water holding capacity had significantly higher in use of inorganic with organic treatments may be due to reduction in bulk density, increase in soil structural indices and rise in organic carbon content of the soil may all be attributable to improved structure. The increased porosity in the FYM application treatments might be due to increased organic matter and clay content, promoting stable aggregates (22).

Table 7. Principal component analysis (PCA) of soil quality parameters studied in soil samples of long-term fertiliser experiment plots

Variables	Components			
	PC1	PC2	PC3	PC4
MWHC	0.231	-0.11	-0.152	-0.002
Porosity	0.212	0.005	0.037	0.308
BD	-0.228	0.115	0.103	0.287
pH	0.122	-0.512	0.027	-0.161
EC	0.18	-0.08	0.474	-0.207
OC	0.239	0.08	0.057	0.014
CEC	0.235	-0.061	0.091	0.193
Avail. N	0.19	0.243	-0.062	-0.272
Avail. P ₂ O ₅	0.163	0.374	0.21	-0.127
Avail. K ₂ O	0.218	0.052	-0.042	0.274
Exch..Ca	0.22	-0.181	0.142	0.229
Exch. Mg	0.186	-0.384	-0.065	0.132
Avail. S	0.159	0.086	0.576	0.126
Iron	0.186	0.356	-0.154	-0.066
Manganese	0.206	0.278	0.169	-0.152
Zinc	0.217	-0.122	0.041	-0.217
Copper	0.191	0.09	-0.41	-0.175
Avail. B	0.2	-0.232	0.02	-0.38
DHA	0.235	-0.016	0.008	0.255
ACP	0.238	0.112	-0.128	-0.102
Urease	0.235	-0.075	-0.093	-0.104
MBC	0.224	0.064	-0.188	0.284
MBN	0.231	0.064	-0.196	0.224
Highest factor	0.239	0.512	0.576	0.380
10 % highest factor	0.215	0.460	0.518	0.342

PC1, PC2, PC3 and PC4: first four principal components obtained through principal component analysis (PCA); MWHC: maximum water holding capacity; BD: bulk density; EC: electrical conductivity; OC: organic carbon; CEC: cation exchange capacity; Avail. N: available nitrogen; Avail. P₂O₅: available phosphorus; Avail. K₂O: available potassium; Exch. Ca: exchangeable calcium; Exch. Mg: exchangeable magnesium; Avail. S: available sulphur; Avail. B: available boron; DHA: dehydrogenase activity; ACP: acid phosphatase activity; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

**Fig. 6.** Correlation between the soil variables and different PCs.

PCs: Principal components; BD: bulk density; SOC: soil organic carbon; EC: electrical conductivity; CEC: cation exchange capacity; Avail. N: available nitrogen; Avail. P₂O₅: available phosphorus; Avail. K₂O: available potassium; Exch. Ca: exchangeable calcium; Exch. Mg: exchangeable magnesium; Avail. S: available sulphur; Avail. B: available boron; BD: bulk density; MWHC: maximum water holding capacity; DHA: dehydrogenase activity; ACP: acid phosphatase; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

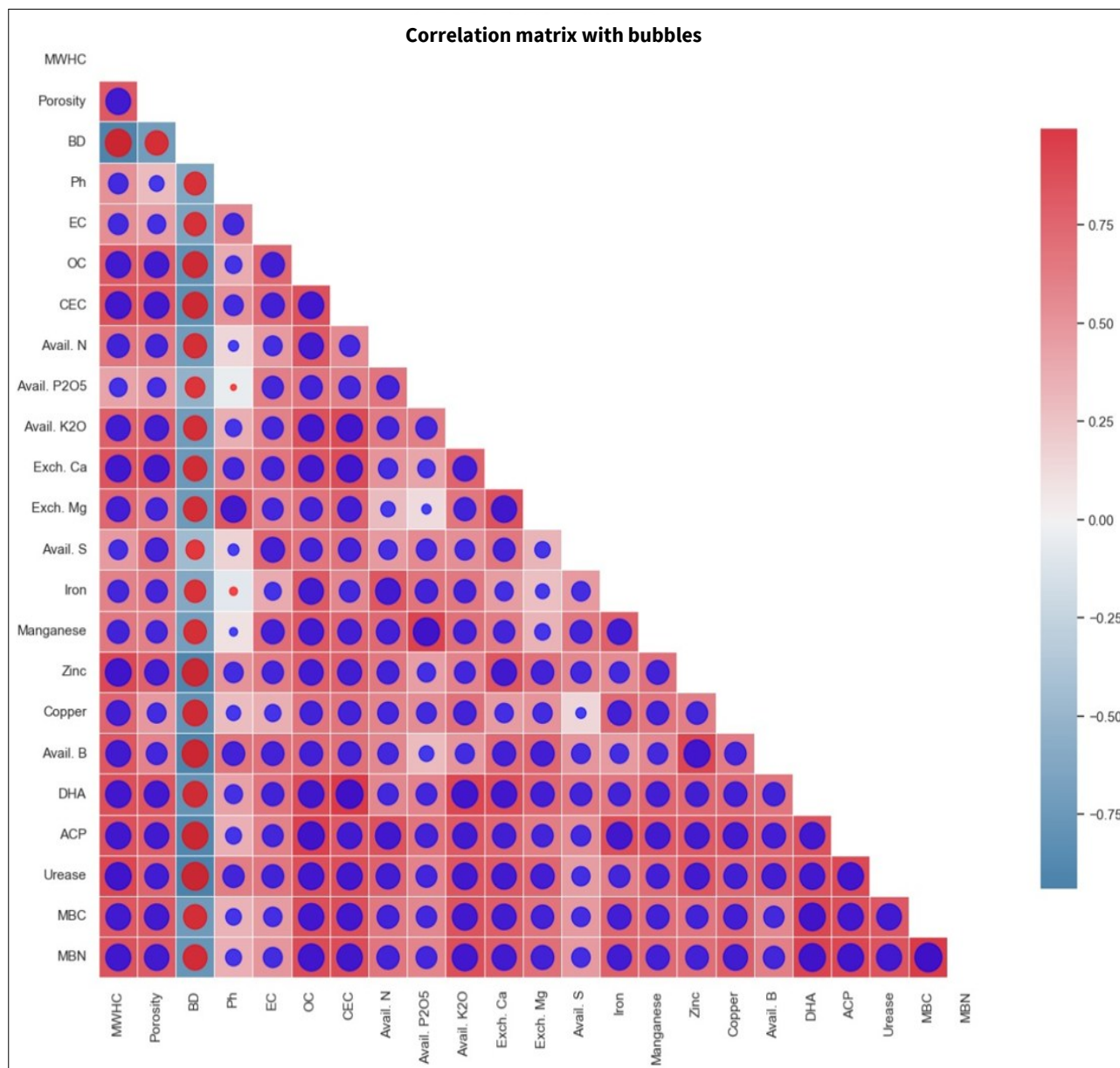


Fig. 7. Correlation between the soil quality variables of principal component.

BD: bulk density; SOC: soil organic carbon; EC: electrical conductivity; CEC: cation exchange capacity; Avail. N: available nitrogen; Avail. P₂O₅: available phosphorus; Avail. K₂O: available potassium; Exch. Ca: exchangeable calcium; Exch. Mg: exchangeable magnesium; Avail. S: available sulphur; Avail. B: available boron; BD: bulk density; MWHC: maximum water holding capacity; DHA: dehydrogenase activity; ACP: acid phosphatase; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

Table 8. Score, weight and soil quality index (SQI) values of selected minimum data set (MDS) variables for each treatment (average of two years)

Treatments	Organic carbon	pH	Available sulphur	Available boron	SQI
T ₁ : 50 % NPK	0.540	0.101	0.043	0.038	0.72
T ₂ : 100 % NPK	0.595	0.094	0.052	0.042	0.78
T ₃ : 150 % NPK	0.668	0.086	0.066	0.036	0.86
T ₄ : 100 % NPK + HW	0.543	0.093	0.058	0.038	0.73
T ₅ : 100 % NPK + lime	0.561	0.101	0.060	0.042	0.76
T ₆ : 100 % NP	0.503	0.090	0.059	0.041	0.69
T ₇ : 100 % N	0.483	0.083	0.042	0.037	0.64
T ₈ : 100 % NPK + FYM	0.704	0.102	0.055	0.049	0.91
T ₉ : 100 % NPK (S-free)	0.497	0.091	0.034	0.035	0.66
T ₁₀ : 100 % NPK + FYM + lime	0.766	0.115	0.065	0.049	0.99
T ₁₁ : Control	0.464	0.110	0.046	0.040	0.66

NPK: nitrogen, phosphorus and potassium; NP: nitrogen and phosphorus; FYM: farmyard manure; HW: hand weeding; SQI: soil quality index.

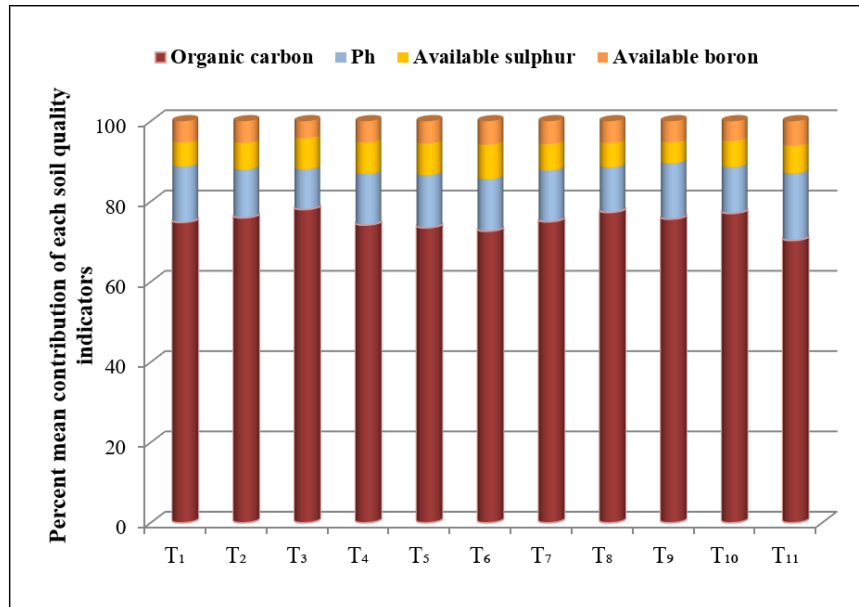


Fig. 8. Percentage contribution of each soil quality indicators towards SQI under finger millet-maize cropping sequence.

Treatment details

T₁: 50 % NPK
 T₂: 100 % NPK
 T₃: 150 % NPK
 T₄: 100 % NPK + hand weeding
 T₅: 100 % NPK + lime
 T₆: 100 % NP

T₇: 100 % N
 T₈: 100 % NPK + FYM
 T₉: 100 % NPK (S)
 T₁₀: 100 % NPK + FYM + lime
 T₁₁: Control

NPK: nitrogen, phosphorus and potassium; NP: nitrogen and phosphorus; FYM: farmyard manure; S: sulphur.

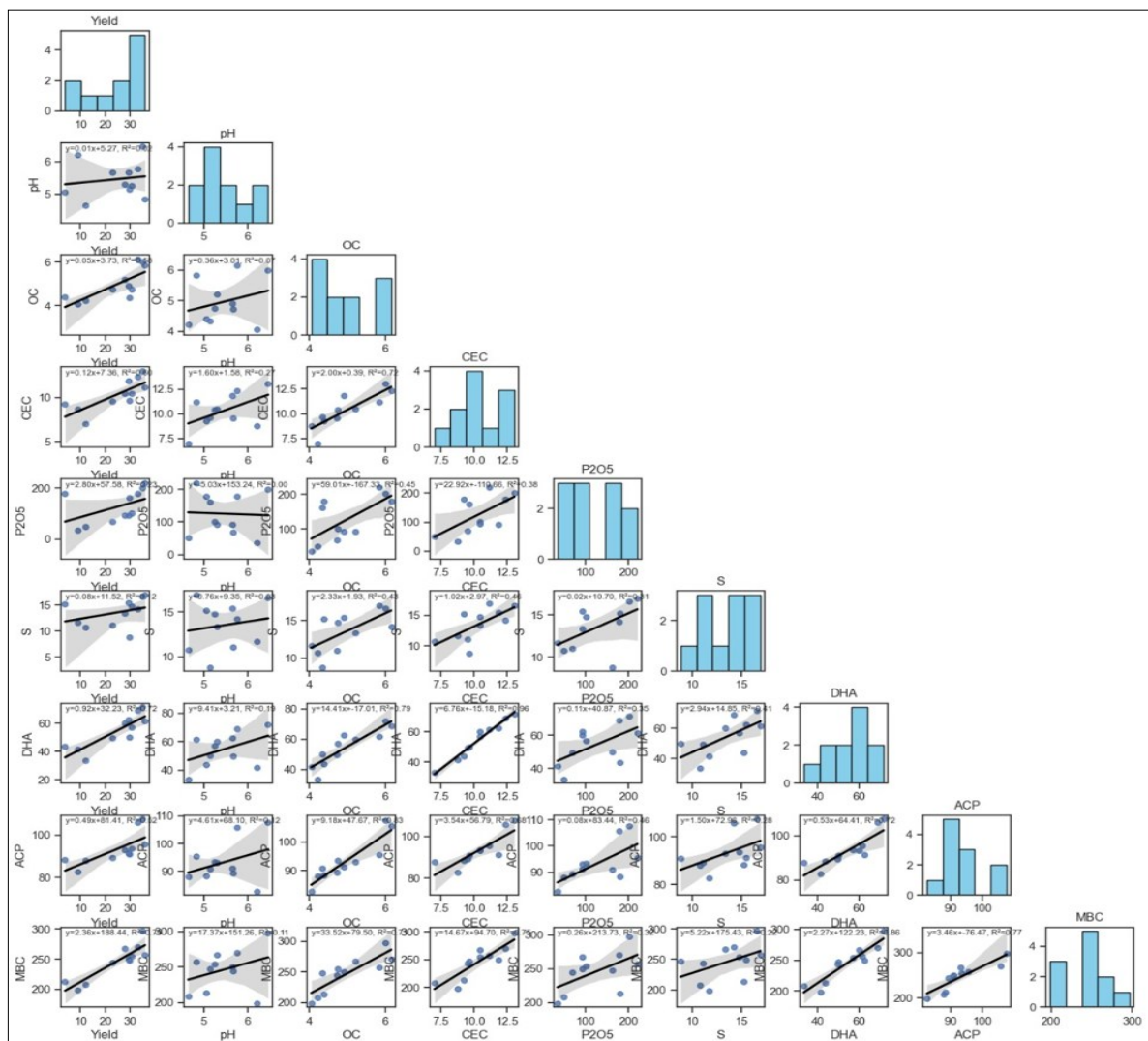


Fig. 9. Correlation of finger millet grain yield with key soil quality indicators.

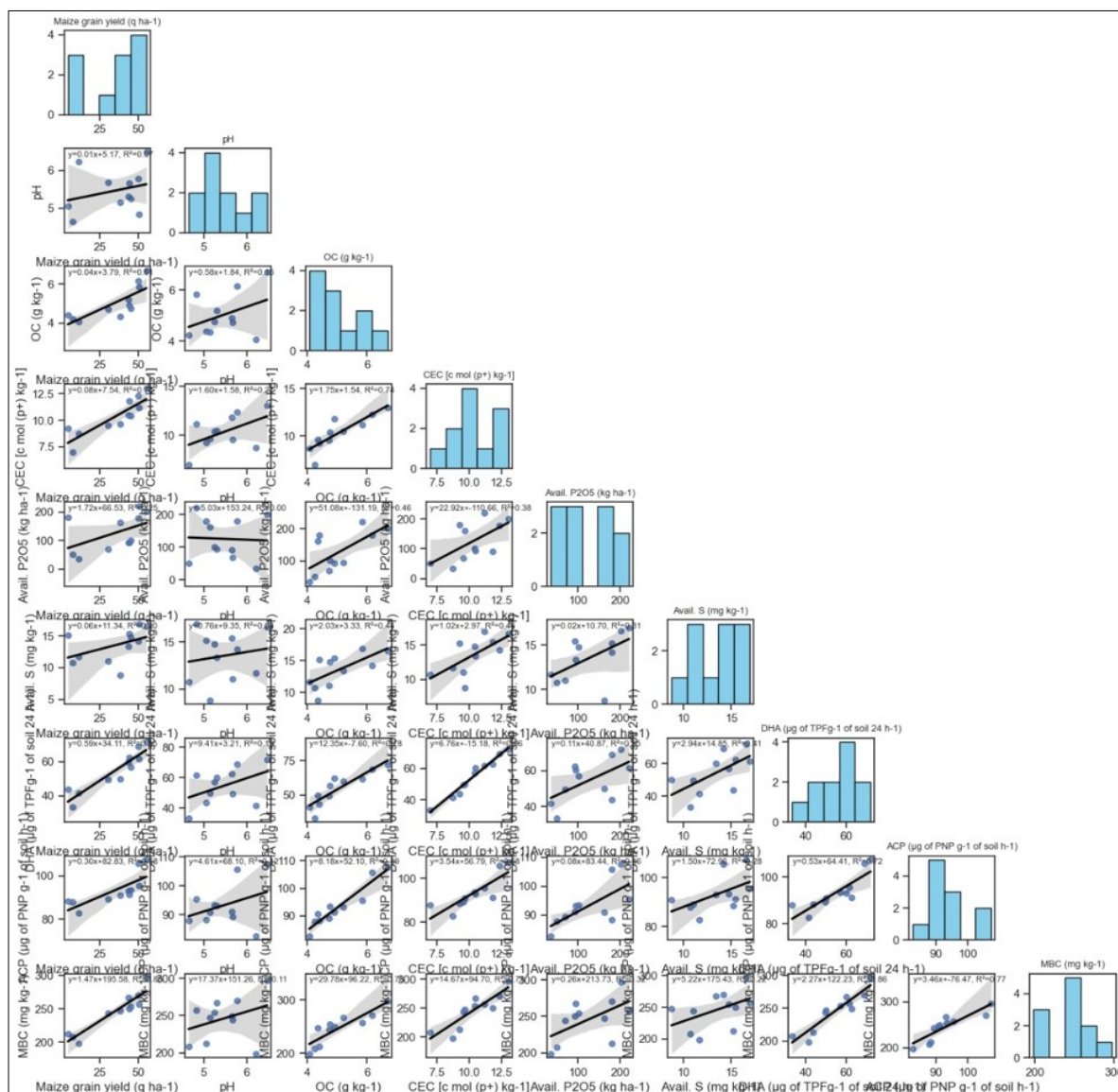


Fig. 10. Correlation of maize grain yield with key soil quality indicators.

Higher soil pH under FYM treatment may be due to the release of basic cations such as Ca^{2+} , Mg^{2+} and K^+ during decomposition (23). When lime is applied to soil, it reacts with it, possibly assisting in the release of hydroxyl ions, which subsequently react with hydrogen ions in the soil to lower acidity (24). The decrease in soil pH under N alone treatment may be due to the acidifying effect of urea during nitrification (25).

Plots receiving FYM had significantly higher organic carbon than those with only fertilisers due to greater biomass production. Cultivation reduces plant residue input and increases soil disturbance, accelerating decomposition through frequent tillage (26). The lowest organic carbon was observed in control and 100 % N treatment, likely due to the absence of fertilisers and manure. Application of lime decreased the OC content significantly compared to corresponding treatments without lime due to enhanced oxidation by lime (27). Application of NPK along with FYM and lime also increases the C stock likely due to enhanced microbial processes, structure of the soil and stabilisation of organic carbon. Lime contributes to the neutralisation of soil acidity, which can enhance the availability of nutrients and microbial health, leading to an increase in SOC (28). Reduction in C stock over the years in control as well as imbalanced fertiliser application treatments might be due to depletion of organic matter (29). Higher C sequestration rate in

integrated application of manure and fertiliser treatments might be due to organic amendments, particularly FYM application, played a pivotal role in promoting SOC gain (30).

The greater availability of N in FYM treated plots may be due to beneficial effects of organic manures and their mineralisation into available N forms (31). Higher application of fertilisers increases the available N due to increased root biomass led to higher organic matter accumulation. This in turn involved in mineralisation of organic N into available N. The slight increase was in available P in super optimal application of fertiliser than integrated application of manure and fertiliser can be explained by only 25–30 % availability of applied P to crops and the rest is fixed in soil (32). In contrast, the use of FYM increases P availability through the release of organic anions during organic matter decomposition by compete with inorganic phosphate (PO_4^{3-}) to reducing phosphate fixation. Use of N alone leads to accelerated depletion of available P may be due to acidifying effect. Decrease in available K in control plots might be due to the continuous exclusion of K from the fertiliser schedules (33). The available K was higher in plots that received both FYM and inorganic fertilisers might be which might be ascribed to the reduction in K fixation and release of K due to the interaction of organic matter with clay.

Except for treatments with FYM and lime, all other treatments had marginally lower exchangeable Ca and Mg content in the soil. This is because FYM is a good source of Ca and thus when it decomposes, it adds to the exchangeable Ca content of the soil (34). Long-term application of calcium carbonate increased exchangeable Ca in the soil and contributed some magnesium, as lime contains Mg impurities in treated plots (35). Application of recommended doses of fertilisers (SSP as P source) in combination with FYM is essential in maintaining available sulphur nutrient status and soil health (36).

The increase in micronutrient levels in soil due to the application of FYM is caused by a variety of factors such as the mineralisation of organically bound forms, the dissolution of less available forms, a drop in the redox potential of the soil, the chelating action of the organic compounds formed during the decomposition of organic materials (37). Application of manure along with inorganic fertilisers increased the B availability compared to alone application might be due to application organic manure upon decomposition increases the production of organic acids which solubilise unavailable B and make available for plants (38).

Higher enzymatic activities in FYM treated plots due to external addition of organic manures helps in carbon build up and promoting microbial and enzymatic activity (39). The imbalanced application of inorganic fertilisers without FYM decreases the above and below ground biomass which affects the microbial biomass carbon and N in turn reduces the enzyme activity (40). Hence, FYM treatment resulted in a higher level of biological activity and stabilisation of extracellular enzymes via complexation with humic substances. The lower urease activity was observed in imbalanced fertiliser application due to the build-up of ammonia, which suppresses urease activity (41).

Application of imbalanced fertiliser and in control leads to deterioration of soil quality over the years. In contrast, applying FYM with balanced fertilisers or lime with 100 % NPK improved soil quality. This integrated nutrient management approach, involving balanced fertilisation, organic manure addition, liming and maintenance of soil organic matter improved the physical characteristics of the soil and maximised nutrient utilisation. Soil quality did not differ much for different depths at the studied sites (42).

The presence of soil pH in MDS is justified because it integrates multiple aspects of soil health i.e. nutrient availability, microbial activity and long-term sustainability (43). Soil pH influences the solubility and mobility of essential nutrients, thus directly affecting plant uptake and microbial processes. Optimal pH levels are critical for sustaining soil biological functions and ensuring long-term soil fertility under diverse cropping systems. The presence of SOC in MDS is justified because it influences the soil structure, nutrient availability and biological activity of soil (44). The SOC is not only a key indicator of soil fertility but also a driver of soil aggregation and long-term carbon sequestration (45). The presence of dehydrogenase activity in MDS is justified because it serves as a measure of the metabolic potential and microbial oxidative activity in soil. It is necessary for the breakdown of organic matter and the cycling of nutrients, particularly when inorganic fertilisers are combined with organic amendments like FYM which stimulate microbial growth and enzymatic functions. According to research, long term application of organic amendments and mineral fertilisers raises the amount of labile organic P fractions in

soil aggregates causes P buildup in soil (46). The combined application of inorganic fertilisers and FYM resulted in better soil quality when compared with the use of inorganic fertilisers alone (47).

The strong positive correlations of microbial biomass carbon and dehydrogenase activity with finger millet and maize yield underscore the critical role of soil microbial health in nutrient cycling and organic matter decomposition (48). Moderate correlations were also observed for cation exchange capacity, organic carbon and ACP activity, reflecting their importance in nutrient retention and enzymatic P release (49). In contrast, available P showed weak positive correlations, suggesting P was already present in non-limiting quantities due to past fertilisation or mineralisation (50). The weak negative correlation between soil pH and crops yield likely results from reduced nutrient availability and altered microbial activity at lower pH levels. Thus, pH shifts may indirectly reduce yield by affecting soil biological processes more than direct chemical limitations.

Conclusion

Based on the results, it can be inferred that under cropping sequence of finger millet and maize without application of nutrients and imbalanced fertiliser application results in crop yield reduction and all the available nutrient status over the years. The higher soil quality index (SQI) values in treatments with balanced and integrated nutrient management practices involving the application of recommended doses of nitrogen, phosphorus and potassium (NPK) fertilisers in combination with farmyard manure (FYM) and lime should be adopted to sustain soil quality, nutrient availability and crop productivity. Imbalanced use of nutrients has triggered the deterioration of soil quality and made the cropping systems vulnerable to unsustainability. Thus, the balanced and integrated application of organic and inorganic nutrient sources is essential to enhance and sustain soil quality and productivity. The present study emphasises that soil quality assessment is a tool that can be used to evaluate the effects of land management practices on soil function and has wider more applications for soil restoration than sustainable agriculture.

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Authors' contributions

SGS designed the research conducted the experiments collected and analysed the data and wrote the original manuscript draft. KGG provided critical guidance on the experimental design data interpretation and manuscript revision. JT and SP contributed to manuscript correction. KR and HDC contributed to the discussion and manuscript editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this authors used ChatGPT for language polishing, grammar correction, formatting of references and improving clarity of sentences. After using this tool, authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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