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SOIL QUALITY AND CARBON DYNAMICS IN LONG-TERM FERTILIZED RICE-BASED CROPPING SYSTEMS OF INDIA: A 30-YEAR ASSESSMENT

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ABSTRACT

Soil quality and organic carbon dynamics are critical determinants of agricultural sustainability, particularly under intensive cropping systems. This study evaluates the long-term (30-year) impacts of varied fertilization practices on Soil Quality Index (SQI), soil organic carbon (SOC) stocks, and carbon sequestration rates across three diverse agro-ecological locations in India: Maruteru (MTU), Titabar (TTB), and Mandya (MND). Five soil parameters (pH, EC, OC, P, K) were integrated into a linear scoring function to compute SQI, while SOC stocks and sequestration were derived from soil carbon content and bulk density. Results indicated that treatments involving organic amendments either solely or in combination with inorganic fertilizers consistently yielded the highest SQI ratings (0.8–1.0, “very good”). Specifically, 100% recommended dose of fertilizers (RDF) with farmyard manure (FYM) and integrated nutrient management (INM) treatments significantly enhanced SOC stocks, with maximum values of 23.56, 30.62, and 13.07 t ha⁻¹ at MTU, TTB, and MND, respectively. Carbon sequestration rates were highest under organic-amended plots, reaching up to 0.40 t C ha⁻¹ yr⁻¹. In contrast, control and imbalanced fertilization led to soil degradation and carbon loss. These findings underscore the vital role of organic inputs in sustaining soil health, enhancing carbon storage, and supporting climate-resilient agriculture in tropical rice-based systems.

Keywords: Soil Quality Index, Soil organic carbon, Carbon sequestration, Long-term fertilizer experiment, Integrated nutrient management, Rice-based cropping system.

Introduction

Agriculture remains the cornerstone of India's economy, supporting livelihoods for a majority of the rural population and contributing significantly to national food security. The sustainability of agricultural production systems is intrinsically linked to soil health, which is increasingly assessed using integrative frameworks such as the Soil Quality Index (SQI) (Andrews *et al.*, 2004; Karlen *et al.*, 1997). SQI holistically combines physical, chemical, and biological soil properties, offering a composite measure of soil functionality under varying management regimes. This approach is essential, as traditional assessments focusing solely on nutrient

status often overlook critical structural and biological dimensions of soil health.

Soil organic carbon (SOC) is a pivotal component of soil organic matter, influencing key processes such as water retention, nutrient cycling, microbial activity, and erosion resistance (Lal, 2015; Paustian *et al.*, 2017). In tropical agricultural systems, SOC dynamics are particularly sensitive to management practices, with studies reporting significant declines under conventional tillage and chemical-intensive farming (Bhattacharyya *et al.*, 2015). It also plays a central role in climate change mitigation through carbon sequestration. Recent studies in Indian ecosystems have highlighted significant spatial variability in SOC

pools across different land uses, emphasizing how management practices shape carbon stocks and overall soil health (Yadav *et al.*, 2025; Srinivasarao *et al.*, 2014). Advances in remote sensing and machine learning have further improved SOC estimation at landscape scales, offering scalable tools for monitoring soil carbon (Mundada and Jain, 2025; Tiwari *et al.*, 2025).

Intensive cereal-based systems, coupled with imbalanced fertilizer use, have accelerated soil degradation, leading to SOC depletion, nutrient imbalances, and reduced biological activity (International Journal for Multidisciplinary Research, 2025). Such degradation not only threatens productivity but also diminishes the soil's capacity to act as a carbon sink. Consequently, there is growing interest in developing indices that reflect carbon stability and soil biochemical quality under different management practices (Rana *et al.*, 2025; Soil organic carbon stability index development, 2024). These indices complement SQI by quantifying the resilience of soil carbon under varying nutrient regimes.

Given the interconnectedness of soil quality and carbon dynamics, there is a pressing need to integrate SQI and SOC assessments to guide sustainable soil management, enhance agricultural resilience, and contribute to climate change mitigation. This study aims to evaluate the long-term effects of fertilization strategies on SQI, SOC stocks, and carbon sequestration in rice-based cropping systems across three major Indian agroecologies.

Material and Methods

Study Sites and Climatic Conditions

The study utilized long-term fertilizer experiments (LTFEs) established in 1989 under the All India Coordinated Research Project on Long-Term Fertilizer Experiments. Three representative locations were selected spanning major rice-growing regions of India:

Maruteru (MTU): Located in Andhra Pradesh (16°17'N, 81°09'E, 10 m altitude), representing the East Coast Plains. The soil is classified as Typic Haplustalf (clay texture) with pH 7.2–7.8. The region experiences a semi-arid subtropical climate with mean annual rainfall of 980 mm and temperature range of 20–35°C.

Titabar (TTB): Situated in Assam (26°36'N, 94°11'E, 95 m altitude), representing the North Eastern Plains. The soil is classified as Aeris Endoaquept (silty clay texture) with pH 5.2–5.8. The climate is humid subtropical with mean annual rainfall of 2180 mm and temperature range of 15–32°C.

Mandya (MND): Located in Karnataka (12°31'N, 76°53'E, 678 m altitude), representing the Southern Plateau. The soil is classified as Typic Rhodustalf (sandy loam texture) with pH 6.5–7.0. The region has a semi-arid tropical climate with mean annual rainfall of 750 mm and temperature range of 18–34°C.

Experimental Design and Treatments

Experiments followed a randomized complete block design with three replications at each location. Eight fertilization treatments were maintained consistently for 30 years (1989–2019) under rice-based cropping systems (rice-rice at MTU and TTB; rice-cowpea at MND). The treatments included:

1. Control (no fertilizer)
2. 100% NK (–P)
3. 100% NP (–K)
4. 100% recommended dose of fertilizer (RDF: NPK)
5. 100% RDF + FYM @ 5 t ha⁻¹
6. 50% RDF + 50% FYM-N
7. 50% RDF + 25% FYM-N + 25% green manure-N (GM-N)
8. FYM @ 10 t ha⁻¹

FYM contained approximately 0.5% N, 0.2% P₂O₅, and 0.5% K₂O on dry weight basis. Green manure was incorporated at 45 days of growth, supplying approximately 30 kg N ha⁻¹.

Soil Sampling and Analysis

Sampling Protocol

Soil samples were collected after harvest of the kharif (monsoon) rice crop in 2019 (30th year of experimentation). Composite samples from 0–15 cm depth were obtained using a systematic sampling approach (5 cores per plot). Samples were air-dried, gently crushed to pass through a 2-mm sieve, and stored for analysis.

Physical and Chemical Analysis

Soil pH and electrical conductivity (EC) were measured in 1:2.5 soil: water suspension using glass electrode and conductivity meter, respectively. Soil organic carbon (SOC) was determined by the Walkley and Black wet oxidation method (Walkley & Black, 1934). Available phosphorus was extracted with 0.5 M NaHCO₃ (pH 8.5) and measured spectrophotometrically (Olsen *et al.*, 1954). Available potassium was extracted with neutral normal ammonium acetate and determined by flame photometry (Jackson, 1973). Bulk density was measured using undisturbed core samples (Blake & Hartge, 1986). Initial soil properties (1989) are presented in

Table 1 : Initial Soil Properties

Cropping system	Mandya (MND)	Maruteru (MTU)	Titabar (TTB)
	Rice-Cowpea (R-CP)	Rice-Rice (R-R)	Rice-Rice (R-R)
Sub ecosystem	Irrigated	Irrigated	Shallow LL
Variety – <i>kharif</i>	IR 20 / KMP 101	MTU-1061	Ranjit
<i>Rabi</i>	C-152	MTU-1010	Lachit
Fertilizers (kg ha ⁻¹) - (NPKZn)			
<i>Kharif</i>	100:50:50:20	60:40:40/90:60:60:50	40:20:20:20
<i>Rabi</i>	Residual crop	120:60:45/80:90:60:50	40:20:20
% Clay	15.2	64.5	42.0
% Silt	8.0	22.0	28.0
% Sand	71.2	12.5	28.5
Soil texture	Sandy loam	Clay	Silty clay
pH (1:1)	5.87	6.28	5.2
Organic carbon (g kg ⁻¹)	3.1	8.9	9.5
EC (dS m ⁻¹)	0.28	0.68	0.28
Available N (kg ha ⁻¹)	290	298	495
Available P ₂ O ₅ (kg ha ⁻¹)	17.6	20.4	13.2
Available K ₂ O (kg ha ⁻¹)	177	385	145
Bulk density (g cc ⁻¹)	1.30	1.19	1.30

Soil Quality Index Calculation

SQI was computed using the framework developed by Andrews *et al.* (2004) with modifications for tropical conditions. Five indicators were selected based on sensitivity to management changes and relevance to rice-based systems: pH, EC, SOC, available P, and available K.

Scoring Functions

Each indicator was transformed to a unitless score between 0 and 1 using linear scoring functions:

- For "more is better" indicators (SOC, P, K):

$$S = (x - x_{min}) / (x_{max} - x_{min})$$

- For "optimum range" indicators (pH):

$$S = 1 - (|x - x_{opt}|) / (x_{opt} - x_{min}) \text{ for}$$

$$x_{min} \leq x \leq x_{opt}$$

$$S = 1 - (|x - x_{opt}|) / (x_{max} - x_{opt}) \text{ for}$$

$$x_{opt} < x \leq x_{max}$$

where $x_{opt} = 6.5$ for pH in rice soils

- For "less is better" indicators (EC):

$$S = 1 - (x - x_{min}) / (x_{max} - x_{min})$$

Threshold values were based on fertility ratings for Indian soils (Singh *et al.*, 2015).

Index Computation

The overall SQI was calculated as the weighted additive index:

$$SQI = \sum_{i=1}^n w_i \times S_i$$

where w_i is the weight and S_i is the score for indicator i . Equal weights (0.2 each) were assigned based on expert judgment and previous studies in similar systems (Masto *et al.*, 2007).

Quality Classification

SQI values were classified as: Very good (≥ 0.8), Good (0.6–0.79), Fair (0.4–0.59), and Poor (< 0.4).

SOC Stocks and Carbon Sequestration Calculation

SOC Stock Computation

SOC stock (t ha⁻¹) for the 0–15 cm layer was calculated as:

$$SOC \text{ stock} = \frac{SOC(\%) \times BD(g \text{ cm}^{-3}) \times Depth(cm) \times 10,000}{100}$$

where 10,000 converts hectare to cm².

Carbon Sequestration

Carbon sequestered (t C ha⁻¹) was calculated as the difference between final (2019) and initial (1989) SOC stocks:

$$C_{seq} = SOC_{final} - SOC_{initial}$$

Carbon Sequestration Rate

Annual carbon sequestration rate (CSR, t C ha⁻¹ yr⁻¹) was computed as:

$$CSR = \frac{C_{seq}}{30}$$

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate for a randomized complete block design. Treatment means were compared using Fisher's protected least significant difference (LSD) at $p < 0.05$. Standard error of means (SE \pm) and coefficient of variation (CV) were calculated. Pearson correlation coefficients were determined to examine relationships among soil properties. Principal component analysis (PCA) was performed to identify key drivers of soil quality variation across treatments and locations. All statistical analyses were conducted using R software version 4.1.2 (R Core Team).

Results and Discussion

Soil Quality Index

SQI values varied significantly among treatments and locations (Table 2). Treatments receiving organic

inputs, either alone or in combination with inorganic fertilizers, consistently achieved the highest SQI ratings ("very good"). At MTU and TTB, all organic-based treatments (T5–T8) recorded SQIs ≥ 0.8 . At MND, the highest SQI (0.8) was observed under 100% RDF + FYM. Control and imbalanced fertilization (T1–T3) resulted in poor SQIs (0.4–0.6), highlighting the degrading effect of nutrient omission and lack of organic inputs. The superior SQI under organic-amended treatments aligns with previous studies highlighting the multifaceted benefits of organic matter in tropical soils (Manna *et al.*, 2005; Majumder *et al.*, 2008). Farmyard manure and green manure incorporation likely improved soil quality through several interconnected mechanisms.

Table 2 : Soil Quality Index under different fertilization treatments across three locations.

Trt. No	Treatment Details	MTU	TTB	MND
T ₁	Control	0.4 (poor)	0.4 (poor)	0.4 (Poor)
T ₂	100% NK (-P)	0.4 (poor)	0.4 (poor)	0.4 (poor)
T ₃	100% NP (-K)	0.6 (good)	0.6 (good)	0.4 (poor)
T ₄	100% RDF	0.6 (good)	0.8 (very good)	0.6 (good)
T ₅	100% RDF + FYM@5t ha ⁻¹	0.8 (very good)	0.8 (very good)	0.8 (very good)
T ₆	50% RDF + 50% FYM-N	0.8 (very good)	0.8 (very good)	0.6 (good)
T ₇	50% RDF + 25% FYM-N + 25%GM-N	1 (very good)	0.8 (very good)	0.6 (good)
T ₈	FYM@10t ha ⁻¹	0.8 (very good)	0.8 (very good)	0.6 (good)

SOC Stocks and Carbon Sequestration

SOC stocks were significantly influenced by fertilization practices (Table 3). The highest stocks were recorded under integrated organic–inorganic treatments: 23.56, 30.62, and 13.07 t ha⁻¹ at MTU, TTB, and MND, respectively. Control plots showed the lowest stocks, with net declines from initial values at all sites. Carbon sequestration rates followed a similar trend, with maximum CSR values of 0.26, 0.40,

and 0.23 t ha⁻¹ yr⁻¹ at MTU, TTB, and MND under organic-amended treatments. The CSR values observed (0.23–0.40 t C ha⁻¹ yr⁻¹) fall within the range reported for tropical agroecosystems (0.1–0.5 t C ha⁻¹ yr⁻¹) by Smith *et al.* (2020) and Surekha *et al.* (2017). These rates, if scaled across India's 44 million hectares of rice area, could sequester 10–18 million tonnes CO₂-equivalent annually a significant contribution to India's Nationally Determined Contributions.

Table 3 : SOC stocks and carbon sequestration under long-term fertilization.

Trt. No	Treatment Details	Final SOC stock (t ha ⁻¹)			SOC Sequestered in 30 in 30 years (t ha ⁻¹)			Carbon sequestration rate (CSR) (t ha ⁻¹ yr ⁻¹)		
		MTU	TTB	MND	MTU	TTB	MND	MTU	TTB	MND
T ₁	Control	15.17	11.31	3.71	-0.72	-7.22	-2.35	-0.02	-0.24	-0.08
T ₂	100% NK(-P)	16.24	17.94	6.05	0.35	-0.59	0.00	0.01	-0.02	0.00
T ₃	100% NP(-K)	18.03	21.45	5.85	2.14	2.92	-0.20	0.07	0.10	-0.01
T ₄	100% RDF	19.64	25.94	6.63	3.75	7.41	0.58	0.12	0.25	0.02
T ₅	100% RDF + FYM@5t ha ⁻¹	23.56	30.62	8.97	7.67	12.09	2.92	0.26	0.40	0.10
T ₆	50% RDF + 50% FYM-N	21.60	27.30	9.95	5.71	8.77	3.90	0.19	0.29	0.13
T ₇	50% RDF + 25% FYM-N + 25% GM-N	22.67	27.89	13.07	6.78	9.36	7.02	0.23	0.31	0.23
T ₈	FYM@10t ha ⁻¹	23.21	30.23	9.75	7.32	11.70	3.70	0.24	0.39	0.12
	SEm±	1.11	1.87	0.66	*	*	*	*	*	*
	CD (p=0.05)	3.38	5.66	1.99	*	*	*	*	*	*
	CV (%)	9.55	13.40	14.23	*	*	*	*	*	*
	Initial OC (%)	0.89	0.95	0.31	*	*	*	*	*	*
	Initial Bulk density (g cc ⁻¹)	1.19	1.30	1.30	*	*	*	*	*	*
	Initial C stock (t ha ⁻¹)	15.89	18.53	6.05	*	*	*	*	*	*

The negative CSR under control treatments (-0.02 to -0.24 t C ha⁻¹ yr⁻¹) indicates these systems are net carbon sources (Table 4.2). The conventional rice-wheat system of the Indo-Gangetic Plains, for instance, has experienced significant yield stagnation attributed partly to deteriorating soil health (Chaudhary *et al.*, 2017). Scaling this across marginally managed croplands in South Asia could represent substantial CO₂ emissions, exacerbating climate change.

Conclusion

Organic amendments, either alone or combined with inorganic fertilizers, significantly improved SQI, with ratings reaching “very good” across all soil types. SOC stocks and carbon sequestration rates were highest under integrated organic–inorganic treatments, emphasizing the role of organic inputs in building soil carbon. Control and nutrient-imbalanced treatments led to soil degradation and carbon loss, highlighting the risks of unsustainable fertilization. The study advocates for the adoption of INM practices in rice-based systems to enhance soil health, ensure long-term productivity, and contribute to climate change mitigation through carbon sequestration.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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