



Carbon Sequestration Potential and Soil Carbon Stock Under Diversified Rice-based Cropping Systems in *Inceptisols* of Eastern India

Sayantani Purkait¹, B. B. Behera¹, A. K. Patra², Sayani Das³, M. R. Nayak⁴, Amaresh Khuntia² and D. P. Dash⁵

¹Dept. of Soil Science, ²Dept. of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (751 003), India

³Dept. of Agronomy, Bidhan Chandra Krishi Viswavidyalaya, West Bengal (741 252) India

⁴Dept. of Silviculture and Agroforestry, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (751 003), India

⁵Krishi Vigyan Kendra, Odisha University of Agriculture and Technology, Malkangiri, Odisha (764 045), India



Corresponding ✉ sdasagron@gmail.com

ID 0009-0008-1638-0569

ABSTRACT

A field experiment was conducted during June, 2023 to May, 2024 at the Central Research Station of Odisha University of Agriculture and Technology, Bhubaneswar, India, under irrigated medium land conditions to evaluate the carbon sequestration potential and soil carbon stock dynamics under diversified rice-based cropping systems in *Inceptisols* of Eastern India. The study was conducted during the seventh crop cycle of an ongoing field experiment comprising twelve rice-based cropping systems in a randomized block design with three replications. The results showed that diversified rice-based cropping systems significantly improved soil organic carbon, carbon stock and bulk density. The lowest bulk density (1.31 Mg m^{-3}) and the highest soil organic carbon (8.0 g kg^{-1}) were recorded under the GM-rice-greengram-cowpea (vegetable) system, followed by GM-rice-cowpea (vegetable)-greengram (7.9 g kg^{-1}). Soil carbon stock increased at all soil depths (0–15, 15–30 and 30–45 cm), with the highest values (15.65 , 8.06 and $5.64 \text{ Mg C ha}^{-1}$, respectively) recorded under the GM-rice-greengram-cowpea (vegetable) system. This system also recorded the highest carbon sequestration potential ($0.51 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$), followed by GM-rice-cowpea (vegetable)-greengram ($0.43 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$). The findings indicate that rice-based cropping systems incorporating green manure and legumes enhance soil carbon storage and sequestration, contributing to sustainable soil management and climate change mitigation.

KEYWORDS: Carbon sequestration, carbon stock, *Inceptisols*, legumes, rice-based cropping system

Citation (VANCOUVER): Purkait et al., Carbon Sequestration Potential and Soil Carbon Stock under Diversified Rice-based Cropping Systems in *Inceptisols* of Eastern India. *International Journal of Bio-resource and Stress Management*, 2026; 17(10), 01-08. [HTTPS://DOI.ORG/10.23910/1.2026.7309](https://doi.org/10.23910/1.2026.7309).

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, author have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Funding: The research was conducted with the kind and supports from Odisha University of Agriculture and Technology.

Conflict of interests: The author has declared that no conflict of interest exists.

RECEIVED on 30th June 2026

RECEIVED in revised form on 04th October 2026

ACCEPTED in final form on 18th October 2026

PUBLISHED on 27th October 2026

1. INTRODUCTION

Climate change is one of the major global challenges affecting agricultural productivity and ecosystem stability. Increasing concentration of greenhouse gases, particularly atmospheric carbon dioxide (CO_2), has intensified global warming and poses a serious threat to crop production (Yuan et al., 2024). Soil acts as a major reservoir of carbon and plays an important role in regulating the global carbon cycle (Wu et al., 2024). Soil organic carbon (SOC) is a key component of soil organic matter that improves soil quality, nutrient cycling, biological activity and crop productivity while contributing to atmospheric CO_2 reduction (Lal, 2004). Globally, soils contain a substantial proportion of terrestrial carbon, with SOC serving as an important pool influencing climate regulation and ecosystem functioning (Yadav et al., 2025). Among the terrestrial carbon pools, soils store more carbon than the atmosphere and vegetation combined, making SOC management essential for maintaining ecosystem sustainability and mitigating climate change (Jaya et al., 2026). Even small increases in SOC can improve soil resilience while reducing atmospheric CO_2 concentrations (Kabato et al., 2025). Agricultural intensification, continuous cropping and improper organic matter management have resulted in depletion of SOC reserves, leading to deterioration of soil health and increased greenhouse gas emissions (Haddaway et al., 2017; Adekiya et al., 2023). Enhancing SOC through sustainable management practices is therefore considered an important strategy for climate change mitigation. Practices such as crop diversification, residue recycling, conservation agriculture and integration of legumes help in increasing biomass return to soil, improving carbon stabilization and maintaining soil fertility (Lal, 2004; Francaviglia et al., 2023). Sustainable agricultural management enhances the quantity and quality of organic matter returned to the soil, promotes aggregate stability and improves nutrient retention (Sahoo et al., 2025), thereby protecting organic carbon from decomposition and contributing to long-term carbon storage. Cropping systems influence soil carbon through differences in crop biomass production, root turnover and residue quality (Ankit et al., 2024). Inclusion of legumes and green manure crops enhances organic matter input and improves carbon accumulation through biological nitrogen fixation and greater biomass addition. Diversified cropping systems involving cereals, pulses, fodders and vegetables have been reported to improve SOC concentration and carbon storage compared to monocropping systems (Mandal et al., 2007; Srinivasarao et al., 2012). The stability of SOC depends on its protection within soil aggregates and continuous addition of organic residues. Carbon sequestration in agricultural soils depends not only on the quantity of biomass returned to the soil but

also on its stabilization within soil aggregates and mineral-associated organic matter, both of which are influenced by cropping system management. Leguminous crops contribute substantial belowground biomass and residues with favourable carbon-to-nitrogen ratios, facilitating efficient nutrient cycling and microbial activity (Yan et al., 2023). Likewise, green manure incorporation supplies fresh organic substrates that enhance microbial processes, improve soil aggregation and increase the stabilization of soil organic carbon over time (Sahil et al., 2026). Rice-based cropping systems are predominant in eastern India due to favourable agro-climatic conditions (Srinivasan, 2025). However, continuous rice monocropping coupled with intensive tillage and inadequate residue recycling often accelerates soil organic carbon depletion, resulting in declining soil health and reduced system sustainability. Diversification of rice-based systems with legumes, green manure and high biomass-producing crops can enhance carbon sequestration potential by improving soil organic matter accumulation and nutrient cycling. Understanding the influence of different rice-based cropping systems on soil carbon stock is essential for developing sustainable climate-resilient agricultural practices (Upadhaya et al., 2022). Although diversified rice-based cropping systems have been widely evaluated for productivity, resource-use efficiency and soil fertility, limited information is available on their influence on soil carbon sequestration potential and soil carbon stock at different soil depths in the *Inceptisols* of eastern India. Such information is essential for identifying cropping systems capable of enhancing long-term carbon storage while maintaining agricultural productivity and developing climate-smart strategies that improve soil health and agricultural sustainability. Therefore, the present study was undertaken to evaluate the carbon sequestration potential and soil carbon stock under diversified rice-based cropping systems in the *Inceptisols* of eastern India with the objective of identifying sustainable cropping systems that enhance soil carbon storage and contribute to climate-resilient agriculture.

2. MATERIALS AND METHODS

2.1. *Experimental site and climatic conditions*

A field experiment was conducted during June, 2023 to May, 2024 at the Central Research Station of Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India (20°15' N latitude, 85°52' E longitude and 25.9 m above mean sea level) under the All India Coordinated Research Project on Integrated Farming Systems. The study was conducted during the seventh crop cycle of an ongoing field experiment under irrigated medium land conditions. The experimental site falls under the East and South Eastern Coastal Plain agro-climatic zone of Odisha. The climate of

the region was subtropical humid with hot summers and monsoon rainfall. The soil of the experimental field was an *Inceptisol* with sandy loam texture.

2.2. Experimental design and treatments

The experiment was laid out in a randomized block design (RBD) with twelve rice-based cropping systems as treatments and three replications. The cropping systems evaluated were rice-groundnut-okra, rice-greengram-okra, green manure-rice-greengram-cowpea (vegetable), green manure -rice-cowpea (vegetable)-greengram, rice-rapeseed-greengram, rice-sunflower-blackgram, rice-oat (fodder)-cowpea (fodder), rice-maize (fodder)-cowpea (fodder), rice-groundnut-blackgram, rice-ricebean-maize, scented rice-broccoli-okra and scented rice-sweetcorn-cowpea (vegetable). All crops were grown following the recommended agronomic practices for respective crops.

2.3. Soil sampling and analysis

Soil samples were collected after completion of the cropping cycle from three depths: 0–15 cm, 15–30 cm and 30–45 cm. Samples were collected from each plot, air dried, processed and used for analysis of soil physical and chemical properties.

2.3.1. Texture

Mechanical analysis of the soil was done to find out the percentage of sand, silt and clay separately by means of Bouyoucos hydrometer method to determine the texture of soil (Piper, 1966).

2.3.2. Bulk density (BD)

Bulk density was determined by core sampler method with dividing the oven-dry soil sample by the total volume of the sample (Dastane, 1972). The bulk density equation is as follows:

$$\text{Soil bulk density (Mg m}^{-3}\text{)} = (\text{Oven-dry sample mass (Mg)}) / (\text{Total volume of soil (m}^3\text{)})$$

2.3.3. pH

Soil pH was determined in 1:2.5 soil and water suspension by using glass electrode pH meter (Jackson, 1967).

2.3.4. Electrical conductivity

Soil EC was determined in 1:2.5 soil and water suspension by using conductivity meter (Jackson, 1967).

2.3.5. Soil organic carbon

Organic carbon content of the soil sample was determined by Walkley and Black's rapid titration method (Jackson, 1973).

2.3.6. Available nitrogen

Available nitrogen was determined by alkaline potassium permanganate method. Nitrogen released as ammonia during distillation of 20 g soil with 100 ml 0.32% of KMnO₄ and 100 ml of 2.5% NaOH was received in 2% boric acid containing mixed indicator and ammonium

borate complex was titrated against standard 0.02 N H₂SO₄ (Jackson, 1973).

2.3.7. Available phosphorous

It was determined by Bray's-I method with shaking 5 g soil in 35 ml of extracting solution (0.03N NH₄F in 0.025N HCl) for 5 min. The filtrate was estimated by spectrophotometer for phosphorous after development of colour by SnCl₂ and measured at 660 nm wavelength (Jackson, 1973).

2.3.8. Available potassium

5 g of processed soil was taken in a 150 ml conical flask and shaken with 25 ml 1N neutral ammonium acetate for 5 min in a mechanical shaker (reciprocating type). Then, the suspensions were filtered through Whatman no 1 filter paper and filtrate were collected in 50 ml beaker. The K concentration of the filtrate was determined by Flame photometer after suitable dilution (Jackson, 1973).

2.3.9. Carbon sequestration estimation in soil

The soil samples from different depths of soil i.e. 0–15 cm, 15–30 cm and 30–45 cm were collected before and after the experiment for estimation of carbon sequestration potential of soil. Carbon stock for different depth of soil was estimated by multiplying SOC content with soil bulk density and soil layer depth (Srinivasarao et al., 2013)

C stock in soil (Mg C ha⁻¹ year⁻¹)

=Depth of soil (m)×Bulk density (Mg m⁻³)×Soil organic Carbon (g Kg⁻¹)×10 C sequestration rate (Mg C ha⁻¹ year⁻¹)

=(Carbon stock in soil after n years of experiment–Carbon stock in soil before initiation of experiment) / Years of experiment

2.4. Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for randomized block design. Treatment means were compared using the critical difference (CD) at *p*=0.05 probability level.

3. RESULTS AND DISCUSSION

3.1. Physico-chemical properties of soil under diversified rice-based cropping systems

Different rice-based cropping systems significantly influenced the physico-chemical properties of soil (Table 1). After seven crop cycles, soil bulk density decreased from the initial value of 1.41 Mg m⁻³, with the lowest bulk density (1.31 Mg m⁻³) recorded under GM-rice-greengram-cowpea (vegetable) and GM-rice-cowpea (vegetable)-greengram systems. The reduction in bulk density was mainly due to higher organic matter addition through legume biomass and crop residues, which improved soil aggregation and porosity. Similar findings were reported by Rakesh et al. (2020).

Cropping system	Bulk density (Mg m ⁻³)	Soil pH	EC (dS m ⁻¹)	Organic carbon (g kg ⁻¹)	Available nutrient (kg ha ⁻¹)		
					N	P	K
Rice-groundnut-okra	1.33	6.04	0.30	7.2	278	12.5	170.0
Rice-greengram-okra	1.33	6.01	0.29	7.3	278	12.7	172.0
GM-rice-greengram-cowpea (veg)	1.31	6.00	0.28	8.0	289	13.7	184.0
GM-rice-cowpea(veg)-greengram	1.31	6.01	0.27	7.9	291	13.5	184.3
Rice-rapeseed-greengram	1.33	6.05	0.29	7.6	283	13.3	179.7
Rice-sunflower-blackgram	1.32	6.03	0.29	7.5	281	13.2	179.7
Rice-oat(fodder)-cowpea (fodder)	1.34	6.04	0.30	7.3	279	13.0	176.0
Rice-maize (fodder)-cowpea (fodder)	1.34	6.02	0.29	7.2	279	12.8	174.0
Rice-groundnut-blackgram	1.33	6.02	0.30	7.3	282	12.5	182.3
Rice-ricebean-maize	1.34	6.04	0.30	7.2	282	12.5	180.3
Scented rice-broccoli-okra	1.34	6.02	0.29	7.2	283	12.7	181.3
Scented rice-sweetcorn-cowpea (veg)	1.33	6.03	0.30	7.3	285	13.1	182.3
SEm±	0.00	0.02	0.01	0.02	0.67	0.04	0.26
CD (<i>p</i> =0.05)	0.01	0.06	0.03	0.07	1.98	0.13	0.77
Initial (2017)	1.41	5.98	0.25	6.8	290	13.8	196

Soil pH remained almost stable after seven crop cycles, ranging from 6.00–6.05, compared to the initial value of 5.98. Soil organic carbon increased under all cropping systems from the initial value of 6.8 g kg⁻¹. The highest SOC was recorded under GM-rice-greengram-cowpea (vegetable) (8.0 g kg⁻¹) followed by GM-rice-cowpea (vegetable)-greengram (7.9 g kg⁻¹) due to continuous addition of root biomass, residues and green manure, enhancing carbon accumulation. Similar improvement in SOC under legume-based systems was reported by Chitale et al. (2011) and Patra et al. (2017).

Available nitrogen decreased in most systems compared to the initial value (290 kg ha⁻¹), while GM-rice-cowpea (vegetable)-greengram maintained higher nitrogen (291 kg ha⁻¹) due to legume inclusion. The highest available phosphorus (13.7 kg ha⁻¹) was recorded under GM-rice-greengram-cowpea (vegetable) and potassium (184.3 kg ha⁻¹) under GM-rice-cowpea (vegetable)-greengram. The improved nutrient status under legume-based systems was attributed to enhanced nutrient cycling and organic matter addition (Jat et al., 2012; Patra et al., 2019).

Overall, diversified rice-based systems involving legumes and green manure improved soil carbon storage and maintained better soil quality, contributing to higher carbon sequestration potential.

3.2. Carbon stock under diversified rice-based cropping systems

Carbon stock of soil at different depths was significantly influenced by different rice-based cropping systems (Table 2–4). After seven crop cycles, soil carbon stock increased

Table 2: Effect of rice-based cropping systems on carbon stocks at depth of 0–15 cm soil

Cropping system	Bulk density (Mg m ⁻³)	Soil organic carbon (g kg ⁻¹)	Carbon stock (Mg C ha ⁻¹)
Rice-groundnut-okra	1.33	7.2	14.45
Rice-greengram-okra	1.33	7.3	14.51
GM-rice-greengram-cowpea (veg)	1.31	8.0	15.65
GM-rice-cowpea(veg)-greengram	1.31	7.9	15.46
Rice-rapeseed-greengram	1.33	7.6	15.19
Rice-sunflower-blackgram	1.32	7.5	14.78
Rice-oat(fodder)-cowpea (fodder)	1.34	7.3	14.57
Rice-maize (fodder)-cowpea (fodder)	1.34	7.2	14.51
Rice-groundnut-blackgram	1.33	7.3	14.53
Rice-ricebean-maize	1.34	7.2	14.51
Scented rice-broccoli-okra	1.34	7.2	14.47
Scented rice-sweetcorn-cowpea (veg)	1.33	7.3	14.63
Initial (2017)	1.41	6.8	14.38

Table 3: Effect of rice-based cropping systems on carbon stocks at depth of 15–30 cm soil

Cropping system	Bulk density (Mg m ⁻³)	Soil organic carbon (g kg ⁻¹)	Carbon stock (Mg C ha ⁻¹)
Rice-groundnut-okra	1.38	3.4	7.09
Rice-greengram-okra	1.37	3.5	7.24
GM-rice-greengram-cowpea (veg)	1.34	4.0	8.06
GM-rice-cowpea(veg)-greengram	1.33	3.9	7.87
Rice-rapeseed-greengram	1.35	3.8	7.65
Rice-sunflower-blackgram	1.35	3.7	7.54
Rice-oat(fodder)-cowpea (fodder)	1.35	3.5	7.09
Rice-maize (fodder)-cowpea (fodder)	1.35	3.5	7.09
Rice-groundnut-blackgram	1.34	3.6	7.32
Rice-ricebean-maize	1.36	3.4	6.92
Scented rice-broccoli-okra	1.37	3.4	6.97
Scented rice-sweetcorn-cowpea (veg)	1.35	3.7	7.47
Initial (2017)	1.42	3.2	6.82

Table 4: Effect of rice-based cropping systems on carbon stocks at depth of 30–45 cm soil

Cropping system	Bulk density (Mg m ⁻³)	Soil organic carbon (g kg ⁻¹)	Carbon stock (Mg C ha ⁻¹)
Rice-groundnut-okra	1.41	2.3	4.93
Rice-greengram-okra	1.41	2.4	5.06
GM-rice-greengram-cowpea (veg)	1.38	2.7	5.64
GM-rice-cowpea(veg)-greengram	1.37	2.6	5.42
Rice-rapeseed-greengram	1.38	2.5	5.26
Rice-sunflower-blackgram	1.39	2.4	5.09
Rice-oat(fodder)-cowpea (fodder)	1.40	2.5	5.33
Rice-maize (fodder)-cowpea (fodder)	1.41	2.4	5.06
Rice-groundnut-blackgram	1.38	2.5	5.26
Rice-ricebean-maize	1.40	2.3	4.91
Scented rice-broccoli-okra	1.41	2.3	4.86
Scented rice-sweetcorn-cowpea (veg)	1.39	2.4	5.06
Initial (2017)	1.45	2.1	4.57

in all cropping systems compared to the initial values of 14.38, 6.82 and 4.57 Mg C ha⁻¹ at 0–15, 15–30 and 30–45 cm soil depths, respectively. The highest carbon stock at 0–15 cm depth was recorded under GM-rice-greengram-cowpea (vegetable) (15.65 Mg C ha⁻¹) followed by GM-rice-cowpea (vegetable)-greengram (15.46 Mg C ha⁻¹). Similar trends were observed at 15–30 cm and 30–45 cm depths, where GM-rice-greengram-cowpea (vegetable) recorded the highest carbon stock of 8.06 and 5.64 Mg C ha⁻¹, respectively.

The higher accumulation of soil carbon under green manure and legume-based systems was mainly due to continuous addition of organic residues, root biomass and greater biomass turnover from leguminous crops. Green manure incorporation enhanced carbon input and promoted stabilization of organic matter in soil. Similar improvement in SOC storage under diversified cropping systems was reported by Russell et al. (2005) and Brar et al. (2013).

3.3. Carbon sequestration potential under diversified rice-based cropping systems

The total carbon sequestration potential (0–45 cm depth)

varied among cropping systems (Table 5). The highest carbon sequestration potential was recorded under GM-rice-greengram-cowpea (vegetable) (0.51 Mg C ha⁻¹ yr⁻¹) followed by GM-rice-cowpea (vegetable)-greengram (0.43 Mg C ha⁻¹ yr⁻¹). The lowest sequestration potential was observed under rice-ricebean-maize and scented rice-broccoli-okra (0.08 Mg C ha⁻¹ yr⁻¹).

The superior carbon sequestration ability of green manure and legume-based systems may be attributed to higher carbon inputs through biomass production, residue recycling and improved soil biological activity. Inclusion of cowpea and greengram enhanced soil carbon retention by increasing organic matter addition and reducing carbon loss through decomposition. Similar enhancement of soil carbon sequestration under diversified cropping systems was reported by Gopinath et al. (2022) and Shuo et al. (2016).

Overall, the results indicated that integration of green manure and legume crops in rice-based systems improved carbon storage and contributed towards climate-resilient and sustainable soil management in *Inceptisols* of Eastern India.

Table 5: Effect of rice-based cropping systems on carbon sequestration potential of soil

Cropping system	C- sequestration potential of soil (Mg C ha ⁻¹ yr ⁻¹)			Total C-sequestration potential (Mg C ha ⁻¹ yr ⁻¹)
	0–15 cm	15–30 cm	30–45 cm	
Rice-groundnut-okra	0.01	0.04	0.05	0.10
Rice-greengram-okra	0.02	0.06	0.07	0.15
GM-rice-greengram-cowpea (veg)	0.18	0.18	0.15	0.51
GM-rice-cowpea(veg)-greengram	0.15	0.15	0.12	0.43
Rice-rapeseed-greengram	0.12	0.12	0.10	0.33
Rice-sunflower-blackgram	0.06	0.10	0.07	0.23
Rice-oat(fodder)-cowpea (fodder)	0.03	0.04	0.11	0.17
Rice-maize (fodder)-cowpea (fodder)	0.02	0.04	0.07	0.13
Rice-groundnut-blackgram	0.02	0.07	0.10	0.19
Rice-ricebean-maize	0.02	0.01	0.05	0.08
Scented rice-broccoli-okra	0.01	0.02	0.04	0.08
Scented rice-sweetcorn-cowpea (veg)	0.04	0.09	0.07	0.20

4. CONCLUSION

Diversified rice-based cropping systems significantly enhanced soil carbon sequestration in the *Inceptisols* of Eastern India. The GM-rice-greengram-cowpea (vegetable) system recorded the highest carbon stock across all soil depths and the greatest carbon sequestration potential, followed by GM-rice-cowpea (vegetable)-greengram. These improvements were attributed to green manure incorporation and greater biomass inputs from legumes, highlighting diversified rice-based systems as an effective strategy for enhancing soil carbon storage, soil health and climate change mitigation.

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