Optimizing sustainability in rice-based cropping systems: a holistic approach for integrating soil carbon farming, energy efficiency, and greenhouse gas reduction strategies via resource conservation practices.

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Abstract

In the context of regenerative agriculture (RA) and sustainability in lowland rice agroecosystems, inefficient resource use leads to reduced agricultural output and significant greenhouse gas emissions (GHG), particularly methane from flooded paddy fields. Adopting regenerative practices such as precision nutrient and water management, conservation tillage, and crop diversification can enhance soil health, reduce emissions, and improve productivity. The adoption of sustainable agricultural practices aligns with several United Nations Sustainable Development Goals (SDGs), including SDG 2 (zero hunger), SDG 13 (climate action), and SDG 15 (life on land). By promoting climate-smart agriculture, regenerative practices in rice farming can contribute to mitigating climate change effects, ensuring food security, and conserving biodiversity.

In this scholarly investigation, we explore the efficacy of resource conservation technologies (RCTs) as nature- based solutions to enhance carbon storage, mitigate GHG emissions, and improve energy efficiency within rice-based cropping systems. Our study revealed that all resource conservation treatments led to increased system productivity and soil organic carbon compared to conventional practices. Among these treatments, zero-tillage exhibited the highest effectiveness in terms of carbon sequestration, with a rate of 0.97 Mg $ha^{-1}y^{-1}$. Zero-tillage consistently demonstrated the highest energy savings, ranging from 52.0–67.8% across analyzed seasons, and emerged as the most effective nature-based solution, with lower greenhouse warming potential compared to conventional practices.

Implementing zero tillage reduces global warming potential, carbon emissions, and greenhouse gas intensity compared to conventional methods. Our findings support zero tillage and green manuring as effective strategies to enhance soil organic carbon levels, reduce emissions, and improve crop productivity in lowland rice-green gram cropping systems, fostering sustainable and climate-friendly agriculture. These findings provide valuable insights into nature-based solutions and resource conservation practices, addressing climate change mitigation, carbon sequestration, energy efficiency, and energy savings in rice-based cropping systems, promoting a more sustainable future.

1. Introduction

Resource conservation technologies (RCTs) have emerged as crucial tools to address agricultural challenges, particularly for small-scale farmers in tropical regions. These technologies are designed to mitigate labour shortages and combat soil degradation resulting from intensive agricultural practices, such as organic matter depletion and disruption of nutrient cycling (Bhan and Behera 2014; Shrestha et al. 2020). With the aim of achieving sustainable agricultural production, RCTs offer various benefits, including energy savings, which are essential for reducing environmental impact and optimizing resource utilization (Hobbs and Govaerts 2010; Kassam et al. 2019). This study focuses on rice-based cropping systems in Eastern India, where the seasonal pattern follows a wet season (kharif) from June to November and a dry season (rabi) from January to April. The fallow period between rice harvests is often characterized by the burning of large amounts of unused crop biomass, leading to detrimental effects on soil health, nutrient loss, and carbon sequestration potential. The implementation of RCTs in rice-based cropping systems is expected to mitigate these issues and enhance soil fertility, nutrient use efficiency, and overall productivity (Hobbs et al. 2007; Powlson et al. 2016).

One significant advantage of RCT practices lies in their potential for energy savings. Conventional rice production involves energy-intensive activities such as field and seedbed preparation, sowing, weeding, and harvesting. However, RCTs, particularly zero tillage, significantly reduce fuel consumption and associated greenhouse gas (GHG) emissions by eliminating or minimizing these activities (Sun et al. 2019). Additionally, RCTs promote soil organic matter preservation and improved soil structure, enhancing energy efficiency and reducing the need for external inputs

(Hobbs 2007). Studies have shown that zero tillage in rice production can lead to energy consumption reductions ranging from 25–50% compared to conventional tillage systems (Htwe et al. 2021; Zhang et al. 2022).

Moreover, resource conservation technologies encompass a range of practices, including zero tillage and biomass management, which offer additional benefits such as nitrogen conservation, soil erosion reduction, and improved water and fertilizer use efficiency (Lal 2015; Chaudhary et al. 2017). These practices contribute to higher yields, lower production costs, better pest and disease control, and minimized GHG emissions. Nevertheless, further investigation is required to better understand the effects of RCTs on soil microbial activity, community diversity, and other biochemical characteristics, which play a crucial role in nutrient management and soil health (Acosta-Martínez et al. 2011; Dash et al. 2018).

The conservation of soil organic carbon (SOC) is vital for sustaining soil fertility and productivity in agro ecosystems, as well as for mitigating the impacts of climate change. Long-term RCT practices present an opportunity to assess the residual effects of tillage and residue management on soil biological properties, microbial abundance, activity, and diversity (Pandey et al. 2013; Mohanty et al. 2017; Dash et al. 2022). The rice-green gram cropping system, with green gram as a leguminous crop grown during the dry season, offers an ideal context to study the effects of RCTs on soil carbon dynamics and quantify greenhouse gas emissions. By examining this cropping system, the research aims to comprehensively investigate resource conservation technologies and their impact on soil carbon storage, greenhouse gas emissions, and energy savings. This analysis provides valuable insights into mitigating nutrient imbalances and soil quality deterioration commonly observed in intensive rice-rice systems (Nayak et al. 2012; Pittelkow et al. 2015).

Based on the above considerations, this study endeavors to address a conspicuous research gap by delving into the dynamics of the direct seeded rice-green gram cropping system. The investigation serves to contribute substantially to the existing gap of literature concerning carbon sequestration, greenhouse gas emissions, and energy efficiency within lowland ecosystems. Uniquely positioned, this research marks a pioneering effort, providing unprecedented insights derived from a comprehensive 5-year long-term experiment. By shedding light on the intricacies of rice-based cropping systems, particularly in the context of resource-conserving technologies, this study not only offers novel perspectives but also underscores the potential of RCTs as nature-based solutions applicable across various rice-pulse cropping systems. These findings hold immense significance, serving as a guiding beacon for policymakers, farmers, and researchers alike, in their collective endeavor to foster agricultural sustainability and mitigate environmental impacts.

2. Materials and methods

2.1 Description of the study area

The research area is situated in block ‘J’ of the Indian Council of Agricultural Research (ICAR)- National Rice Research Institute (NRRI), Cuttack, Odisha, as depicted in Fig. 1. The geographical coordinates of the area are 20º 44' N, 85º 94' E, with an elevation of 24 meters above the mean sea level. The region is primarily characterized as an irrigated agro-ecosystem, and the soil is classified as *Aeric Endoaquept*, which has a sandy clay loam texture consisting of 32% clay, 12% silt, and 56% sand, according to the Soil Survey Staff (2010). The experiment was started in the Kharif season of 2012, with the soil at the experimental site having 6.2 g kg^{-1} of total organic carbon, 22.8 kg ha^{-1} of Olsen P, and 263 kg ha^{-1} of $KMnO_4$ extractable N (available N). Table 1 provides a detailed overview of the physico-chemical properties of the soil.

Table 1
Physico-chemical properties of initial soil of the experiment.

Soil properties	Values
Sand (%)	56
Silt (%)	12
Clay (%)	32
Electrical Conductivity (dS m^{-1})	0.49
pH (1:2:: soil: water)	6.86
Olsen P (Kg ha^{-1})	22.8
Ammo. acetate ex. K (Kg ha^{-1})	265
$KMnO_4$ extractable N (kg ha^{-1})	263
$NH4^+$-N (kg ha^{-1})	35.2
NO_3-N (kg ha^{-1})	27.7
Total organic carbon (TOC) g kg^{-1}	6.2
Microbial biomass carbon (MBC) µg g^{-1}	74.6
Readily mineralizable carbon (RMC) µg g^{-1}	91.5
Potassium permanganate oxidizable carbon ($KMnO_4$-C) µg g^{-1}	116.8
Water soluble carbon (WSC) µg g^{-1}	49.9
Acid hydrolysable carbon (AHC) µg g^{-1}	564.6

2.2 Climate of the study area

The study area has a hot, moist, and sub-humid climate, with a total annual rainfall of 1312 mm in 2015 and 1293 mm in 2016. More than 75% of the rainfall is received during the months of May to September. In 2015, the mean maximum and minimum temperatures were 31.8˚C and 22.6˚C, respectively, while in 2016, they were 32.0˚C and 22.8˚C, respectively, as shown in supplementary figure (Fig. S2).

2.3 Experimental design and Treatment details

In 2012, a long-term experiment on resource conservation practices was established and conducted. The study was designed using a randomized block design (RBD) with 10 m × 9 m sized plots and seven treatments, which were replicated three times. Initially, from 2012 to 2014, the experiment was conducted using a rice-rice system in the wet and dry seasons, respectively. Later, the system was shifted to a rice-wet season and green gram-dry season. Table 2 provides the details of the treatments followed in both seasons. The wet season treatments remained the same throughout the experiment, whereas in the dry season, rice was replaced with green gram.

Table 2
Treatment details of the experiment under various resource conservation technologies in rice-green gram cropping system.

Treatments	Wet season (Rice)		Dry season (Green gram)
CP-LS	Conventional practice as control (power tiller driven puddling + manual sowing (WDS) + 100% RDF + manual weeding & harvesting)	Followed by	Tillage + dry direct manual line sowing + RDF
BM-LS	Tillage + Dry direct sowing + brown manuring (*Sesbania aculeata*) + knock down of by 2,4-D at 25 days after sowing + 75% N + chemical weeding + mechanical weeding and harvesting	Followed by	Tillage + dry direct manual line sowing + RDF
GM-LS	Tillage + Dry direct sowing + green manuring intercropping (incorporation through cono-weeder at 25 days after sowing) + 75% N + mechanical weeding and harvesting	Followed by	Tillage + dry direct manual line sowing + RDF
WDM-LS	Wet direct seeded by drum seeder + 100% RDF + mechanical weeding and harvesting	Followed by	Tillage + dry direct manual line sowing + RDF
ZT-ZT LS	Zero tilled dry direct seeded with glyphosate + residue retention (30 cm above the ground) + 100% N + chemical weeding (Bispyribac sodium) + mechanical harvesting	Followed by	Zero Tillage + dry sowing line (dibbling) + RDF
GM CLCC-N-LS	Paired row dry direct drill seeded rice with manuring (*Sesbania aculeata*) intercropping (incorporation at 25 days through cono-weeder) + customized leaf colour-based nitrogen application + mechanical weeding and harvesting.	Followed by	Tillage + dry direct manual line sowing + RDF
BC-LS	Wet direct seeded by drum seeder + Biochar application (5 t/ha) + 100% RDF + mechanical weeding and harvesting	Followed by	Tillage + dry direct manual line sowing + RDF
Design: RBD Replication: 3 Variety (rice): *Pooja* Variety (green gram): *Samrat*			

2.4 Crop establishment

The plots in the conventional tillage treatments were prepared by using a power tiller for preparatory tillage followed by ploughing or puddling. However, in zero tillage, no ploughing was performed and instead, sowing was done using a dibbler. Before sowing in the zero tillage treatments, glyphosate (herbicide) 41% EC was sprayed 7 days prior. For the wet (Kharif) season rice, *Pooja* variety was sown in the first week of June with a seed rate of 60 kg ha^{-1} and a row to plant space of 20 × 15 cm. The recommended dose of fertilizer for the region was applied, which included 80: 40: 40 kg ha^{-1} (N: P_2O_5: K_2O). Nitrogen was applied in three splits, with 50% basal and 25% each as two top dressings. Phosphorus and potassium were applied as a single dose as basal through single super phosphate (SSP) and muriate of potash (MOP), respectively. In the green manuring and brown manuring treatments, Sesbania aculeata was intercropped at a rate of 25 kg ha^{-1}. In the green manuring treatment, 30-day-old intercropped Sesbania plants were incorporated using a cono weeder. Similarly, in the brown manuring treatment, spraying of 2-4-D @ 0.5 kg ai/ ha was done at 30 days after sowing (DAS). Irrigation water was applied at every 3–5 days interval. Standard recommended practices were followed to control weeds, insects, and diseases.

In the dry (rabi) season, the Samrat variety of green gram (*Vigna radiata L.*) was sown in the first week of January with a seed rate of 25 kg ha^{-1} and a row to plant space of 30 × 10 cm. A recommended dose of 20: 40: 20 kg ha^{-1} (N: P_2O_5:

K_2O) was applied to the green gram. Full doses of N, P, and K were applied at sowing. To maintain the required plant-to-plant spacing, thinning of plants was done after 2 weeks of sowing.

2.5 Soil sampling

Initially, before commencing the experiment, soil sampling was conducted to analyze the initial soil characteristics. At the end of each crop season, a composite sample comprising of three samples from each plot was collected using a probe auger from 0–10 cm. The soil samples were air dried for seven days and processed through a 2 mm sieve. The processed samples were then packed in sealed plastic jars to analyze the soil carbon fractions. To estimate C-sequestration, soil samples were randomly collected after crop harvesting from each treatment from a soil depth of 0–30 cm. To determine bulk density, intact soil samples were collected using a core sampler.

2.6 Soil organic carbon estimation

The Walkley and Black (1934) method was used to determine the soil organic carbon content. A 500 ml Erlenmeyer flask was filled with 1 g of dry soil and 10 ml of 1N $K_2Cr_2O_7$ was added. Then, 20 ml of concentrated H_2SO_4 was added rapidly while directing the stream into the suspension. After 30 minutes, 200 ml of distilled water was added to the flask to end the reaction. The samples were titrated using freshly prepared anhydrous 0.5 N ferrous ammonium sulfate and diphenylamine (0.5 g reagent grade diphenylamine dissolved in 20 ml of distilled water and 100 ml of concentrated H_2SO_4) was used as the indicator.

2.6.1 Total organic carbon and soil organic carbon stock

The determination of Total Organic Carbon (TOC) involved wet digestion with potassium dichromate and a mixture of 3:2 H_2SO_4:85% H_3PO_4, at a temperature of 120°C for two hours in a digestion block, according to Snyder and Trofymow (1984). TOC mass was calculated by multiplying the TOC content (g kg^{-1}) with bulk density (Mgm^{-3}) and soil depth and expressed as Mg ha^{-1}. The formula used for calculating the mass of TOC in the surface layer was as follows (Pathak et al. 2011).

$$\mathrm{MTOC} = \mathrm{TOC\%} \times \mathrm{BD} \times \mathrm{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, MTOC is the mass of total TOC (Mg ha^{-1}), TOCs is the percentage of total organic carbon, BD is bulk density (Mg m^{-3}), and T is the thickness of the soil layer (cm). To estimate the carbon storage/ stock, the initial and final TOC in the surface soil (0–15 cm) were compared for different treatments. The increase in C stock in soil was used to calculate the soil organic carbon storage. The difference between the final and initial TOC mass under

different treatments were used to determine the C stock build-up, which is expressed as the ratio of the final TOC mass to the initial TOC mass using the formula (Dash et al. 2017):

$$\mathrm{Cstock} = \frac{\mathrm{FinalTOCmass}}{\mathrm{InitialTOCmass}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

2.7 Energy analysis

The methodology for estimating input and output energy, energy ratio, energy savings, energy spent per unit grain yield, and net C gain in each treatment is described as follows (Chaudhary et al. 2017; Yadav et al. 2018):

The total input and output energy for all agricultural operations in each treatment were estimated considering both manual and mechanical. Inputs including rice and dhaincha (S*esbania*) seeds, fertilizers, and agricultural operations such as sowing, weeding, fertilizer and pesticide applications, and harvesting were considered components of total input energy (Ei). Grain yield, straw yield, and husk yield were considered components of total output energy (Eo). The specific conversion factors used for the energy analysis, as presented in Supplementary table (Table S1), were applied for the calculation.

The energy use efficiency (EUE) was calculated using the equation (Htwe et al. 2021; Choudhary and Meena 2022):

$$EUE = \frac{Eo}{Ei} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where ‘Eo’ and ‘Ei’ are the total input energy and total output energy of the treatment.

Energy savings (ES) were calculated using the equation:

$$\mathrm{Energysavings}\,(\%) = \frac{EiC - EiX}{EiC} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

‘EiC’ represents the total input energy in the control treatment, while ‘EiX’ represents the total input energy in a specific treatment.

Energy spent per unit of grain yield was calculated using the equation:

$$\mathrm{Energyspentperunitgrainyield} = \frac{EiX}{Yg} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where ‘Yg’ is the grain yield and ‘EiX’ is defined in Eq. (4).

To estimate net C gain, the input and output energy were converted into equivalent C using a conversion factor of 1GJ energy ~ 20.15 kg C, as suggested by Lal (2004).

$$\mathrm{NetCgain} = \frac{(\mathrm{EquivalentCinEo} - \mathrm{EquivalentCinEi})}{1000} \ldots\ldots\ldots\ldots\ldots (6)$$

Where ‘Eo’ and ‘Ei’ are defined in Eq. (3).

2.8 Greenhouse gas emissions

2.8.1 Collection and analysis of methane and nitrous oxide

Gas samples for CH_4 and N_2O were collected using a closed-chamber technique with chambers that measured 53 cm × 37 cm × 71 cm (length × width × height) (Bhattacharyya et al. 2013; Dash et al. 2017). Aluminum base plates were placed in the soil of all plots prior to gas sampling and left in place until rice harvesting. To measure emissions, six rice hills were covered with a perspex chamber and placed on the base plate channel, which was filled with water to ensure an airtight seal. A battery-operated fan mixed the air inside the chamber, and gas samples were collected using Tedlar gas-sampling bags (M/s Aerovironment Inc.) drawn with a 50 mL syringe and a 24-gauge hypodermic needle at 0-, 15-, and 30-minute intervals for CH_4 and N_2O analysis. Emissions observed during morning hours were considered representative for the entire day (Zhang et al. 2010; Bhattacharyya et al. 2013). A gas chromatograph (TRACE 1110, M/s Thermo Scientific) fitted with a flame ionization detector (FID), electron capture detector (ECD), and Porapak Q column (6 feet long for CH_4 and 13 feet long for N_2O, 1/8-inch outer diameter, 80/100 mesh size, stainless steel column) was used to measure CH_4 and N_2O concentrations. Gas sampling occurred every 5 to 7 days throughout the year, and fluxes of CH_4 and N_2O for days without sampling were calculated by successive linear interpolation of the average emissions on the sampling days (Dash et al. 2017). Seasonal cumulative emissions of CH_4 and N_2O were determined by adding up the daily fluxes on sampling and non-sampling days and expressed in kg ha^{-1}.

$$\mathrm{CH_4flux}\left(\mathrm{mgm^{-2}hr^{-1}}\right)=\frac{\left(\Delta \mathrm{X_{CH_4}}\times \mathrm{EBV_{STP}}\times 16\times 60\times 10^{-3}\right)}{22.4\times \mathrm{A}\times \mathrm{T}}\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

$$\mathrm{N_2Oflux}\left(\mu \mathrm{gm^{-2}hr^{-1}}\right)=\frac{\left(\Delta \mathrm{X_{N_2O}}\times \mathrm{EBV_{STP}}\times 44\times 60\times 10^{-3}\right)}{22.4\times \mathrm{A}\times \mathrm{T}}\ldots\ldots\ldots\ldots\ldots(8)$$

$\Delta \mathrm{X_{CH_4}}$ = Difference between CH_4 concentrations (ppm) of initial (0 minute) and final (30 minute) sample.

$\Delta \mathrm{X_{N_2O}}$ = Difference between N_2O concentrations (ppb) of initial (0 minute) and final (30 minute) sample.

EBV_{STP} = Effective chamber volume at standard temperature and pressure (liter),

T = Time gap between initial and final sampling after placement of chamber.

A = Area occupied by the base plate (m^2).

2.8.2 Global warming potential, carbon equivalent emission and greenhouse gas intensity estimation

The Global Warming Potential (GWP) is an indicator that measures the cumulative radiative forcing caused by a unit mass of gas emitted in the present and until a chosen future time horizon, as defined in IPCC (2014). This index is commonly used to assess the ability of each greenhouse gas to trap heat in the atmosphere in comparison to a standard gas, typically CO_2. To evaluate GHG emissions, the IPCC factors are used to calculate the GWP for a 100-year time frame, which provides an integrated measure of the combined warming potential of all gases.

$$GWP=25*CH_4+298*N_2OkgCO_2equivalentha^{-1}\ldots\ldots\ldots\ldots(9)$$

CH_4 and N_2O efflux values under different treatments (IPCC 2014).

The CEE and GHGI of the treatments were calculated using the following equations (Dash et al. 2017):

$$CEE(Kg^{-1})=GWP\times \frac{12}{44}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

$$GHGI(Kg^{-1})=\frac{GWP}{grainyield}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

2.9 Yield

2.9.1 Rice yield

The sun-dried produce from the net plots was threshed to obtain grains, which were then winnowed, cleaned, and weighed. The resulting yield in kilograms per plot was adjusted to 14% moisture using a digital grain moisture meter and then converted to weight per hectare.

2.9.2 Green gram yield

After the process of threshing, winnowing and sun drying of the harvested grain, the yield from each plot was measured and recorded separately. The recorded yield was then converted into metric tons per hectare (t ha^{-1}), which is a commonly used unit for measuring agricultural productivity. This conversion helps in the comparison and analysis of the yield of different plots, providing valuable information for farmers and researchers to make informed decisions about crop management and production strategies. Proper record keeping and accurate measurements of yield are crucial in ensuring optimal crop yield and sustainability in agriculture.

2.9.3 Rice equivalent yield

To calculate the equivalent yield in terms of kharif crop, such as paddy in a rice-based cropping system, the following formula can be used. First, the total yield of each crop grown in the same area during the year must be determined.

$$REY = \frac{Yield of greengram \times MSP of greengram}{MSP of rice} \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

MSP = minimum support price in this year

2.10 System productivity

System productivity is a measure of the amount of yield produced per unit area over a specified period. In the agricultural sector, this measure is often expressed in terms of the equivalent yield of a single commodity, such as rice. The period used for this calculation is typically one agricultural year, which is equivalent to 365 days. To arrive at the equivalent yield, the total yield of all crops produced within that one-year period is added together and expressed as megagrams per hectare (Mg ha^{-1}).

2.11 Statistical analysis

In our study, we utilized separate data sets for soil organic carbon, yield parameters, energy savings and greenhouse gas emissions parameters throughout the entire duration of the research. To evaluate the data, we conducted a comparative analysis of variance for each season. After calculating the means, we applied Duncan's Multiple Range Test (DMRT) to compare them at the 5% probability level of significance. To perform the statistical analysis, we used SAS 9.2 software. These methods enabled us to examine the differences between the variables and draw meaningful conclusions from our research findings.

3. Results

3.1 Soil carbon dynamics

3.1.1 *Soil organic* carbon

Different resource conservation technologies (RCTs) resulted in marked variation in soil organic carbon (SOC) contents, with the highest value observed in zero tillage (ZT-ZT LS) and the lowest in conventional practice (CP-LS). At the end of the experiment, the SOC content increased by 14.3% in ZT-ZT LS, 12.9% in green manuring (GM-LS), 11.5% in green manuring- customized leaf colour based N application (GM (CLCC-N)-LS), 10.0% in brown manuring (BM-LS), and 6.9% in biochar application (BC-LS) treatments, compared to the CP-LS (Table 3). Soil organic carbon content predictably rises with increased carbon input until the soil reaches a state of C-saturation. Various studies have indicated that the application of inorganic fertilizer, alone or combined with organic manures, has led to higher SOC content (Blair et al. 2006; Purakayastha et al. 2008; Bhattacharyya et al. 2013). This is attributed to the significant carbon supplementation resulting from manure application and increased root biomass. Balanced fertilization and the retention of crop residues are expected to further boost SOC accumulation, as they enhance primary production and facilitate the return of crop residues to the soil. In rice-paddy systems, specific factors such as anaerobic conditions and a unique flooded moisture regime lasting 3–4 months can stimulate higher C storage (Dash et al. 2017). The lack of oxygen under submerged conditions slows down SOC decomposition rates (Kukal and Benbi 2009).

Table 3
Soil organic carbon (SOC) content during wet and dry seasons under different RCTs.

	Soil organic carbon (g Kg^{-1})			
Treatments	Dry season 2015	Wet season 2015	Dry season 2016	Wet season 2016
CP-LS	5.2^{d}	5.3^{f}	5.4^{e}	5.5^{e}
BM-LS	5.7^{b}	5.7^{cd}	6.0^{bc}	6.2^{bc}
GM-LS	5.9^{ab}	6.0^{ab}	6.2^{ab}	6.4^{ab}
WDM-LS	5.2^{d}	5.4^{ef}	5.6^{d}	5.7^{de}
ZT-ZT LS	6.1^{a}	6.1^{a}	6.3^{a}	6.6^{a}
GM (CLCC-N)-LS	5.9^{b}	5.9^{bc}	6.1^{b}	6.2^{bc}
BC-LS	5.5^{c}	5.6^{de}	5.8^{cd}	6.0^{cd}
LSD ($p \leq 0.05$)	0.2	0.2	0.2	0.3

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

3.1.2 Soil organic carbon stock

The SOC stock (0–30 cm soil depth) at the end of 2 cycles of each rice-rice and rice- green gram was estimated and the stock was determined by subtracting the value from the pre-treated initial value (Fig. 2). To compare the systems (rice-rice and rice-green gram), the SOC stock at the end of rice-rice was subtracted from the value that obtained at initial stage (before commencement of rice-rice system), similarly SOC stock at the end of rice-green gram was subtracted from the value that obtained from rice-rice system. The stock was higher under rice-rice than rice-green gram cropping system and was significantly varied among the resource conservation treatments. Soil organic carbon stock in rice-rice cropping system over initial was ranged from 0.41–1.9 t ha^{-1}, whereas in rice-green gram over rice-rice cropping system it was 0.34–1.62 t ha^{-1} under different RCTs. The highest storage was recorded under zero tillage (ZT-ZT LS) and the lowest in conventional (CP-LS) treatment under both the cropping system and the order of SOC stock change in different RCTs were zero tillage (ZT (CLCC-N) LS) > green manuring (GM-LS) > green manuring with customized N application (GM-ZT LS) > brown manuring (BM-LS) > biochar application (BC-LS) > wet direct drum seeding (WDS-LS) > conventional practice (CP-LS).

The variation in SOC stock change over control (CP-LS) showed significant differences among various RCTS. The highest SOC stock change was observed under the zero-tillage treatment, while the lowest SOC stock change was recorded under the WDM-LS treatment. Comparing SOC stock change over conventional control in different RCTs, the order of magnitude was as follows: zero tillage (ZT (CLCC-N) LS) > green manuring (GM-LS) > green manuring with customized N application (GM-ZT LS) > brown manuring (BM-LS) > biochar application (BC-LS) > wet direct drum seeding (WDS-LS) (Fig. 3). Research by Henneron et al. (2015) demonstrated that continuous rice cropping for two years resulted in 11–12% greater C sequestration compared to the maize-rice rotation, affirming the positive impact of resource conservation practices on C stock. Among the resource conservation technologies studied, zero tillage, residue management, and establishment methods significantly influenced soil carbon stock. Zero tillage protects aggregate-associated carbon from microbial decomposition, safeguarding soil aggregate-bound carbon and the sub-surface carbon pool, which leads to SOC sequestration (Six et al. 2004; Purakayastha et al. 2008). Another crucial factor in soil carbon build-up is the incorporation and retention of crop residues, which plays a substantial role alongside zero tillage. Crop residue input has been shown to be a primary factor in stabilizing soil carbon (Chivenge et al. 2007; Singh et al. 2011). In fact, zero tillage with residue retention treatments in rice-wheat cropping systems in the eastern Indo-Gangetic plains of India showed almost four times higher carbon input from crop residues compared to conventional tillage treatments (Sapkota et al. 2017). Consequently, treatments involving zero tillage and residue retention exhibited higher SOC stocks than conventional practices (Paudel et al. 2014; Bhaduri and Purakayastha 2014). The high lignin content in rice straw has been found to slow decomposition, contributing to greater carbon accumulation in the soil (Bhatia et al. 2005). The adoption of zero tillage or conservation tillage practices presents a promising opportunity to enhance carbon storage by creating a conducive environment that favours dominant fungal decomposition over bacterial decomposition. This fungal decomposition process produces more recalcitrant decomposition products, highlighting its potential significance in bolstering long-term carbon retention, as observed by Soudzilovskaia et al. (2015).

The variation in soil organic carbon sequestration depends on several factors, including microbial population, moisture levels, and temperature fluctuations (Govaerts et al. 2008). To conserve soil carbon, residue retention through practices like green manure and rice straw incorporation, as well as different tillage methods, are crucial (Duiker and Lal 1999; Anyanzwa et al. 2011; Corsi et al. 2012). Our study aligns with these findings, showing the significance of residue retention and tillage practices in soil carbon conservation. In our research, we observed that the rice-green gram system experienced higher carbon losses due to increased respiration, leading to a comparatively lower potential for long-term soil organic carbon sequestration compared to the rice-rice system. This underscores the importance of considering different cropping systems' impacts on soil carbon dynamics. While Hutchinson et al. (2007) reported no significant impact on soil organic carbon when wheat was replaced with lentils in a long-term crop rotation, it is essential to note that their study did not assess soil carbon levels in deeper soil layers. Other studies have confirmed that deep-rooted crops like alfalfa can lead to higher levels of soil organic carbon in deeper soil depths (Gregorich et al. 2005). Furthermore, rotational diversity has been found to play a vital role in soil carbon accrual. It enhances the ability of soil-inhabitant microbial communities to rapidly degrade plant residues and protect carbon in aggregates (Tiemann et al. 2015). Based on the research conducted by Choudhry et al. (2014), the integration of direct seeded rice alongside zero tillage, with a focus on residue retention, displayed highly encouraging prospects for achieving a sustainable increase in yield (8.3%) and notable enhancements in soil health. The study was conducted over a period of five years in sandy loam reclaimed sodic soil in the hot semi-arid region of the Indian subcontinent. The results revealed significant enhancements in soil aggregation (53.8%) and Soil Organic Carbon (SOC) sequestration (33.6%) compared to conventional tillage practices with transplanted rice.

This study also made a comparison to assess the effect of cropping system on SOC sequestration over the assessment period. The rice-rice system (first two years) and rice-green gram system (next two years) behaved differently for SOC pools and SOC stocks. For assessing SOC change in the soil, the initial soil value before treatment imposition (pre-treatment) is required to fix it as the boundary line (Olson 2013). Many researchers have compared and reported the change in SOC sequestration between treated and untreated plots while considering conventional practices as the baseline (Nayak et al. 2012; Shahid et al. 2017).

3.2 Rice yield, rice equivalent yield and system yield

In both years of the study, rice yield was consistently higher in the GM-LS treatment compared to all other treatments. However, during the dry season of 2015, the higher rice equivalent yield was observed under ZT-ZT LS treatment at 3.32 Mg ha^{-1}. On the other hand, in the dry season of 2016, the GM-LS treatment showed the highest REY at 3.56 Mg ha^{-1}. During the first year, there was no significant variation in rice yield between treatments, but in the subsequent year, the GM-LS treatment recorded the highest yield. In the dry season, the ZT-ZT LS treatment exhibited a higher REY compared to other treatments. The rice yields were consistent across all RCT treatments in 2015. However, in the kharif season of 2016, it was observed that the green manuring treatment led to the highest grain yield. This increase in yield was attributed to the incorporation of green manure at 25 days after sowing, which effectively suppressed weed growth and provided a regulated supply of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), in addition to improving the physical conditions of the soil (Singh et al. 2011).

The System yield recorded higher in the RCT treatments than the control treatment. In the first year of the study, there was no significant difference in SY among the treatments; however, in the second year, the RCT treatments recorded a higher SY compared to the control treatment (Table 4). In order to stay competitive with the changes in trade and the rapid growth of non-agricultural activities, lowland rice must find ways to increase its productivity. In the rabi season of 2016, the highest grain yield was achieved with the Zero Tillage (ZT) treatment after five years of commencement of the study. The initial year of no-till operation showed lower yields, which could account for the differences observed. These findings align with the results reported by Jat et al. (2014). Additionally, ZT was found to provide energy-saving benefits due to reduced herbicide and tillage costs, along with the yield premium, as identified earlier by Erenstein et al. (2008). Despite the slight increase in herbicide and tillage costs, the yield premium resulted in an overall net gain for ZT. The research also revealed that green manuring contributed to the highest grain yield, mainly because it ensured a continuous supply of essential nutrients, particularly N, P, and K, while also improving the soil's physical conditions, as documented by Bhattacharyya et al. (2013) and Ghimire et al. (2017).

Table 4
Rice, rice equivalent and system yield during wet and dry season under different RCTs.

	Rice Yield ($Mg\ ha^{-1}$)	**REY ($Mg\ ha^{-1}$)**	**System Yield ($Mg\ ha^{-1}$)**	**Rice Yield ($Mg\ ha^{-1}$)**	**REY ($Mg\ ha^{-1}$)**	**System Yield ($Mg\ ha^{-1}$)**
Treatments	Wet season	Dry season	Annual	Wet season	Dry season	Annual
CP-LS	4.92[a]	2.78[a]	7.7[a]	4.63[e]	2.87[c]	7.49[d]
BM-LS	5.1[a]	3.14[a]	8.24[a]	5.06[b]	3.46[a]	8.52[b]
GM-LS	5.24[a]	3.12[a]	8.36[a]	5.38[a]	3.56[a]	8.94[a]
WDM-LS	5.03[a]	2.83[a]	7.86[a]	4.66[e]	3.00[bc]	7.66[d]
ZT-ZT LS	4.87[a]	3.32[a]	8.18[a]	4.86[cd]	3.27[ab]	8.13[bc]
GM (CLCC-N)-LS	5.17[a]	2.95[a]	8.12[a]	4.96[bc]	3.20[abc]	8.16[bc]
BC-LS	5.07[a]	2.91[a]	7.98[a]	4.77[d]	3.02[bc]	7.79[cd]
LSD ($p \leq 0.05$)	NS	NS	NS	0.10	0.36	0.42

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

3.3 Energy estimation

The energy calculation results are presented in Table 5, encompassing data for the years 2015 and 2016, along with distinctions between the dry and wet seasons. Various parameters were examined, including Input Energy, Output Energy, Energy Ratio, Energy Spent for unit grain production, Net C Gain, and Energy Savings (%). During the dry season of 2015, the input energy ranged from 9.59 GJ ha^{-1} to 12.61 GJ ha^{-1}, while the output energy varied from 59.17 GJ ha^{-1} to 71.38 GJ ha^{-1}. The energy ratio, which reflects the efficiency of energy utilization, ranged from 4.69 to 7.45. Additionally, the energy spent for unit grain production ranged from 2.90 GJ kg^{-1} to 4.57 GJ kg^{-1}. This metric provides insight into the energy investment required to produce a specific amount of grain. The net C gain, measuring the carbon sequestration potential, ranged from 0.94 to 1.25. Higher values indicate a more significant potential for carbon capture, which is crucial in environmental considerations. As for energy savings, the ZT-ZT LS treatment exhibited the highest percentage at 58.20%.

Table 5
Input, output energy estimation, energy use efficiencies, and energy savings parameters of rice-green gram system under different resource conservation technologies.

Year/ season	Treatment	Input energy (GJ ha^{-1})	Output energy (GJ ha^{-1})	Energy use efficiency	Energy spent per unit grain (GJ t^{-1})	Net C gain (GJ kg^{-1})	Energy savings (%)
Dry season, 2015	CP-LS	12.61^{a}	59.17^{b}	4.69^{c}	4.57^{a}	0.94^{c}	-
	BM-LS	12.61^{a}	68.13^{ab}	5.40^{bc}	4.02^{b}	1.12^{b}	15.01^{c}
	GM-LS	12.61^{a}	71.38^{a}	5.66^{b}	4.06^{ab}	1.19^{ab}	20.47^{b}
	WDM-LS	12.61^{a}	61.80^{b}	4.90^{c}	4.47^{ab}	0.99^{c}	4.40^{e}
	ZT-ZT LS	9.59^{b}	71.38^{a}	7.45^{a}	2.90^{c}	1.25^{a}	58.20^{a}
	GM (CLCC-N)-LS	12.61^{a}	63.98^{b}	5.07^{c}	4.28^{ab}	1.04^{bc}	8.07^{d}
	BC-LS	12.61^{a}	63.70^{b}	5.05^{c}	4.34^{ab}	1.03^{bc}	7.59^{d}
	LSD ($p \leq 0.05$)	0.01	6.55	0.57	0.54	0.13	0.62
Wet season, 2015	CP-LS	30.85^{a}	143.80^{d}	4.66^{g}	6.27^{a}	2.28^{e}	-
	BM-LS	26.29^{d}	151.72^{a}	5.77^{d}	5.17^{c}	2.53^{a}	23.61^{d}
	GM-LS	25.29^{f}	150.06^{b}	5.94^{b}	4.87^{c}	2.52^{ab}	27.08^{b}
	WDM-LS	28.92^{b}	148.40^{c}	5.13^{f}	5.75^{b}	2.41^{d}	9.98^{f}
	ZT-ZT LS	19.54^{g}	142.91^{d}	7.31^{a}	4.02^{d}	2.49^{b}	56.41^{a}
	GM (CLCC-N)-LS	25.68^{e}	149.39^{bc}	5.89^{c}	5.00^{c}	2.50^{b}	24.59^{c}
	BC-LS	27.80^{c}	148.66^{bc}	5.35^{e}	5.49b^{c}	2.44^{c}	14.57^{e}
	LSD ($p \leq 0.05$)	0.08	1.49	0.05	0.53	0.03	0.71
Dry season, 2016	CP-LS	12.61^{a}	62.19^{b}	4.93^{d}	4.42^{a}	1.00^{c}	-
	BM-LS	12.61^{a}	73.37^{a}	5.82^{b}	3.66^{b}	1.23^{ab}	17.83^{c}
	GM-LS	12.61^{a}	74.58^{a}	5.91^{b}	3.55^{b}	1.25^{ab}	19.75^{b}
	WDM-LS	12.61^{a}	64.31^{b}	5.10^{c}	4.21^{ab}	1.04^{bc}	3.38^{f}

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

Year/ season	Treatment	Input energy (GJ ha^{-1})	Output energy (GJ ha^{-1})	Energy use efficiency	Energy spent per unit grain (GJ t^{-1})	Net C gain (GJ kg^{-1})	Energy savings (%)
	ZT-ZT LS	9.59^{b}	72.07^{a}	7.52^{a}	2.93^{c}	1.26^{a}	52.00^{a}
	GM (CLCC-N)-LS	12.61^{a}	68.14^{ab}	5.40^{bc}	3.95^{b}	1.12^{b}	9.48^{d}
	BC-LS	12.61^{a}	64.93^{b}	5.15^{c}	4.19^{ab}	1.06^{bc}	4.36^{e}
	LSD ($p \leq 0.05$)	0.01	7.08	0.57	0.46	0.14	0.57
Wet season, 2016	CP-LS	30.85^{a}	135.46^{d}	4.39^{f}	6.67^{a}	2.11^{e}	-
	BM-LS	26.29^{d}	145.50^{bc}	5.54^{c}	5.20^{d}	2.41^{bc}	25.83^{c}
	GM-LS	25.29^{e}	151.13^{a}	5.98^{b}	4.70^{f}	2.54^{a}	35.81^{b}
	WDM-LS	28.92^{b}	137.68^{d}	4.76^{e}	6.20^{b}	2.20^{d}	8.33^{e}
	ZT-ZT LS	18.32^{g}	135.46^{d}	7.40^{a}	3.77^{g}	2.37^{c}	67.82^{a}
	GM (CLCC-N)-LS	24.46^{f}	146.46^{b}	5.99^{b}	4.93^{e}	2.46^{b}	36.07^{b}
	BC-LS	26.58^{c}	141.75^{c}	5.33^{d}	5.57^{c}	2.33^{c}	21.26^{d}
	LSD ($p \leq 0.05$)	0.08	3.79	0.16	0.16	0.08	0.88

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

During the wet season of 2015, the input energy ranged from 19.54 GJ ha^{-1} to 30.85 GJ ha^{-1}, while the output energy varied from 135.46 GJ ha^{-1} to 151.72 GJ ha^{-1}. This resulted in energy ratios ranging from 4.66 to 7.40, indicating a highly efficient energy conversion process. The energy required for producing a unit of grain varied from 4.02 GJ kg^{-1} to 6.67 GJ kg^{-1}. Additionally, carbon sequestration was observed, with net C gain ranging from 2.11 to 2.54. The treatment with ZT-ZT LS exhibited the highest energy savings at 56.4%.

Similarly, in the subsequent seasons of 2016 (both dry and wet), a similar analysis was conducted with the same treatments. The energy parameters demonstrated comparable trends to those observed in the previous seasons, with variations based on the specific treatments applied. Notably, the ZT-ZT LS treatment consistently displayed remarkable energy savings, ranging from 52.0–67.8% across all seasons. In this study, we evaluated the effectiveness of various resource conservation technologies (RCTs) treatments in optimizing energy utilization and minimizing wastage during grain production. Our results indicated that among these treatments, ZT-ZT LS emerged as the best treatment in terms of energy utilization, followed by green manuring, green manuring with customized leaf colour-based nitrogen application, and brown manuring, compared to conventional practice. One of the key factors influencing energy utilization in agriculture is the input energy required for crop production. Input energy includes the energy used in tractor operations, irrigation, fertilizers, pesticides, and other inputs. ZT-ZT LS treatment showed a significant reduction in input energy compared to conventional practice (Lal 2015; Dash et al. 2022). The adoption of zero tillage reduces the need for ploughing and reduces fuel consumption in tractor operations, leading to lower overall input energy requirements.

Higher EUE and energy savings with lower energy spent per unit grain results have also been reported in other studies in rice-base cropping systems in South Asia in different conservation tillage practices (Gathala et al. 2020). In another study conducted by Gathala et al. (2016), the authors investigated the variation in Energy Use Efficiency (EUE) in relation to different parameters, including nutrient availability, water management, and other factors. The study aimed to understand the influence of these variables on the efficient use of energy in agricultural systems.

These findings align with previous studies that have emphasized the importance of adopting sustainable agricultural practices to optimize energy utilization and promote environmental sustainability (Smith et al. 2014; Zhang et al. 2021). The results underscore the potential benefits of implementing the ZT-ZT LS treatment in terms of energy efficiency and savings, which can contribute to the overall sustainability of agricultural systems.

Effective energy utilization is crucial for sustainable agriculture. It refers to the amount of energy converted into useful work, such as biomass production or grain yield. Our findings suggest that ZT-ZT LS treatment resulted in higher effective energy utilization compared to conventional practice (Yadav et al. 2018; Choudhury et al. 2022). The reduced soil disturbance and improved soil health associated with zero tillage contribute to enhanced nutrient availability, root development, and overall crop growth, leading to higher energy conversion into grain production.

Furthermore, resource conservation technologies aim to minimize wastage and improve overall sustainability in agriculture. Our results indicate that ZT-ZT LS treatment effectively minimizes wastage by optimizing energy utilization and reducing input requirements (Dash et al. 2022). The reduced soil erosion, improved water retention, and enhanced nutrient management associated with zero tillage contribute to better resource conservation and sustainable grain production.

3.4 Methane (CH_4) emission

The methane flux exhibited variations during the dry and wet seasons, with values ranging from 0.17 to 0.81 mg m^{-2} ha^{-1} in the dry season and 0.26 to 6.22 mg m^{-2} ha^{-1} in the wet season. Notably, higher methane fluxes were observed during the wet season compared to the

dry season. Among the different treatments, the GM-LS treatment consistently showed the highest methane flux, significantly surpassing the fluxes observed in the other treatments. Conversely, the ZT-ZT LS treatment consistently exhibited the lowest methane flux during both seasons. The peaks of methane fluxes occurred at specific growth stages of the crops. In the year 2015 and 2016, the highest methane fluxes were observed during the panicle initiation (PI) stage of rice and at the pod filling (PF) stage of green gram (Fig. 4).

Looking at the annual methane emissions across the treatments during both the dry and wet seasons (Table 6), significant variations were recorded. The GM-LS treatment resulted in the highest annual methane emissions (99.9 and 113.9 kg ha^{-1}) for the respective years, while the ZT-ZT LS treatment had the lowest emissions (64.1 and 81.0 kg ha^{-1}). Furthermore, it was observed that during the wet season, methane emissions in rice significantly increased by 87.7–89.5% in 2015 and by 85.1–87.2% in 2016 under different treatments, compared to the emissions recorded in the dry season. It is well established that application of different fertilizers, especially in combination with manure, can enhance the bioavailable pool of organic C and promote the production of CH_4 by methanogenic microbes (Zheng et al. 2007; Bhattacharyya et al. 2013). The amount of CH_4 produced is likely to depend on the availability of carbon resources for microbes. The particular C/N ratio and N availability in GM-LS treatment favour decomposition, leading to a higher net C mineralization and CH_4 emission. The application of green manure and crop residues can enhance the emission of methane by providing additional C substrates compared to unfertilized conditions (Lu et al. 2000). However, in GM (CLCC-N)-LS treatment, dry direct seeded rice, although associated with green manuring, minimizes CH_4 emission compared to the GM-LS treatment because some aeration is present, promoting methane oxidation.

Table 6
Seasonal methane emissions from different resource conservation technologies.

	2015					2016				
Treatments	**Dry season**	**Dry Fallow**	**Wet season**	**Wet Fallow**	**Annual**	**Dry season**	**Dry Fallow**	**Wet season**	**Wet Fallow**	**Annual**
CP-LS	7.7^{c}	2.4^{cd}	64.8^{e}	1.6^{e}	76.7^{e}	10.2^{c}	6.3^{e}	69.2^{d}	6.2^{e}	91.9^{d}
BM-LS	8.5^{b}	3.1^{b}	76.8^{b}	2.3^{c}	90.8^{b}	10.8^{b}	7.0^{c}	80.^{b}	6.7^{c}	105.0^{b}
GM-LS	8.9^{a}	3.4^{a}	85.0^{a}	2.6^{a}	99.9^{a}	11.3^{a}	7.3^{a}	88.3^{a}	7.0^{a}	113.9^{a}
WDM-LS	7.6^{d}	2.3^{d}	62.4^{f}	1.8^{e}	74.1^{f}	10.0^{d}	6.3^{f}	66.9^{e}	6.2^{f}	89.3^{e}
ZT-ZT LS	6.6^{e}	1.4^{e}	55.0^{g}	1.1^{f}	64.1^{g}	8.8^{e}	5.3^{g}	61.4^{f}	5.5^{g}	81.0^{f}
GM (CLCC-N)-LS	8.5^{b}	3.1^{b}	69.1^{c}	2.4^{b}	83.2^{c}	10.9^{b}	7.1^{b}	73.2^{c}	6.8^{b}	98.0^{c}
BC-LS	7.7^{c}	2.5^{c}	66.2^{d}	2.0d	78.3^{d}	10.0^{d}	6.4^{d}	70. 0^{d}	6.3^{d}	92.7^{d}
LSD ($p \leq 0.05$)	0.07	0.09	0.88	0.06	1.05	0.09	0.06	0.81	0.05	0.98

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

The application of fertilizers with crop residues can enhance labile C pools, which are easily utilized by methanogens, promoting CH_4 emission (Zheng et al. 2007; Dash et al. 2023). Our study found that the incorporation of biomass (*Sesbania*) with suitable N input favours decomposition, net methanogenesis, and increased CH_4 emission (Bhattacharyya et al. 2013). Soil organic carbon was significantly higher in the rice residue incorporation technique, which resulted in higher CH_4 emission. Substrates such as green manure and rice residue produce acetate after decomposition, which is a key component for the growth of methanogens.

On the other hand, in zero tillage transplanting, minimum disturbance and aeration might reduce CH_4 emission compared to other treatments. Zero tillage reduces weed seed germination and growth, moderates soil temperature, and reduces water loss through evaporation. It has been reported that CH_4 emissions from rice fields range from 16.2 to 120 kg ha^{-1} during the entire season (Pathak et al. 2002; Bhattacharyya et al. 2020). The incorporation of straw could increase CH_4 emissions under flooded conditions, but management of the straw under aerated conditions and temporary aeration of the soils can mitigate these effects. In our study, we found significantly less CH_4 emission in ZT as compared to other treatments. Zero-tillage, when compared to conventional practice, reduced CH_4 emissions by 12–18% in kharif season, likely due to the combined effects of zero tillage and associated soil aeration in DSR. Ahmad et al. (2009) also obtained similar results, reporting a 28% reduction in CH_4 emissions under ZT relative to conventional tillage.

3.5 Nitrous oxide (N_2O) emission

Throughout the study period, distinct seasonal variations were observed in N_2O fluxes under different treatments. The levels of nitrous oxide fluxes showed considerable variations due to varying treatments and the timing of fertilizer addition during the crop-growing periods. In the case of green gram, regardless of the treatment, two N_2O emissions peaks were consistently observed, one during the early vegetative stage and another during the pod filling stage. In the wet season, three N_2O emissions peaks were noted, which coincided with N fertilizer application.

The average N_2O fluxes under different treatments during both dry and wet seasons were found to range from 36.7 to 82.9 μg m^{-2} h^{-1} and 8.3 to 66.8 μg m^{-2} h^{-1}, respectively. Notably, the N_2O fluxes were higher during the dry seasons, while they were significantly lower during the wet season. Among the treatments, the highest N_2O flux was observed under GM-LS during dry seasons, whereas the lowest flux was recorded under WDM-LS treatment. In contrast, during the wet season, GM-LS treatment exhibited the highest N_2O flux, and GM (CLCC-N)-LS treatment displayed the lowest N_2O flux (Fig. 5). Nonetheless, the impact of RCTs on N_2O emissions during both the dry and wet seasons was considerable, as depicted in Table 7. The GM-LS treatment exhibited the highest annual cumulative N_2O emission (3.07 and 3.15 kg ha^{-1}), which was significantly greater than the emissions from other treatments. Conversely, the GM (CLCC-N)-LS treatment demonstrated the lowest annual N_2O emission (2.41 and 2.54 kg ha^{-1}) in both years. In terms of seasons, N_2O emissions were generally higher during the dry season compared to the wet season, except for WDM-LS in both years and BC-LS in 2016. Two major microbial processes, nitrification, and denitrification are responsible for N_2O emissions from rice soils. Although nitrification is an aerobic process and denitrification is an anaerobic process, both cycles can occur in soils. While nitrification and denitrification are significant sources of N_2O production, higher C availability under anaerobic conditions leads to increased production (Tirol-Padre et al. 2016; Jahangir et al. 2022). The present study also showed that enzymatic activities, such as urease, were higher under the green manuring treatment, which promoted the growth of microbial populations and ultimately generated more N_2O flux compared to other techniques. The reduced N_2O emission in real-time N-management techniques was attributed to the demand-based supply of N fertilizer, which reduced N losses.

Table 7
Seasonal N_2O emissions from different resource conservation technologies.

	2015					2016				
Treatments	**Dry season**	**Dry Fallow**	**Wet season**	**Wet Fallow**	**Annual**	**Dry season**	**Dry Fallow**	**Wet season**	**Wet Fallow**	**Annual**
CP-LS	1.07^c	0.30^g	0.82^f	0.23^g	2.42^e	1.11^c	0.32^g	0.90^f	0.22^g	2.55^f
BM-LS	1.08^b	0.41^b	0.99^b	0.33^b	2.82^b	1.12^b	0.43^b	1.03^c	0.31^b	2.90^b
GM-LS	1.15^a	0.47^a	1.08^a	0.36^a	3.07^a	1.19^a	0.49^a	1.13^a	0.35^a	3.15^a
WDM-LS	0.95^g	0.38^d	0.96^c	0.29^d	2.58^d	0.99^f	0.40^d	1.03^c	0.28^d	2.70^d
ZT-ZT LS	1.04^d	0.35^e	0.91^d	0.26^e	2.56^d	1.04^d	0.36^e	0.93^e	0.25^e	2.59^e
GM (CLCC-N)-LS	0.98^f	0.32^f	0.85^e	0.26^f	2.41^e	1.02^e	0.34^f	0.94^d	0.24^f	2.54^f
BC-LS	1.00^e	0.39^c	0.99^b	0.30^c	2.68^c	1.04^d	0.41^c	1.05^b	0.29^c	2.79^c
LSD ($p \leq 0.05$)	0.01	0.01	0.01	0.004	0.024	0.01	0.01	0.01	0.004	0.01

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

3.6 Global warming potential, Carbon equivalent emission and Greenhouse gas intensity

The seasonal mean GWP showed variations between the wet and dry seasons. In the dry season of 2015 and 2016, the estimated GWP ranged from 590.5 to 773.5 and 773.4 to 972.5 kg CO_2 eq. ha^{-1}, respectively. However, during the wet season of the same years, it was higher, ranging from 1883.6 to 2836.6 and 2186.8 to 3059.5 kg CO_2 equivalent ha^{-1} (Tables 8 and 9). Comparing different treatments, the GM-LS treatment had the highest GWP, while the ZT-ZT LS treatment had the lowest GWP in both the dry and wet seasons. Specifically, the ZT-ZT LS treatment showed a significant reduction in GWP compared to the conventional practice. In the dry season of 2015 and 2016, the reduction was approximately 5.8% and 6.5%, respectively. Similarly, in the wet season of the same years, the reduction was approximately 12.8% and 9.9%, respectively.

Table 8
Annual global warming potential (GWP), carbon equivalent emission (CEE) and greenhouse gas intensity (GHGI) from soil under different resource conservation technologies in the year 2015.

	GWP (Kg CO_2 eq. ha^{-1})		CEE (Kg C ha^{-1})		GHGI (kg CO_2 eq. kg^{-1} grain)	
Treatments	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
CP-LS	626.6^{e}	2160.3^{e}	170.9^{e}	589.2^{e}	0.23^{a}	0.44^{c}
BM-LS	721.4^{b}	2566.5^{b}	196.7^{b}	700.0^{b}	0.23^{f}	0.50^{b}
GM-LS	773.5^{a}	2836.6^{a}	210.9^{a}	773.6^{a}	0.25^{e}	0.55^{a}
WDM-LS	628.5^{e}	2130.6^{e}	171.4^{e}	581.1^{e}	0.22^{c}	0.42^{d}
ZT-ZT LS	590.5^{f}	1883.6^{f}	161.1^{f}	513.7^{f}	0.18^{g}	0.39^{e}
GM (CLCC-N)-LS	689.0^{c}	2280.6^{c}	187.9^{c}	622.0^{c}	0.23^{d}	0.44^{c}
BC-LS	652.6^{d}	2248.4^{d}	178.0^{d}	613.2^{d}	0.22^{b}	0.44^{c}
LSD ($p \leq 0.05$)	6.2	24.1	1.7	6.6	0.01	0.01

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

Table 9
Annual global warming potential (GWP), carbon equivalent emission (CEE) and greenhouse gas intensity (GHGI) from soil under different resource conservation technologies in the year 2016.

	GWP (Kg CO_2 eq. ha^{-1})		CEE (Kg C ha^{-1})		GHGI (kg CO_2 eq. kg^{-1} grain)	
Treatments	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
CP-LS	827.5^{e}	2427.0^{e}	225.7^{e}	661.9^{e}	0.29^{a}	0.52^{d}
BM-LS	917.9^{b}	2798.4^{b}	250.3^{b}	763.2^{b}	0.27^{f}	0.55^{b}
GM-LS	972.5^{a}	3059.5^{a}	265.2^{a}	834.4^{a}	0.27^{e}	0.57^{a}
WDM-LS	829.7^{e}	2392.2^{e}	226.3^{e}	652.4^{e}	0.28^{c}	0.51^{e}
ZT-ZT LS	773.4^{f}	2186.8^{f}	210.9^{f}	596.4^{f}	0.24^{g}	0.45^{f}
GM (CLCC-N)-LS	888.9^{c}	2537.9^{c}	242.4^{c}	692.1^{c}	0.28^{d}	0.51^{c}
BC-LS	848.9^{d}	2492.7^{d}	231.5^{d}	679.8^{d}	0.28^{b}	0.52^{c}
LSD ($p \leq 0.05$)	3.8	15.9	1.1	6.1	0.01	0.01

[Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram.]

Carbon Equivalent Emission was assessed across all treatments during both dry and wet seasons. The GM-LS treatment exhibited notably higher CEE compared to the other treatments. In the dry season, CEE levels ranged from 161.1 to 210.9 kg C ha^{-1} and 210.9 to 265.2 kg C ha^{-1} in the years 2015 and 2016, respectively. In the wet season of the same years,

CEE ranged from 513.7 to 773.6 kg C ha^{-1} and 596.4 to 834.4 kg C ha^{-1}, respectively (Table 8 and Table 9). In contrast to CP-LS treatment, the ZT-ZT LS treatment resulted in a significant reduction in CEE by 5.7% and 12.8% in the dry seasons of 2015 and 2016, respectively. Similarly, during the wet seasons of the same years, the ZT-ZT LS treatment led to a reduction in CEE by 6.6% and 9.9%, respectively.

During the wet season, a higher level of greenhouse gas intensity was recorded compared to the dry season. Notably, the GM-LS treatment exhibited significantly higher GHGI compared to other treatments. However, the ZT-ZT LS treatment demonstrated a reduction in global warming potential per grain yield by 21.7% and 17.2% when compared to CP-LS. Similarly, the ZT-ZT LS treatment also resulted in a reduction of 11.4% in comparison to CP-LS (Tables 8 and 9). In this study, six resource conservation techniques (RCTs) including zero tillage, integrated nutrient management (green manuring), and crop diversification were employed in a lowland rice-green gram system to assess the global warming potential (GWP). The results showed that zero tillage and crop diversification practices had lower emission potential compared to conventional agricultural practices. This finding is consistent with previous studies conducted in upper and lower IGPs on zero tillage and crop diversification (Pathak et al. 2011). The GWP of CH_4 and N_2O gases during the wet season (rice cultivation) were higher compared to the dry season (green gram cultivation). Additionally, the average GWP of paddy rice cultivation over all seasons was higher, as reported by Linquist et al. (2012). A meta-analysis report showed that the rice-rice cropping system had significantly higher GWP values compared to rice-maize cropping system. Various studies have been conducted on greenhouse gas emission mitigation in comparison to conventional practices and conservation agriculture (Pathak et al. 2003; Jat et al. 2014; Sapkota et al. 2014; Laik et al. 2014). Conservation agriculture practices led to decreased emissions, total GWP, and yield-scaled emissions (Bhatia et al. 2012; Chauhan et al. 2012).

In this investigation of rice-green gram systems, the greenhouse gas intensity (GHGI) or yield-scaled global warming potential was used as the computation base for seasonal measurement. The results showed that the zero-tillage treatment and green gram crop season had the lowest GHGI. Two studies on the rice-wheat system in IGP also demonstrated a decrease in GHGI under zero tillage (Bhatia et al. 2010; Pandey et al. 2012).

4. Conclusions

This study provides compelling evidence on the effectiveness of resource conservation technologies as nature-based solutions in rice-based cropping systems. The implementation of RCTs led to notable improvements in soil organic carbon levels compared to conventional practices, resulting in enhanced system productivity. The incorporation of biomass in RCT practices played a crucial role in increasing SOC and its fractions, while zero tillage practices proved particularly effective in reducing losses and promoting carbon sequestration in the soil. Our research also revealed that the rate of carbon sequestration was higher in rice-rice cropping systems, particularly when employing zero tillage practices. Furthermore, zero tillage practices not only contributed to lower GHG emissions but also maintained crop yields, making them a promising option for resource conservation and GHG mitigation in rice-based cropping systems. It is important to underscore the significance of adopting sustainable resource management techniques, including appropriate tillage practices and organic amendments, in rice cultivation. By optimizing soil carbon storage and dynamics, resource conservation technologies have the potential to minimize GHG emissions, increase carbon storage and energy savings, and promote the buildup of SOC in lowland rice-green gram cropping soils in tropical regions. In conclusion, the combination of energy savings and emission reduction achieved through the implementation of RCTs in rice-based cropping systems represents a powerful and sustainable approach to agricultural practices. By optimizing energy use efficiency, reducing GHG emissions, and promoting carbon sequestration, these nature-based solutions not only contribute to climate change mitigation but also provide opportunities for improved resource management and long-term sustainability. The findings of this study highlight the importance of embracing and implementing RCTs to achieve emission reductions, carbon storage, energy savings, and SOC enrichment in rice-based cropping systems, ultimately leading to more sustainable and resilient agricultural practices.

Declarations

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Authors' contributions

P.K. Dash performed the experiments, collected data, and prepared first draft manuscript. P. Bhattacharyya designed the project and manuscript correction. S.R. Padhy analysized soil samples and statistical analysis. Md. Shahid designed the project and field maintenance. A.K. Nayak contributed to the development of key concepts and paper writing. All co-authors contributed to the manuscript by discussion, writing, and comments.

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Data availability

All data generated for this manuscript are included within the text and tables.

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Conflict of interest

The authors declare no competing interests.

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Figures

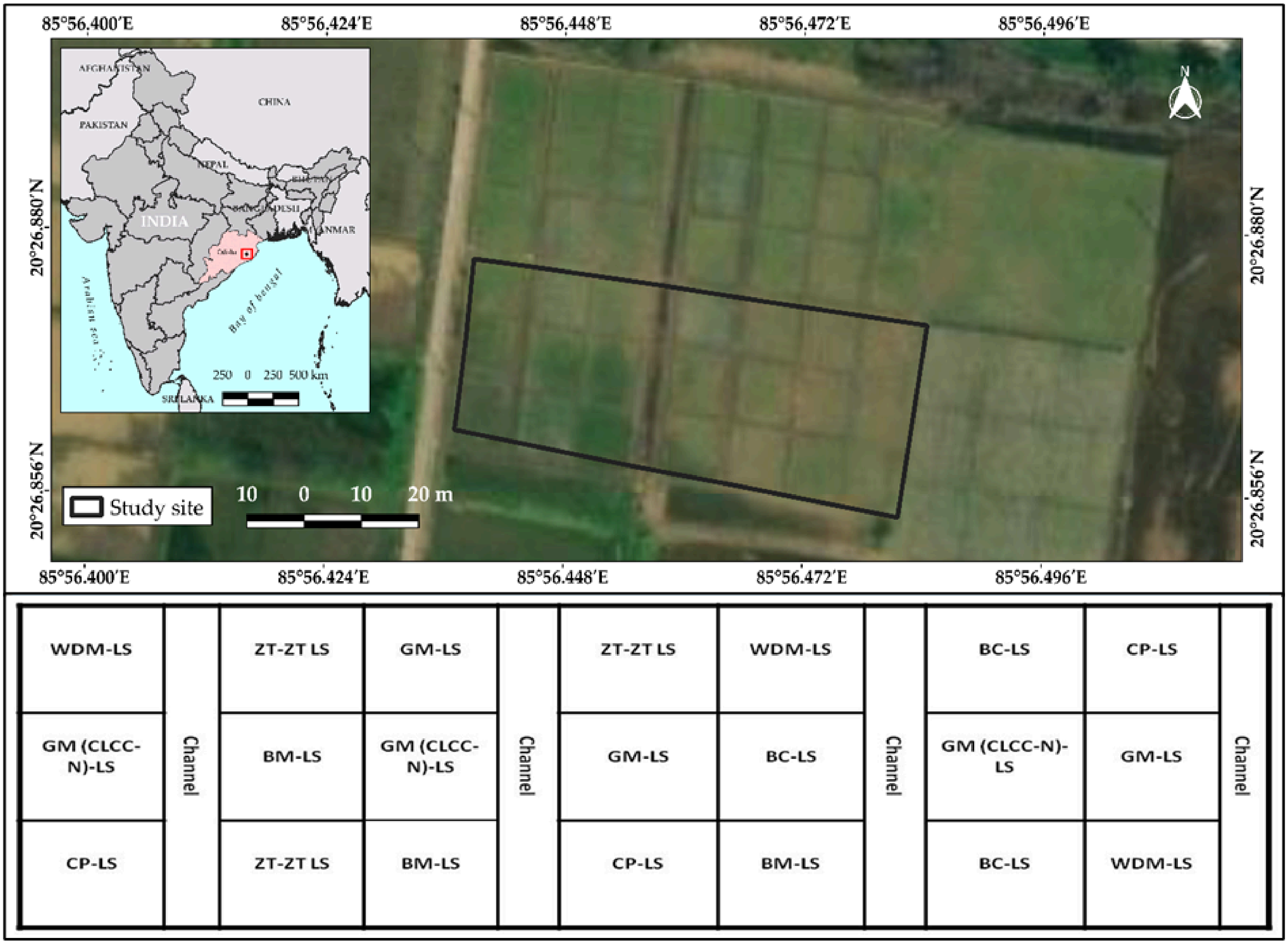

Figure 1

Location map, study site along with field layout of the experiment.

[Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram]

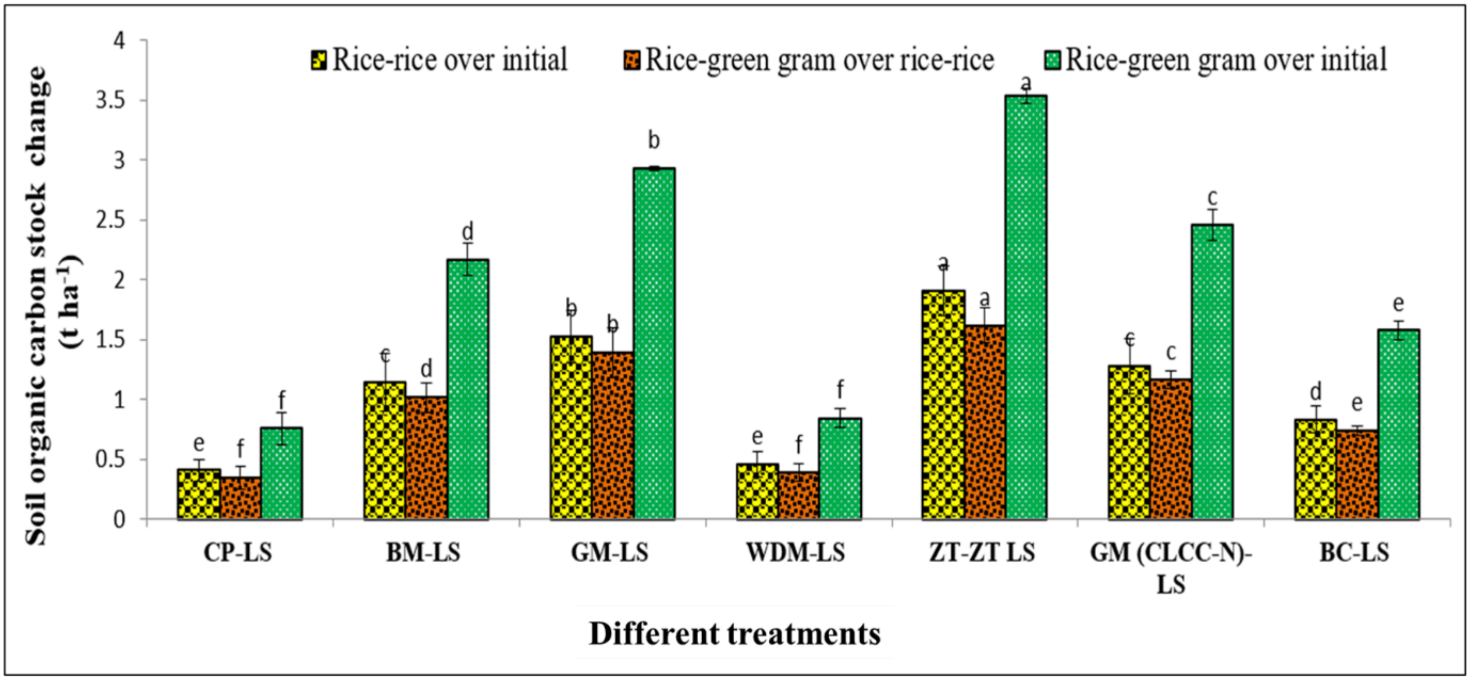

Figure 2

Soil organic carbon (SOC) stock change in two cropping systems under different RCTs (rice-rice over initial, rice-green gram over rice-rice and rice-green gram over initial).

[Note: vertical bars represent standard error for three replicates. In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram]

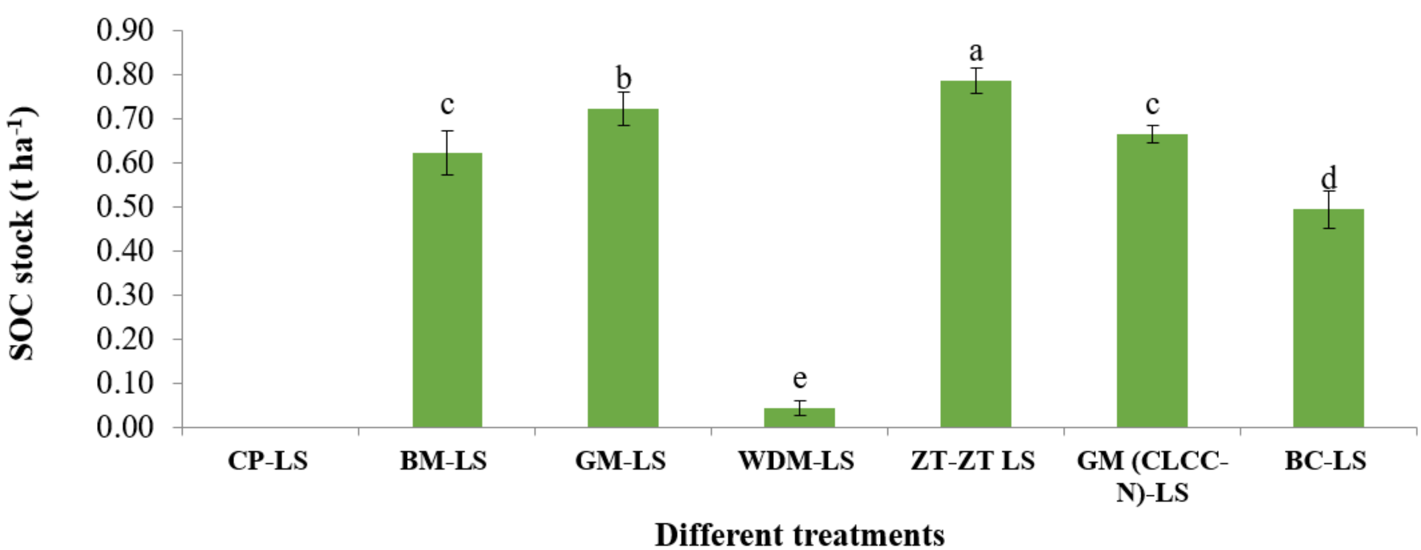

Figure 3

Soil organic carbon (SOC) stock change in rice-rice cropping system under different RCTs over conventional practice.

[Note: vertical bars represent standard error for three replicates. In each column the mean values followed by common letters are not significantly different (p≤ 0.05) between treatments by Duncan's multiple range test (DMRT). Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram]

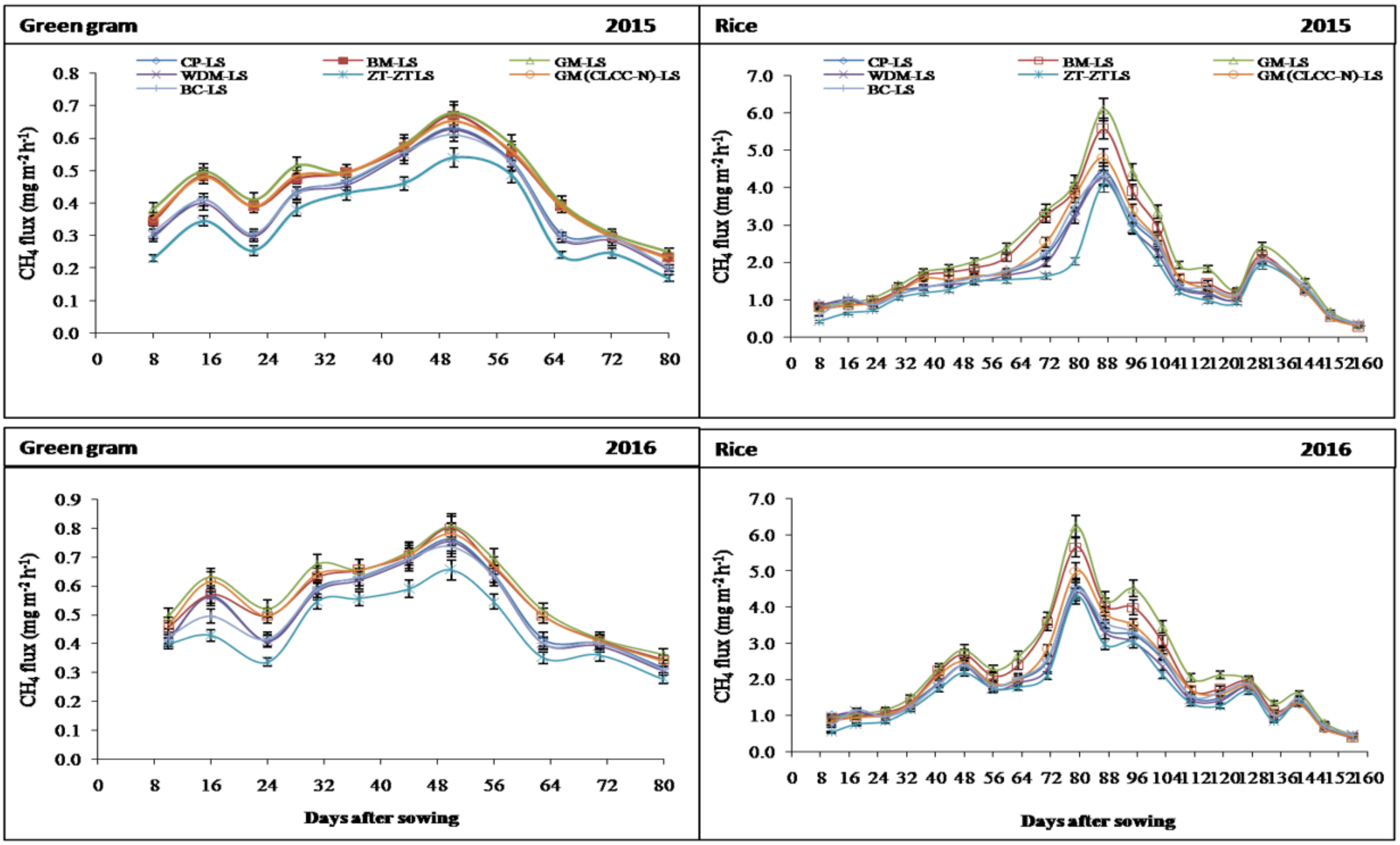

Figure 4

Methane flux in different resource conservation treatments under green gram and rice during 2015 and 2016.

[Note: vertical bars represent standard error for three replicates. Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram]

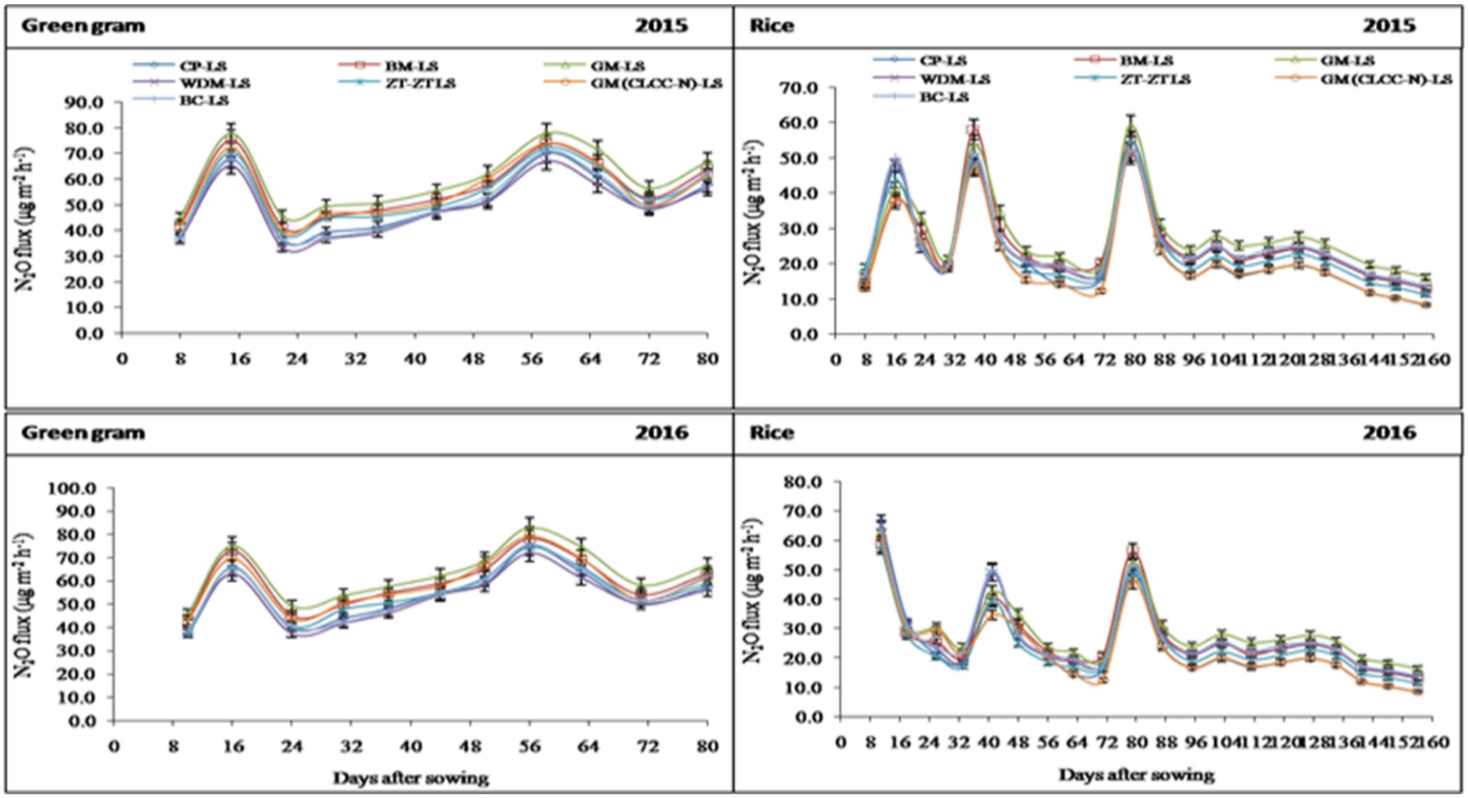

Figure 5

Nitrous oxide flux in different resource conservation treatments under green gram and rice during 2015 and 2016.

[Note: vertical bars represent standard error for three replicates. Here, CP-LS: conventional practice followed by line sowing of green gram; BM-LS: brown manuring followed by line sowing of green gram; GM-LS: green manuring followed by line sowing of green gram; WDM-LS: wet drum seeding followed by line sowing of green gram; ZT-ZT LS: zero tillage followed by zero tillage line sowing of green gram; GM-CLCC-N-LS: green manuring- customized leaf colour chart based nitrogen application followed by line sowing of green gram; BC-LS: biochar followed by line sowing of green gram]

Supplementary Files

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- Graphicalabstract.jpeg
- SupplementaryFiguresandTables.pdf