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Carbon sequestration and greenhouse gas emissions for different rice cultivation practices

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ABSTRACT

Traditional rice farming systems require large amounts of water for irrigation, labour for transplanting culms and tending fields, and therefore, emit large amounts of greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Adopting alternative rice farming practices could reduce greenhouse gas emissions and increase carbon (C) sequestration. In this study, an on-site field experiment was conducted to assess the contribution of carbon by farm operations involved in the three types of rice cultivation practices: conventional (CVN), the system of rice intensification (SRI), and zero-tillage (ZTL). The study was aimed to examine the carbon indices under three different rice cultivation methods to assess the ecosystem services and disservices associated with carbon sequestration and emission. Results showed that fertilizer application significantly contributed to GWP among the three cultivations. In the CVN and ZTL plots, the GWP was higher for CH_4 and N_2O. However, all three cultivation strategies acted as carbon sinks, with SRI cultivation yielding the highest sequestration values. The lower CF, higher CS, and higher CER values were obtained for SRI field plots than the other two cultivation practices. The ratio between ecosystem services and disservices in terms of US$ was highest for SRI, followed by ZTL and CVN cultivations. In summary, sustainable agriculture could promote by applying organic manure in the context of SRI cultivation in the water-scarce zones and ZTL cultivation in the tropical upland zones, where such cultivation is not yet practised. Not only will this increase net carbon sequestration, but it will also benefit farmers soon in terms of yield.

1. Introduction

Rice (*Oryza sativa*) cultivation worldwide is a probable greenhouse gas (GHG) emission source. About 10–12 % of global anthropogenic emissions come from methane (52 %) and nitrous oxide (84 %) (IPCC, 2014; Smith et al., 2007). Total GHG emissions from fields are the sum of direct emissions from cropland soils and indirect emissions from fertilizers, pesticides, the operation of machines and irrigation (IPCC, 2014). The production, formulation, storage, transportation and use of agricultural equipment result in the burning of fossil fuels and the use of alternative energy sources, which entail the production of carbon dioxide (CO_2) and other greenhouse gases, with negative impacts on the environment (Lal, 2004). CO_2 emission is seen as the linchpin, as its atmospheric concentration has risen by an alarming 41 % over 164 years. It corresponds to the increase in global mean temperature (Etheridge et al., 1996; Tans and Keeling, 2014). One of the promising approaches to mitigating the unforeseen risks caused by the atmospheric abundance of CO_2 and other greenhouse gases is to sequester carbon in the permanent pools of soil layers (Kerr, 2007).

Abbreviations: AL, Amount of individual agricultural input (kg^{-1} ha^{-1} crop season^{-1} or kWh^{-1} ha^{-1} crop season^{-1}); B_c, Total fixed C in biomass (kg CO_2-eq ha^{-1} crop season^{-1}); BD, Bulk density; B_{grain}, Grain yield, kg ha^{-1} crop season^{-1}; B_{root}, Root biomass, kg ha^{-1} crop season^{-1}; B_{shoot}, Shoot biomass, kg ha^{-1} crop season^{-1}; B_{total}, Total carbon in biomass of rice (Grain + straw + root biomass); *CER*, Carbon efficiency ratio; CF, Carbon footprint; C_f, Average cost of afforestation in India (US $t^{-1} CO_2); C_{ndcf}, Net direct CO_2 fixed (kg CO_2-eq ha^{-1} crop season^{-1}); C_o, Carbon output; CS, Carbon sustainability index; C_t, Indian C tax; E_{CO2}, Direct CO_2 emissions from paddy soils and plant respiration (kg CO_2-eq ha^{-1} crop season^{-1}).; E_{DIS}, Monetary value of disservice (US $ ha^{-1}); EF, GHG emission factor of individual agricultural input (kg CO_2 eq^{-1} kg or kg CO_2 eq^{-1} kWh).; E_{GHG}, Total amount of equivalent CO_2 emission (kg CO_2 eq ha^{-1}); E_{input}, Total C-eq emissions induced by agricultural inputs (kg CO_2-eq ha^{-1} crop season^{-1}).; EM_{CH4}, On-site seasonal farm emission of CH_4 (kg ha^{-1}); EM_{N2O}, Sum total of on-site seasonal farm emission of N_2O (kg ha^{-1}) and the indirect N_2O emission; $E_{N\text{-}indirect}$, Amount of nitrogen lost due to leaching and volatization process (kg N ha^{-1}).; E_{NL}, IPCC emission factor for leached nitrogen (kg N_2O-N ha^{-1}); E_{NV}, IPCC emission factor for volatilization (kg N_2O-N kg^{-1} NH_3-N); E_{SER}, Ecosystem service values of C sequestration (US $ ha^{-1}); E_{tot}, Total emission is the sum of E_{input} and E_{GHG}.; *GY*, Rice grain yield (kg ha^{-1}); GY_C, Grain yield of rice (in terms of C); *NL*, Amount of nitrogen lost through the process of leaching (kg N ha^{-1}); *NV*, Amount of ammonia emitted from fertilizer application (kg N ha^{-1}); SD, Soil depth; SOC, Soil organic carbon; SOCS, SOC stock (kg ha^{-1}).

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Rice fields act as necessary carbon (C) sinks and have immense potential to store large amounts of resilient carbon in all terrestrial ecosystems (Liu et al., 2006; Stern et al., 2007; Xie et al., 2007a, b). McConkey et al., 1999 suggested that for every 3.7 kg of CO_2 removed from the atmosphere, 1 kg of soil organic carbon (SOC) is sequestered in the soil. Carbon sequestration is considered one of the primary ecosystem services obtained from agroecosystems (Costanza et al., 1997). The mode of carbon sequestration in agroecosystems occurs through soil-fixed carbon through crop residues and soil organic carbon gains (SOC) (Palm et al., 2014).

Therefore, carbon fluxes in agroecosystems involve carbon emissions and carbon sequestration. A holistic approach to understanding carbon fluxes was made through the joint assessment of carbon analysis indices and ecosystem services of carbon sequestration. Direct emission of greenhouse gases, especially CH_4 and N_2O, from agro-ecosystems has long been used as a traditional indicator of environmental impact. Recently, however, researchers have broken new ground to determine the efficiency and sustainability of different rice-growing techniques. The carbon budget and the sustainability of other cultivation techniques are monitored using the Carbon Footprint (CF) as the leading indicator (Farag et al., 2018). The sum of the total GHG emissions (both direct and indirect) of a production system forms the carbon footprint (CF), measured in CO_2 equivalents (CO_2-eq) (ISO, 2018). The Carbon Sustainability Index (CS) and the Carbon Efficiency Ratio (CER) have become ideal tools for assessing the impact of agricultural activities on the environment (Weinheimer et al., 2010). It tries to develop a climate-friendly consumption policy and measures to reduce GHG emissions from the farming sector (Ponsioen and Blonk, 2012; Yan et al., 2015). Minimizing carbon costs and maximizing ecosystem services of carbon sequestration of farm products are the research gaps in the current scenario (Williams and Wikström, 2011).

The system of Rice Intensification (SRI) and Zero-Tillage (ZTL) are considered advanced rice cultivation techniques over conventional (CVN) due to their multiple advantages (Batuwitage, 2002). Previous research on SRI farming techniques addressed water use efficiency; socio-economic structure of farmers (Sinha and Talati, 2007), nutrient use efficiency, crop rotation effect (Kumar et al., 2020), water productivity and mitigation of global warming (Alam et al., 2020), transplant at different phyllochron stages (Biswas et al., 2021), energy efficiency (Nirmala et al., 2021), tillage effect (Kar et al., 2021), farm activities in SRI (Meesala and Rasala, 2022), weed management (Nazir et al., 2022). The latest research on carbon sequestration and emission concerning ZTL include residue management practice (Kumar et al., 2022) and fertigation techniques in the rice field (Juhi et al., 2022). The three cultivation techniques (CVN, SRI, ZTL) differ in several factors (viz., fertilizer application, tillage operation, irrigation management, seedbed preparation, transplantation of seedlings etc.). CVN, or conventional cultivation technique, is India's most widely used rice cultivation technique. Here, seedbed and main plots are treated with inorganic fertilizers (N, P, K at recommended dosage). The main fields are thoroughly tilled, and rice culms (5–6 seedlings) of 25–30 days old are transplanted randomly per hill in the main plot. The SRI and ZTL practices are alternate wetting and drying technique. The soils are not flooded continuously and drained at regular intervals. The seedbed and the main plot are both treated with organic fertilizers under SRI. The main fields are tilled, and a 10–15 days old seedling (single) or 2 to 3 phyllochron stage seedlings are transplanted singly per hill at 25×25 cm square grid pattern. In the ZTL, there is no seedbed, main field plots are not tilled, and direct seeding of germinated rice seeds is sown with the help of a rice grain planter machine (Thakur et al., 2010). The carbon indices such as carbon footprint, carbon sustainability index and carbon efficiency ratio, as well as carbon sequestration, are some of the lesser explored areas of research. They could be considered metrics to understand the carbon balance of the agricultural system. It could be hypothesized that improved conservation and sustainable agriculture would minimize carbon costs and enhance economic viability. To validate the hypothesis, the present research aimed to analyze the carbon indices among three different rice cultivation techniques and assess the ecosystem services and disservices associated with carbon sequestration.

2. Literature review

Sinha and Talati (2007) investigated the impact of SRI on farmers in West Bengal, India. They discovered that SRI had higher net returns than the traditional system. Alam et al. (2020) used a variety of newer and improved rice growing tactics to try to reduce the limits of rice agriculture, such as dwindling ground water and shrinking land area. They compared the diverse impacts of different strategies on soil health, agricultural and water productivity, and the ability to mitigate global warming. They noted that no single cultivation approach could be proven to be superior. Instead, efforts should be made to identify the most appropriate technique for each agro-climate, local population, soil structure, and farm type. Later, Biswas et al. (2021) used the Agricultural Production Systems Simulator (APSIM)-Oryza crop model to assess the effects of alternative transplanting dates on rice water consumption under SRI agriculture. They used the model to simulate consumption water footprints (CWFs), a metric that measures how much water rice uses. They demonstrated the advantages of early rice transplantation and higher yields in SRI with minimal farm operations. Meesala and Rasala (2022) provide a modern view of the potential of SRI cultivation for policy-making from an Indian perspective. SRI approaches have been evaluated in terms of their impact on farm input costs, plant growth characteristics, as well as social and economic effects on farmers. They noted that farmers using SRI techniques during cultivation experienced higher yields and net returns relative to their total expenditure. Nazir et al. (2022) tested weed management methods using SRI, conventional, and direct-seeding cultivation techniques. They used a variety of herbicides to improve the application rates to increase rice grain yields while reducing the potential of weeds to remove nutrients.

West and Marland (2002) studied rice cultivation management practices, such as pesticide use, irrigation, and farm machinery, to determine the carbon sequestration capacity of rice fields and net CO_2 emissions. Field plots without any form of tillage activity had lower CO_2 emissions and higher carbon sequestration than plots with conventional tillage. Juhi et al. (2022) used fertigation strategies to boost soil organic carbon pools and yields in ZTL rice cultivation. Kumar et al. (2022) conducted a long-term field experiment in East India to reduce the carbon footprint of rice cultivation. They compared traditionally transplanted rice to direct-seeded rice with two distinct tillage operations (ploughed and no-till) and residue management. They discovered that residue management with pulse-based crops was the most energy efficient, had the smallest carbon footprint, and had the highest economic returns.

Das and Adhya (2014) investigated how different mixtures of chemical and organic manure affected GHG emissions in rice fields. They concluded that an optimum management technique could mitigate CH_4 and N_2O emissions from rice fields. Biochar treatment in Chinese rice fields was employed by Liu et al. (2016) as a means of preventing global warming. According to the researchers, the patch made from corn straw and modified with biochar had the lowest GWP. Xu et al. (2019a, b) conducted another experiment using biochar, and their findings were consistent with the previous one, lowering carbon footprint with biochar application in study sites. Jiang et al. (2019) improved nitrogen fertilizer rates in Chinese rice fields. They discovered that ecosystem service values changed from positive to negative, showing that rice fields served as a net carbon sink at low nitrogen rates and a net carbon source at higher nitrogen rates. Yan et al. (2022) showed that the use of cattle manure along with proper water management could lead to the accumulation of soil organic carbon in agricultural soils. Rob et al. (2022) noted yield increase in addition to carbon sequestration with the application of organic manure in the rye fields of Germany.

3. Methods

3.1. Site description

The field trials were conducted between 2018 and 2020 with three crop growing seasons for Kharif, and three crop growing seasons for Rabi. The three-year experiment was carried out at Crop Research and Seed Multiplication Farm (CRSMF); (Latitude: 23°14′58.04″N and 23°15′19.44″N and Longitude: 87°50′34.29″E and 87°50′43.95″E), Burdwan, India (Fig. 1). The baseline study of the soil indicated silt-loam type texture consisting of 21.53 ± 2.01 % sand, 37.34 ± 3.11 % silt and 25.51 ± 3.02 % clay. The average bulk density, particle density

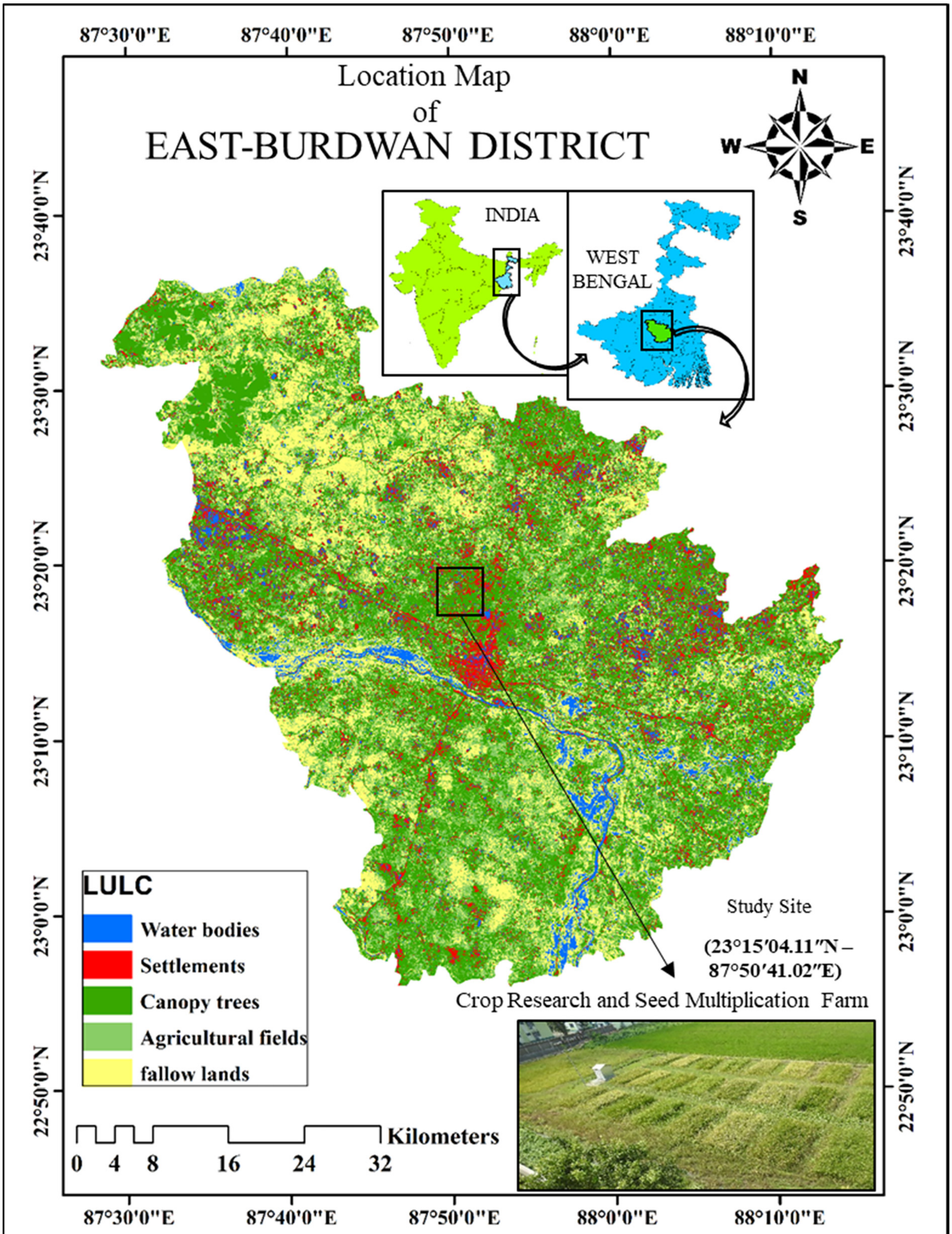

Fig. 1. Study site at Crop Research and Seed Multiplication Farm, Burdwan, India.

and porosity at 0-15 cm depth ranged between 1.01 and 1.12 g cm^{-3}, between 2.09 and 2.55 g cm^{-3} and between 50 and 60 %, respectively. The average soil pH and conductivity (1:10 soil-water suspension) were approximately 6.90 and 0.26, respectively (Jackson, 1972). Available phosphorus and available potassium (kg ha^{-1}) were estimated using the Olsen method (Olsen, 1954) and the flame photometer method (Black et al., 1965), respectively. The available phosphorus and potassium concentration in the trial plots was 52.4 kg ha^{-1} and 429.75 kg ha^{-1}, respectively. DTPA-extractable micronutrients such as available zinc, boron, sulfur and copper are important for rice growth. Their average concentrations were 5.25 ppm, 0.56 ppm, 16.27 ppm and 3.29 ppm, respectively.

3.2. Experimental design and cultivation practices

Four widely used varieties of rice, viz. var. MTU 1010, var. IET 4786, var. IET 17430 and var. IET 9947 were cultivated under SRI, CVN and ZTL methods of cultivation. In this region, SRI and CVN rice cultivation are practised in Rabi (sowing: January–February; harvest: March–April) and Kharif (sowing: July–August; harvest: October–November) seasons. ZTL is only practised in the Kharif season as soil temperature, and moisture do not support the germination of directly-seeded rice seeds. All four types of rice have a limited lifespan of 110 to 120 days. They were either semi-dwarf or dwarf grains. Sheath rot, brown spot, bacterial leaf blight, sheath blight, panicle, and leaf blast were among the diseases to which all four kinds were relatively resistant. Additionally, they resisted pest attacks from species, including the shoot borer and brown plant hopper (Gangopadhyay et al., 2022).

The water regime is an essential factor concerning three types of cultivation. Continuous flooding irrigation was used to manage conventional farming (CVN). The rice culms were planted under CVN cultivation in a flooded field with 5–7 cm of standing water. For the duration of the vegetative stage (S2), a water depth of 5–6 cm was maintained. Plots were maintained flooded with a thin layer of 1–2 cm of water after the panicle commencement stage (S3). The fields were drained ten to fifteen days before the harvest stage (S4).

In contrast, intermittent irrigation management was practised for both the System of Rice Intensification (SRI) and Zero tillage (ZTL). In the SRI plots, water was applied to the main field plots 5 days before transplant, and the water used was sufficient to moisten without flooding the plots thoroughly. The alternate Wetting and Drying (AWD) cycle was employed with shallow standing water (1–2 cm water depth) during irrigation, altered with the dry period. The water was drained 7 days after ponded water's disappearance throughout the vegetative growth period (S2). After panicle initiation (S3), plots were flooded with a thin layer of 1–2 cm water. The fields were drained 15 days before harvest (S4).

The direct seeding of rice in the ZTL plots depends upon the rainfall the main plots receive (S1 stage). The average rainfall at the time of transplant of seeds was 3.07 mm day^{-1} in the Kharif seasons of the three-year study period. The period corresponds to the sowing of seeds in the seed-beds of CVN and SRI cultivations. Later, the entire process of water regime management was maintained following the SRI cultivation.

The Randomized Complete Block Design (RBD) was used to arrange four replicates (6 m × 3 m) of rice varieties for the three cultivation practices (Sekhar et al., 2019). The rice seeds of the four types were soaked in water for 1 day. Seeds were sown separately in SRI seedbeds and conventional seedbeds. The seedbed preparation was done with organic manure and inorganic fertilizers for the SRI and CVN, respectively. The Rice Grain Planter machine was used for no-till rice cultivation or ZTL. A brief comparison of the three cultivation techniques is shown in Table 1. Rice samples and rhizosphere soil were collected every 10 days throughout the growing season. Rice straw, root, and shoot were oven dried (at 60 °C to constant weight) and the agronomic parameters such as plant height, tiller count, root length, root biomass and aboveground dry weight at successive phenological stages were calculated using weighing balance. After completion of the last harvest, yield attributes such as panicle number, spikelet count per panicle, percentage of filled spikelets, 1000 grain weight and grain yield were also analyzed (Ao et al., 2010; Garnett et al., 2009; Han et al., 2015).

3.3. Data collection and analysis

3.3.1. Direct measurement of GHG emissions

Weekly measurements of greenhouse gases were taken throughout the study using a greenhouse gas analyzer (HORIBA JAPAN, VA-5000-VS-5000) and the static glass chamber method. On the soil's surface, 45 × 45 × 150 cm glass chambers were positioned. At intervals of 30 min, sampling was carried out in triplicate. The mean daily flux rate of GHGs (CO_2, CH_4, and N_2O) corresponds to the emission from the static chambers at 9:00–11:00, 15:00–17:00, and 21:00–23:00.

The greenhouse gas fluxes were measured based on the rates of gas concentration change per time unit and headspace volume of the

Table 1
Comparison of the three cultivation techniques (CVN-conventional, SRI-System of Rice Intensification, and ZTL-Zero-tillage) adopted for the experiment in the Crop Research and Seed Multiplication Farm.

Cultivation techniques	CVN	ZTL	SRI
Seed application rate in seedbed	50 kg ha^{-1}	30 kg ha^{-1}	5 kg ha^{-1}
Tillage in main plot	Tilled	No-Tilled	Tilled
Seedbed preparation	Present	Absent	Present
Seedling age transplantation	25–30 days old seedling	Direct-seeding.	10–15-days old seedling (single) or 2 to 3 phyllochron stage seedlings
Planting space and density	5–6 seedling per hill in random manner	Freshly germinated seeds were planted using Rice grain Planter machine.	1 seedling per hill was transplanted in a square pattern of 25 × 25 cm
Water management	The rice culms were transplanted in completely flooded field with 5–7 cm of standing water. A water depth of 5–6 cm was maintained throughout the vegetative stage. After panicle initiation, plots were kept flooded with a thin layer of 1–2 cm of water. The plots were drained 10–15 days before harvest.	In case of SRI and ZTL plots, water was applied to the field plots 5 days prior to transplant. The amount of water applied was just sufficient to completely moisten without flooding the plots. Alternate wetting and drying (AWD) cycle was employed with shallow standing water during wet periods altered with dry period. The plots were irrigated (1–2 cm water depth) and water was drained at a 7 days interval after the disappearance of ponded water throughout the vegetative growth period. After panicle initiation, plots were kept flooded with a thin layer of 1–2 cm of water. The plots were drained 15 days before harvest.	
Nutrient management	Chemical fertilizers (N, P and K) at a rate of 60:30:30 kg ha^{-1} were applied in the CVN and ZTL plots by three separate applications at the basal, active tillering and panicle initiation stages.		Organic fertilizer (cow dung manure: vermicompost:1:1) was applied to the SRI plots in an amount of 5 t ha^{-1}.

chamber per soil area; the air temperatures were measured inside the closed chamber during gas sampling. The GHG fluxes were estimated using equation (Eq. (1)) (Bulmer et al., 2017).

$$GHGflux = \frac{\left(\frac{dG}{dt}\right) \times V \times P}{(R \times T \times A)} \quad (1)$$

where *GHG flux* is the CO_2 flux (mmol m^{-2} h^{-1}), CH_4 flux (μmol m^{-2} h^{-1}), and N_2O flux (μmol m^{-2} h^{-1}), d*G*/dt is the slope of a linear regression between GHG concentrations and deployment times (ppmv h^{-1}), *V* is the headspace volume (L) of the static chamber, *P* is the barometric pressure and equals to 1 atm, *R* is the ideal gas constant (8.205746×10^{-5} atm m^2 K^{-1} mol^{-1}), *T* is the average air temperature (°K) inside the closed chamber at each time of measurement, and *A* is the cross-sectional area (m^2) of the bottom of the static chamber. In the present study, the unit of GHGs was converted to mg m^{-2} h^{-1}.

3.3.2. GHG emissions associated with farm operations

The carbon dioxide equivalent (CO_2-eq) emissions related to farm inputs were estimated using the following equation (Eq. (2)):

$$E_{input} = \sum AL \times EF \quad (2)$$

where, E_{input} is the sum of carbon dioxide equivalent emissions induced by agricultural inputs (kg CO_2-eq ha^{-1} crop $season^{-1}$). *AL* is the quantity of individual agricultural input (kg^{-1} ha^{-1} crop $season^{-1}$ or kWh^{-1} ha^{-1} crop $season^{-1}$), *EF* is the specific GHG emission factor of individual agricultural input when it was manufactured and/or applied (kg CO_2-eq^{-1} kg or kg CO_2-eq^{-1} kWh). The CO_2-eq coefficient factors for GHG emissions from agricultural inputs are shown in Table 2.

Some nitrogen is lost through leaching and volatilization from the nitrogen-based inorganic fertilizers in CVN and ZTL and organic manure in SRI. Fields under CVN and ZTL cultivation with inorganic N treatment leached a higher proportion of applied N (0.78 %) than fields under SRI cultivation with organic manure (0.46 %) (Meng et al., 2014). The fraction of N lost through the volatilization process was assumed to be 10 % of the applied inorganic and organic amendments (IPCC, 2006). To estimate the contribution of N_2O, the proportion of leached and volatilized N was multiplied by their respective emission factors (IPCC, 2006) (Eq. (3)).

$$E_{N-indirect} = (NL \times ENL + NV \times ENV) \times \frac{44}{28} \quad (3)$$

where, *NL* = Amount of nitrogen lost through the process of leaching (kg N/ha), E_{NL} = IPCC emission factor for leached nitrogen (0.0075 kg N_2O-N/ha), *NV* = Amount of ammonia emitted from fertilizer application, E_{NV} = IPCC emission factor for volatilization (0.01 kg N_2O-N/kg NH_3-N).

3.3.3. Carbon budget

In carbon budget analysis, the first step is to estimate the carbon footprint (CF). For this estimation, a protocol was designed to set the system boundaries (Chen et al., 2020). In the current research, the system boundary included all agricultural activities throughout the rice growing season from seed to harvest. The CF of rice production was assessed by having total GHG emissions from farm inputs and non-CO_2 emissions (CH_4 and N_2O) from paddy fields. It includes the direct emissions of greenhouse gases throughout the life cycle of crop production as well as the indirect greenhouse gas emissions caused by the high hidden carbon costs from various inputs of agricultural material production, packaging and transport of the inputs (Gan et al., 2012). CO_2 emissions emitted directly from rice soils were not included in the CF calculation because the carbon sequestered by plant biomass is higher than their emission (IPCC, 2014).

The carbon budget under different farming practices was estimated by indices such as CF, Carbon Sustainability Index (CS), Carbon Efficiency Ratio (CER). The activities within the system boundary have been grouped into agricultural inputs and outputs. Agricultural resources include raw materials or fertilizers, seeds, diesel, pesticides and electricity. Farm outputs include GHG emissions from paddy fields (CH_4 and N_2O) and rice biomass (grain yield, aboveground and belowground biomass).

3.3.3.1. Carbon footprint (CF). The carbon footprint is the aggregation of the total emissions of greenhouse gases (GHGs) from different sources and reactions of a given product or system from its manufacture to its final destination. CO_2 equivalent (CO_2-eq) is used to represent CH_4 and N_2O. IPCC (2014) proposed values for individual greenhouse gases' global warming potential (GWP). It is expressed in carbon dioxide equivalents (CO_2eq). The IPCC (2014) defines CO_2eq as the concentration of CO_2 that would produce the same radiative forcing as a given mixture of CO_2 and other forcing components over 100 years. CO_2 has a global warming potential of 1, N_2O has a global warming potential of 298, while CH_4 has a global warming potential of 34 (Oo et al., 2018).

In the present study, the CF estimation was performed in two tiers: Tier 1 is the Global Warming Potential (GWP) in kg CO_2 equivalent h^{-1} of all on-site direct non-CO_2 emissions from rice field soils (Eq. (4)). Tier 2 consists of indirect emissions resulting from farm inputs and is calculated (Eq. (2)).

$$E_{GHG} = EM_{CH4} \times 34 + EM_{N2O} \times 298 \quad (4)$$

where, EM_{CH4} is the on-site seasonal farm emission of CH_4 (kg ha^{-1}).

EM_{N2O} is the sum total of on-site seasonal farm emission of N_2O (kg ha^{-1}), and the indirect N_2O emission calculated by Eq. 2.34 and 298 are the GWPs for CH_4 and N_2O, respectively, with respect to CO_2 over a 100-yr time horizon.

Table 2
Farm input categories and emission factors of GHG emissions under Conventional (CVN), System of Rice Intensification (SRI) and Zero-Tillage (ZTL)used in the study.

Farm input categories	Items	Units	Emission factors	References	Agricultural inputs						
					Unit	Application rate					
						CVN		SRI		ZTL	
						Seedbed	Main field	Seedbed	Main field	Seedbed	Main field
Fertilizers	Urea	kg CO_2-eq kg^{-1} N	7.48	Chen et al., 2015	kg ha^{-1}	50	60	–		–	60
	Superphosphate	kg CO_2-eq kg^{-1} P_2O_5	0.72	Chen et al., 2015	kg ha^{-1}	50	30	–		–	30
	Potassium chloride	kg CO_2-eq kg^{-1} K_2O	0.62	Chen et al., 2015	kg ha^{-1}	50	30	–		–	30
	Organic fertilizer	kg CO_2-eq kg^{-1}	0.22	Guo and Gifford, 2002	kg ha^{-1}	–		2500	5000	–	
Seeds		kg CO_2-eq kg^{-1}	1.84	Xue et al., 2014	kg ha^{-1}	50		5		30	
Diesel		kg CO_2-eq kg^{-1}	3.21	Zhang et al., 2013	kg ha^{-1}	3.5		3.5		2	
Herbicide		kg CO_2-eq kg^{-1}	6.3	Lal, 2004	kg ha^{-1}	4.5		4.5		4.5	
Electricity		kg CO_2-eq kWh^{-1}	1.12	Zhang et al., 2013	kWh ha^{-1}	1894		1003		1003	

CF from agriculture was estimated through the following equation (Eq. (5)), (Lal, 2004, Pandey et al., 2014; Xu et al., 2019a, b).

$$CF = \frac{E\ tot}{GY} \tag{5}$$

where, total emission (E_{tot}) is the sum of E_{input} and E_{GHG}.GY = the rice grain yield (kg ha^{-1}).

3.3.3.2. Carbon Sustainability Index (CS). Carbon Sustainability index for each year was calculated following Lal (2004), Eq. (6).

$$CS = \frac{Co - Ci}{Ci} \tag{6}$$

where, CS is the carbon sustainability index, C_o is carbon output, and C_i is carbon input. The C_o is the C content of the total biomass of the rice plants and the C-eq emissions of $CH_4$and N_2O (E_{GHG}). The C_i is the C-eq of all the agricultural inputs required for rice cultivation (E_{input}).

3.3.3.3. Carbon efficiency ratio (CER). The CER is defined as the ratio of grain yield of rice (in terms of C) by E_{GHG} in terms of carbon equivalent (Eq. (7) and Eq. (8)) (Bhatia et al., 2010).

$$CER = \frac{GY_C}{E_{GHG}} \tag{7}$$

$$GY_C = GY \times \frac{2}{5} \tag{8}$$

where GY_C is the grain yield of rice (in terms of C), GY is the rice grain yield (kg ha^{-1}), and 2/5 is the C content of total biomass (Dubey and Lal, 2009).

3.3.3.4. Soil organic carbon (SOC). Air-dried soil samples were passed through a 0.15-mm sieve. The concentration of SOC was analyzed using the modified Walkley Black method. SOC stock (SOCS) (kg ha^{-1}) was calculated as following Guo and Gifford (2002), Eq. (9).

$$\mathrm{SOCS}\left(\mathrm{kg\ ha^{-1}}\right) = \mathrm{SOC}\ (\%) \times \mathrm{BD}\ (\mathrm{g/cm3}) \times \mathrm{SD}\ (\mathrm{cm}) \times 1000 \tag{9}$$

where, BD is the bulk density, SD is the soil depth. The difference at the start and end of the SOCS value during Rabi and Kharif was used to estimate the seasonal change in the SOCS (ΔSOCS), Eq. (10).

$$\Delta\mathrm{SOCS} = (\mathrm{SOCS\ initial} - \mathrm{SOCS\ final}) \times \left(\frac{44}{12}\right) \tag{10}$$

3.3.3.5. Carbon sequestration (C_{seq}). Carbon sequestration was estimated using the following equation (Eq. (11))

$$C_{\mathrm{seq}} = C_{\mathrm{ndcf}} + \Delta\mathrm{SOCS} - E_{\mathrm{input}} \tag{11}$$

where, C_{ndcf} is the net direct CO_2 fixed (kg CO_2-eq ha^{-1} crop season^{-1}) in rice agro-ecosystems, which was calculated using the equation (Eq. (12)).

$$C_{\mathrm{ndcf}} = \mathrm{Bc} - E_{\mathrm{CO2}} \tag{12}$$

where Bc is total fixed carbon in biomass (kg CO_2-eq ha^{-1} crop season^{-1}) (Eq. (13)) and E_{CO2} is the direct CO_2 emissions from paddy soils and plant respiration (kg CO_2-eq ha^{-1} crop season^{-1}). The E_{CO2} was measured directly from the rice fields using GHG analyzer.

$$Bc = B_{total} \times \frac{2}{5} \times \frac{44}{12} \tag{13}$$

Total carbon in rice biomass (B_{total}) is the total amount of fixed carbon in harvested grain, straw biomass, and root biomass (Dubey and Lal, 2009), Eq. (14).

$$B_{\mathrm{total}} = B_{grain} + B_{shoot} + B_{root} \tag{14}$$

where, B_{grain} (grain yield, kg ha^{-1} crop season^{-1}), B_{shoot} (shoot biomass, kg ha^{-1} crop season^{-1}), and B_{root} (root biomass, kg ha^{-1} crop season^{-1}); 2/5 is the conversion coefficient for estimation of C content from the total biomass of plants (Dubey and Lal, 2009); and 44/12 is the coefficient for conversion of C to CO_2.

3.4. Ecosystem service of carbon sequestration

The monetary value of ecosystem services of C sequestration (E_{SER}) was determined by the Indian carbon tax and the afforestation cost in India (Xiao et al., 2005), Eq. (15)

$$E_{SER} = \frac{1}{2}\left(C_f + C_t\right) \times C_{seq} \tag{15}$$

where, E_{SER} represents the ecosystem service values of C sequestration (US \$/ha) and C_f indicates the average cost of afforestation in India (US \$ 42.17/t CO_2, Ashutosh et al., 2019); C_t represents the Indian carbon tax (US\$ 5.3/t CO_2, Economic Times, 2020).

Rice fields act as a net carbon sink by offsetting the capture of more carbon from the atmosphere and emissions. If the value of the ecosystem service is positive, there is an economic gain (Heimann and Reichstein, 2008). The total GHG emissions from paddy fields (both direct emissions on site and indirect emissions from farm inputs) multiplied by the carbon tax (Ct) gave the Monetary Value of Disservice (E_{DIS}), Eq. (16) (Rasheed et al., 2021).

$$E_{DIS} = E_{tot} \times C_t \tag{16}$$

The unit conversion from kg CO_2-eq ha^{-1} to t CO_2-eq ha^{-1} was done for convenience to represent all the results in the present study.

3.5. Statistical analysis

The effects of treatment factors (cultivation practice and rice cultivars) on CF, CS, CER, SOC, C_{seq} of paddy fields were analyzed by two-way analysis of variance (ANOVA) using SPSS statistical software. Treatment mean comparisons were performed with a probability of 5 % using the post-hoc test-Duncans Multiple Range Test (DMRT).

4. Results and discussion

4.1. Emissions due to farm operations

The cumulative carbon dioxide-equivalent emission (t CO_2 – eq ha^{-1}) for all farm categories was highest for conventional cultivation (CVN) followed by System of Rice Intensification (SRI) and Zero-tillage cultivation (ZTL). Emissions from different types of farm operations were 4.78 t CO_2 – eq ha^{-1}, 3.23 t CO_2 – eq ha^{-1} and 2.53 t CO_2 – eq ha^{-1} under CVN, SRI and ZTL, respectively. The contribution of farm inputs to total carbon equivalent emissions (t CO_2-eq ha^{-1}) was 56.82 %, 55.08 % and 55.34 % under CVN, SRI and ZTL, respectively. The current study is in accord with the results of Chen et al. (2020), where a 24.6–122.2 % increase in the GHG emissions was observed as a result of nitrogen fertilization treatment (corresponding to the CVN cultivation of the present study)compared to no nitrogen fertilization treatment(corresponding in part to SRI plots of the present study). Moreover, the general pattern of these farm input components in all cultivations was in descending order across all growing seasons, such as fertilizer application followed by irrigation, fuel consumption, seeds and herbicide. The percentage share of the individual farm activities (fertilizer application, seeds, crop protection, fuel consumption, and irrigation) in the total CO_2-eq emission varied greatly depending on the cultivation method. The CO_2-eq emission caused by fertilizer application was 47.1 %, 51.7 % and 45.5 % under CVN, SRI and ZTL cultivation. Seed application contributed around 1.9 %, 0.3 % and 2.2 % under CVN, SRI and ZTL cultivation, respectively. The herbicide application contributed nearly 0.6 %, 0.9 %, 1.1 % under CVN, SRI and ZTL cultivation, respectively. Fuel economy contributed about 10.9 %, 16.1 % and 11.7 % to CVN, SRI and ZTL cultivation, respectively. For irrigation, the carbon-equivalent emission was relatively high, contributing about 39.6 %, 31.0 % and 39.5 % under CVN, SRI and ZTL cultivation, respectively (Fig. 2).

4.2. Carbon dioxide-equivalent emission (CO_2-eq emission)

The contribution of CO_2-eq GHG emissions arising directly from the field as a result of cultivation to the net CO_2-eq emissions from paddy fields varied widely. Under CVN, the contribution of CH_4 and N_2O emissions was about 37.26 % and 5.92 %, respectively. In the SRI cultivation, CH_4 and N_2O contributed approximately 34.48 % and 10.38 %, respectively. In the case of ZTL cultivation, the CH_4 and N_2O emissions released into the atmosphere were about 30.63 % and 14.02 %, respectively. In addition, it was found that the GWP for CH_4 was highest among CVN, followed by SRI and ZTL ($p < 0.05$). Over the entire investigation period, the GWP for CH_4 was 3.23 t CO_2-eq ha^{-1}, 2.05 t CO_2-eq ha^{-1} and 1.41 tCO_2-eq ha^{-1} for CVN, SRI and ZTL, respectively. In contrast, the GWP for N_2O was highest among ZTL, followed by SRI and CVN ($p < 0.05$). Over the entire study period, the GWP for N_2O was 0.46 t CO_2-eq ha^{-1}, 0.58 t CO_2-eq ha^{-1} and 0.61 t CO_2-eq ha^{-1} for CVN, SRI and ZTL, respectively. The total carbon equivalent emissions from rice fields ranged between 7.36 and 11.0 t CO_2-eq ha^{-1}, between 5.15 and 7.16 t CO_2-eq ha^{-1} and between 4.15 and 4.92 t CO_2-eq ha^{-1} under CVN, SRI and ZTL cultivation respectively. A significant difference was observed in the total carbon equivalent emissions among cultivations and varieties and are represented in Fig. 3. The seasonal average rate of GHG flux rate (mg m^{-2} h^{-1}) of CH_4, CO_2 and N_2O in Rabi and Kharif rice growing seasons during the study period are shown in Table S1 and Table S2.

It was inferred from Table S3 and S4 that cumulative emission of GHG showed the same pattern as the GHG flux of CH_4, CO_2 and N_2O, respectively. Seasonal cumulative emission of CH_4 was higher in CVN than SRI in Rabi season ($p < 0.05$). In the Kharif season, the higher emission was observed in CVN followed by SRI and ZTL. Higher cumulative emission of N_2O was observed in ZTL followed by SRI and CVN. It was observed that there was a significant difference in cumulative emission of GHGs (CH_4, CO_2 and N_2O) among the three cultivation practices (CVN, SRI, ZTL). Moreover, a significant difference in cumulative emissions among varieties was observed throughout the three-year study period (2018–2020) in cumulative CH_4 and CO_2 emissions. However, no such difference was observed in the case of cumulative N_2O emission among varieties. The total carbon dioxide equivalent emission (t CO_2-eq ha^{-1}) and total carbon sequestration (t CO_2-eq ha^{-1}) under different rice cultivation practices (CVN, SRI, ZTL) during Rabi and Kharif seasons are shown in Tables S5 and S6 respectively.

During Rabi season, only var. IET 17430 showed the lowest total carbon dioxide equivalent emission in 2018; other cultivars showed almost similar carbon dioxide equivalent emission patterns in the successive years in the CVN cultivation. However, the total carbon sequestration was higher in both IET 17430 and IET 9947 in the CVN cultivation. In the SRI, all the varieties showed no significant difference in carbon dioxide equivalent emission. However, the var. IET 9947 showed the highest sequestration ability among the varieties and IET 17430.

During the Kharif season, in the CVN cultivation, IET 4786 showed the lowest carbon dioxide equivalent emission among all the varieties during the study period. In the SRI, both IET 17430 and IET 9947 showed the lowest carbon dioxide equivalent emission. The same varieties again dominated the CO_2 sequestration ability in the same cultivation system. In the ZTL cultivation, the carbon dioxide equivalent emission and carbon dioxide sequestration showed no significant difference among varieties. Hence it could be inferred that during the Kharif season, var.

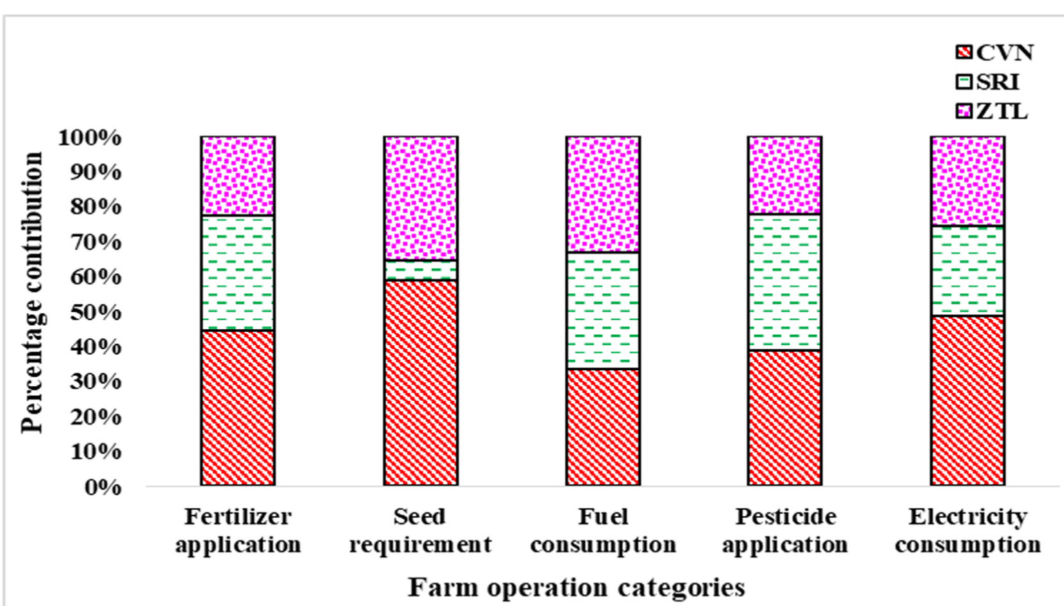

Fig. 2. Percentage contribution of different categories of farm operations (viz. fertilizer application, seed requirement, crop protection, fuel consumption, and irrigation) to the total carbon-equivalent emission (t CO_2 – eq ha^{-1}). CVN- Conventional cultivation, SRI – System of rice intensification, ZTL – Zero tillage.

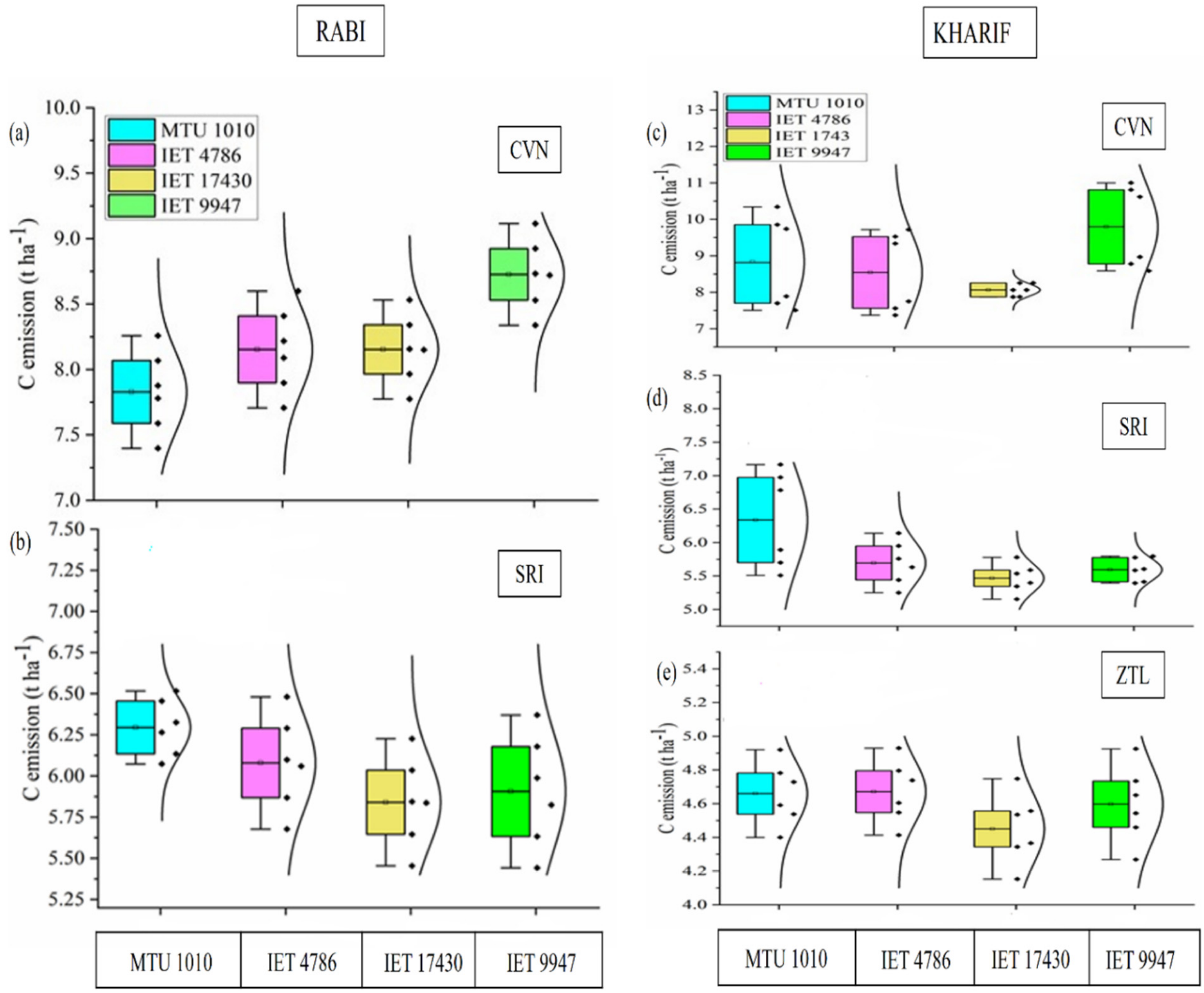

Fig. 3. Carbon-equivalent emissions (t CO_2 –eq ha^{-1}) from rice fields under three methods of cultivation (CVN- Conventional cultivation, SRI – System of rice intensification, ZTL – Zero tillage) for four rice varieties (viz. var. MTU 1010, var. IET 4786, var. IET 17430, var. IET 9947) during Rabi rice growth season (Fig. 3a-CVN and Fig. 3b-SRI) and Kharif rice growth season (Fig. 3c-CVN, Fig. 3d-SRI, Fig. 3e-ZTL. Each box plot shows the data distribution, mean and median value, data distribution curve, standard error, and box range.

IET 17430 could be the preferred rice variety in SRI cultivation. IET 4786 could be the preferred variety in the CVN cultivation, and the farmers could select any combinations for ZTL cultivation.

The present results reflect that in the CVN cultivation, the percentage contribution of CH_4 towards the total emission was higher than that of SRI followed by ZTL. In contrast, the percentage contribution of N_2O towards the total emission was higher in ZTL followed by SRI and CVN. The observations confirmed that CH_4 contributed more to the total carbon dioxide equivalent emissions from rice fields than N_2O, which immensely contributed immensely to the CF calculation. The present results are in accord with the interpretation provided by the DeNitrification–DeComposition (DNDC) model in combination with the Representative Concentration Pathway (RCP) by Chen et al. (2020). They found that $CH_4$was the main contributor to CF (43.9–58.3 % of total CF) over a 35 year prediction period from 2015 to 2050. It could be interpreted that the water regime, fertilizer application type, and tillage played a role in defining the pattern of methane production and emission from rice fields. The organic fertilizer under SRI field plots was applied at the rate of 5 t ha^{-1} at the time of main plot preparation.

The water regime of SRI fields was different from CVN fields. Throughout the vegetative stage (S2), the field plots were intermittently irrigated with wet, flooded, and drained periods. For an average 110- day variety rice, the panicle initiation starts approximately 50–55 days after transplant. Accordingly, 6–7 AWD cycles were performed within the entire vegetative stage under SRI depending upon the rainfall pattern of that year. In contrast, CVN plots had no such AWD cycles and were continuously flooded throughout the vegetative phase. Redox potential (Eh) of the soil is an essential factor for the production of CH_4 in agricultural fields. Flooding reduces the Eh of the soils of rice fields. The redox potential of the soil for the generation of CH_4 emission in the rice fields is between −100 and −200 mV (Yagi and Minami, 1990). In the present study, the Eh of the CVN field plots submerged under water was around −150 mV, which is optimum for the initiation of CH_4 production. In addition, the soil of the present study site was between 6.4 and 7.8 that helps in the emission process of CH_4 from the rice field under CVN. Frequent drainage under SRI cultivation exposed the upper surface of SRI field plots, and minimized the optimum soil conditions for CH_4 production. The penetration of oxygen to the soil facilitates the decomposition of organic matter with subsequent oxidation of CH_4 (Zhang et al., 2012; Kim et al., 2014). Hence, reduced CH_4 production was observed in the SRI and ZTL field plots. After panicle initiation to harvest, all cultivation practices had the same irrigation management (1–2 cm, water depth). The data gathered from GHG analyzer placed in the field showed a peak in CH_4 production during S3 stage in all cultivation practices. However, the peaks for SRI and ZTL cultivations did not surpass the peak showed by CVN cultivation. In addition, ZTL is a conservation farming approach without tillage. The soil was left undisturbed, resulting in a much higher bulk density. Increasing bulk density decreases the volume fraction of large pores (Kim et al., 2014). The above observations are consistent with various other studies (Cai et al., 1997; Bronson et al., 1997; Oo et al., 2018).

In paddy fields, there is always a trade-off between CH_4 production and N_2O production (Liu et al., 2010; Zschornack et al., 2016; Zhou et al., 2018). N_2O is a product of denitrification in anaerobic environments, while nitrification occurs in aerobic soils (Ball et al., 1999). Drainage converts soil conditions to aerobic, which promotes N_2O production (Granli and Bockman, 1994; Zheng et al., 2000). Flooded plots are reported to encourage nitrification and denitrification (Abao et al., 2000). Therefore, in the CVN plots, the combination of the two mechanisms (denitrification and nitrification) led to a reduced N_2O emission. In the present study, ZTL shows the highest N_2O emission among the three cultivation methods. This is consistent with the observation of Ball et al. (1999) and Vinten et al. (2002). The GWPs for CH_4 and N_2O calculated by Oo et al. (2018) concerning an Indian scenario were consistent with the available results of this study.

4.3. Carbon sequestration

Total carbon sequestration (t CO_2-eq ha^{-1}) was highest under SRI, followed by ZTL and CVN cultivation. The total carbon sequestration by rice fields ranged between 12.58 and 49.51 t CO_2-eq ha^{-1}, between 27.46 and 96.19 t CO_2-eq ha^{-1}, and between 38.84 and 62.02 t CO_2-eq ha^{-1} under CVN, SRI and ZTL cultivation respectively. A significant difference was found for the total carbon equivalent sequestration (t CO_2-eq ha^{-1}) in all three cultivation practices throughout the study period, regardless of rice growing season and rice varieties ($p < 0.05$), Fig. 4. During the study period, all three rice cultivation practices, viz. SRI, CVN, ZTL acted as a pool for greenhouse gases (i.e., sequestration > emission), although the size of the pool varied with different cultivation techniques ($p < 0.05$).

Carbon sequestration is influenced by the number of components such as above and below-ground biomass, carbon content, carbon dioxide emission, and grain yield (Eqs. (10)–(13)). Sequestration ability of the selected varieties involves a significant variation of the components described above. In Rabi season, no variation was observed in shoot biomass among the varieties in the CVN cultivation, whereas in SRI, higher shoot biomass was observed in the var. IET 9947 in 2018. However, the shoot biomass was almost the same for all the varieties in 2019 and 2020. In CVN cultivation, the root biomass showed no significant difference among the varieties throughout the period of study. However, in the SRI cultivation, the var. IET 9947showed higher root biomass in each year among other types. In the Kharif season, the higher root biomass was observed in var. IET 9947 in 2018 only. Later, for 2019–2020, higher shoot biomass was observed in IET 17430 in the CVN cultivation. In the SRI cultivation, no such variation was observed among the varieties. In the ZTL cultivation, higher shoot biomass was observed in IET 17430 in 2018. However, the shoot biomass was the same for all the varieties in 2019–2020. The root biomass was the same and higher in IET 17430 and IET 9947 in all the study periods. In SRI cultivation, IET 9947 showed higher root biomass throughout the study. In ZTL cultivation, IET 17430 showed higher root biomass in 2018 only. No such variation was observed in 2019–2020.

Therefore, it could be said that the SRI dominates over CVN concerning root and shoot biomass. It was observed that var. IET 9947, var., and IET 17430 dominated SRI cultivation during Rabi and Kharif seasons, respectively.

There is strong evidence that the carbon density in rice soils is higher than in upland soils. This implies that rice fields have significant carbon sequestration potential (Xie et al., 2007a, b). Under the anaerobic soil conditions of CVN paddy fields, organic matter degradation and remineralization of native SOC activity were lower than in aerobic soil conditions of SRI and ZTL soils (Witt et al., 2000; Liping and Erda, 2001). Therefore, the carbon removal process rate was low in the CVN plots. The formation of humus constituent passive pools of SOC is maximized under partially oxidizing conditions (Post et al., 2004). Abundant oxygen promotes mineralization, and the process slows with reduced oxygen conditions. AWD management under SRI and ZTL practices provides optimal soil conditions that are neither too oxidized nor too reduced. Such conditions favour the occurrence of an oxidative polymerization reaction that stabilizes carbon (Post et al., 2004). The results of the present study showed that the SRI had the highest carbon sequestration potential throughout the study period. The increase in the carbon sequestration in the SRI field plots was inferred at the time of the harvest (S4 stage) of the third-year study (0.76 ± 0.07 %), when compared to the baseline study at the start of the experiment at first year (0.52 ± 0.05 %), ($p < 0.05$). The increase was not significant enough for CVN and ZTL ($p > 0.05$). Hence, it could be said that if SRI practice is continued long-term, the organic carbon pool increase could be expected. Rajkishore (2013) advocated that the soil of the SRI cultivation practices retains more significant proportions of passive pools of soil carbon such as humic acid, and fulvic acid. The addition of vermicompost and cow dung manure to the SRI field plots resulted in an increase in organic carbon stock and increased soil carbon sequestration. This slight increase in the soil organic carbon (SOC) stock provided reduced atmospheric carbon concentration conditions. Additionally, incompletely decomposed organic compounds build up in paddy soils, increasing the amount of carbon with organic amendments (Sahrawat, 2010). According to Urmi et al. (2022), animal manure is more successful in constructing SOC because it contains more humified and resistant carbon forms and is less susceptible to microbial degradation. However, the conditions in the CVN and ZTL field plots were different. The addition of NPK fertilizers did not show such an increase in carbon content in the fields. The estimation of carbon sequestration involved several factors such as carbon content in aboveground and belowground biomass, gain yield, etc. These factors were superior under SRI than under CVN and ZTL cultivation. Rahman et al. (2022) treated rice soils with organic manures such as cow dung, vermicompost, and poultry manure and showed enhanced carbon sequestration potential and carbon content in the soil. The present study is in accord with the above findings.

4.4. Carbon indices

There was a significant difference in CF, CS, and CER between the cultivation methods and the four rice varieties ($p < 0.05$). During the Rabi season, the CF was 2.30 ± 0.03 and 0.69 ± 0.02 for CVN and SRI, respectively. The was 3.96 ± 0.24 and 14.88 ± 0.86, and CER was 0.45 ± 0.02 and1.73 ± 0.16 in the CVN and SRI cultivations, respectively (Fig. 5). Likewise, the values did not differ much in the Kharif season. The CF was 2.02 ± 0.04, 0.62 ± 0.01 and 1.45 ± 0.04 for CVN, SRI and ZTL, respectively. The CS and CER values were 5.77 ± 0.28, 11.89 ± 0.37 and 10.63 ± 0.68; and 0.54 ± 0.05, 1.67 ± 0.13 and 0.85 ± 0.09 in the CVN, SRI and ZTL cultivations respectively (Fig. 6). The results were following the works of other authors (Pathak et al., 2010; Farag et al., 2013; Yan et al., 2015). Experiments conducted on flooded rice fields in China showed different average values of CF, such as 0.37 (Cheng et al., 2015), 1.60 (Zhang et al., 2017) and 0.80 (Yan et al., 2015). Farag et al. (2013) reported a value 1.90 in the rice fields of Egypt, which is relatively closer to the present research.

The carbon footprint is essentially the ratio of total agricultural emissions and rice grain yields. SRI showed the highest grain yields among the three rice cultivation methods, followed by CVN and ZTL. CVN cultivation contributed to maximum CF throughout the study period, followed by CTL and SRI. The lower CF cultivation would be the more promising and cost-effective crop technique for rice. Thus, SRI cultivation could be the better candidate among all cultivation types. This could be explained through the total emission from the SRI and the grain yield by dint of the active tillers in the SRI field plots. Compared to CVN and ZTL, the GHG emission was less in the SRI field plots. The aboveground biomass was more due to more plant-plant spacing and efficient procurement of nutrients by the rice plant of SRI field plots,

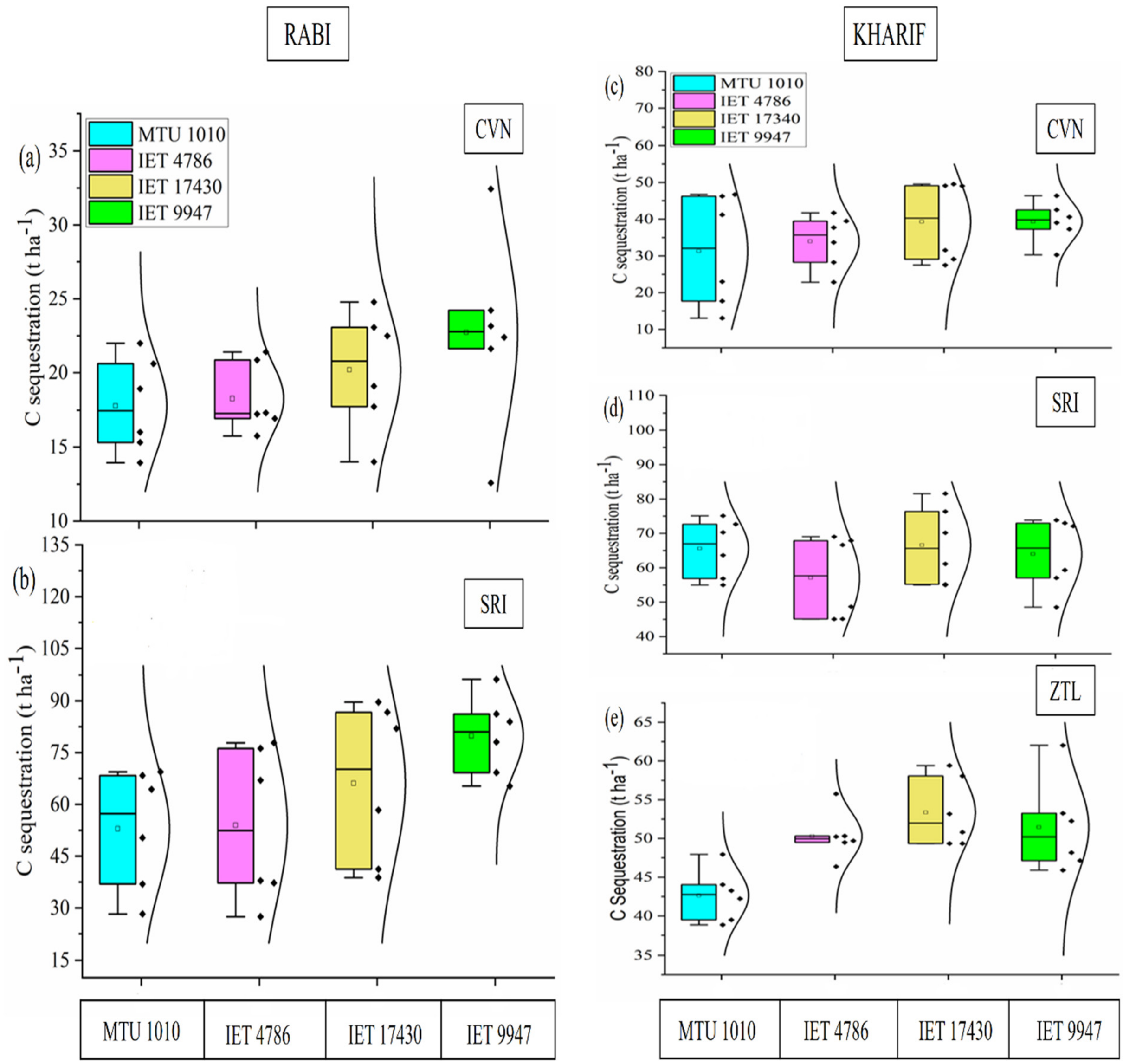

Fig. 4. Carbon-equivalent sequestrations (t CO_2 –eq ha^{-1}) from rice fields three methods of cultivation (CVN- Conventional cultivation, SRI – System of rice intensification, ZTL – Zero tillage) for four rice varieties (viz. var. MTU 1010, var. IET 4786, var. IET 17430, var. IET 9947) during Rabi rice growth season (Fig. 4a-CVN and Fig. 4b-SRI) and Kharif rice growth season (Fig. 4c-CVN, Fig. 4d-SRI, Fig. 4e-ZTL). Each box plot shows the data distribution, mean and median value, data distribution curve, standard error, and box range.

resulting in more active tillers and yield. The nutrient competition was more in CVN and ZTL plots due to less plant-plant spacing and, thus, caused the lesser number of active tillers and grain yield.

SRI showed the highest CS score, followed by ZTL and CVN throughout the study. Emissions from farms were highest for CVN, moderate for SRI and lowest for ZTL. Since there was a more significant difference between the carbon output values and the carbon input values in the SRI field plots, it can be said that the SRI might be the more sustainable rice cultivation practice. The present study observed that both SRI and ZTL cultivation had higher CER values due to their higher grain yield in terms of carbon dioxide equivalent emission (CO_2 equivalent). This condition was reversed in the case of CVN cultivation. Therefore, the SRI and the ZTL could be effective alternatives to reduce CH_4 and N_2O emissions. It was observed that the var. IET 17430 showed the lowest CF and highest CER values among CVN and SRI cultivation. And the var. IET 9947 showed the highest CS values. Hence var. IET 17430 was the most suitable variety in terms of lower carbon emissions and rice production per unit in this region, but not as sustainable as the var. IET 9947. The var. IET 17430 with the lowest CF values and highest CS showed lower carbon emission and highest sustainability, but the var. IET 9947, with the highest CER values, showed better grain production per unit. The CF, CS and CER under different rice cultivation practices (CVN, SRI, and ZTL) during Rabi and Kharif season are presented in the Table S7 and S8.

4.5. Rice grain yield, aboveground and belowground biomass

There was a significant difference in grain yield (t ha^{-1}) among the cultivation practices for all the crop cycles throughout the study period ($p < 0.05$). SRI showed superior grain yield (t ha^{-1}) than CVN cultivation under the Rabi season. The average grain yield during the Rabi season ranged from 4.57 to 18.52 t ha^{-1} and from 3.01 to 8.95 t ha^{-1} for SRI and CVN, respectively. During the Kharif season, SRI showed the highest grain yield, followed by CVN and ZTL. The average grain yield during the Kharif season ranged from 6.75 to 19.06 t ha^{-1}, from 3.00 to 12.43 t ha^{-1} and from 1.81 to 12.25 t ha^{-1} for SRI, CVN and ZTL, respectively. During the Rabi season, there was a significant difference in grain yield among four rice cultivars that are considered in the present study ($p < 0.05$) (Table S9).

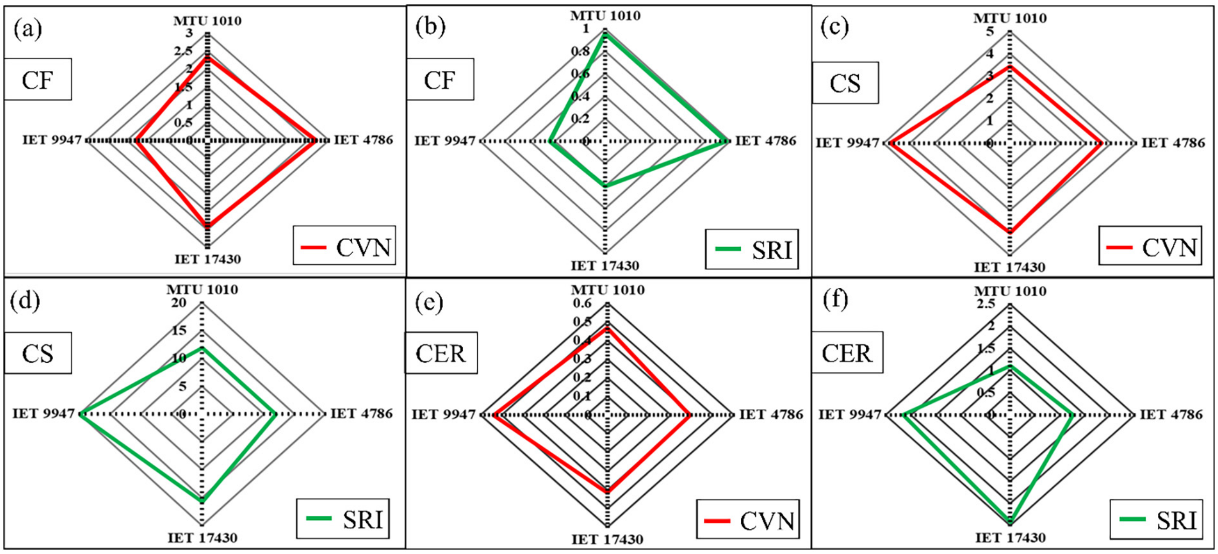

Fig. 5. Carbon indices (CF, CS, CER) for four rice varieties (viz. var. MTU 1010, var. IET 4786, var. IET 17430, var. IET 9947) during the Rabi season under two methods of cultivation (CVN- Conventional cultivation, SRI – System of rice intensification). CF-Carbon footprint, CS- Carbon sustainability index, CER – Carbon efficiency ratio. Fig. 5a-CF of CVN and 5b-CF of SRI, Fig. 5c-CS of CVN and 5d-CS of SRI, Fig. 5e-CER of CVN and 5f - CER of SRI.

It was observed from Table S10 and Table S11, that there was a significant difference in both root and shoot biomass (t ha^{-1}) among the cultivation practices during the Rabi and Kharif seasons. A general pattern was observed where both shoot and root biomass remained higher under SRI cultivation than CVN during Rabi and CVN and ZTL during the Kharif season. The average shoot biomass during the study period ranges from 3.95 to 14.88 t ha^{-1}, from 8.52 to 19.46 t ha^{-1} and from 5.10 to 14.50 t ha^{-1} under CVN, SRI and ZTL, respectively. Similarly, the root biomass ranges between 1.20 and 9.20 t ha^{-1}, between 2.83 and 13.05 t ha^{-1} and between 0.90 and 8.60 t ha^{-1} under CVN, SRI and ZTL, respectively. A significant difference among varieties ($p < 0.05$) was observed during the major part of the study period. The root and shoot biomass results during Rabi and Kharif seasons are tabulated in Tables S10 and S11, respectively. The changes in the soil physical and chemical properties during rice harvest from the field under the three cultivations are provided in Table S12.

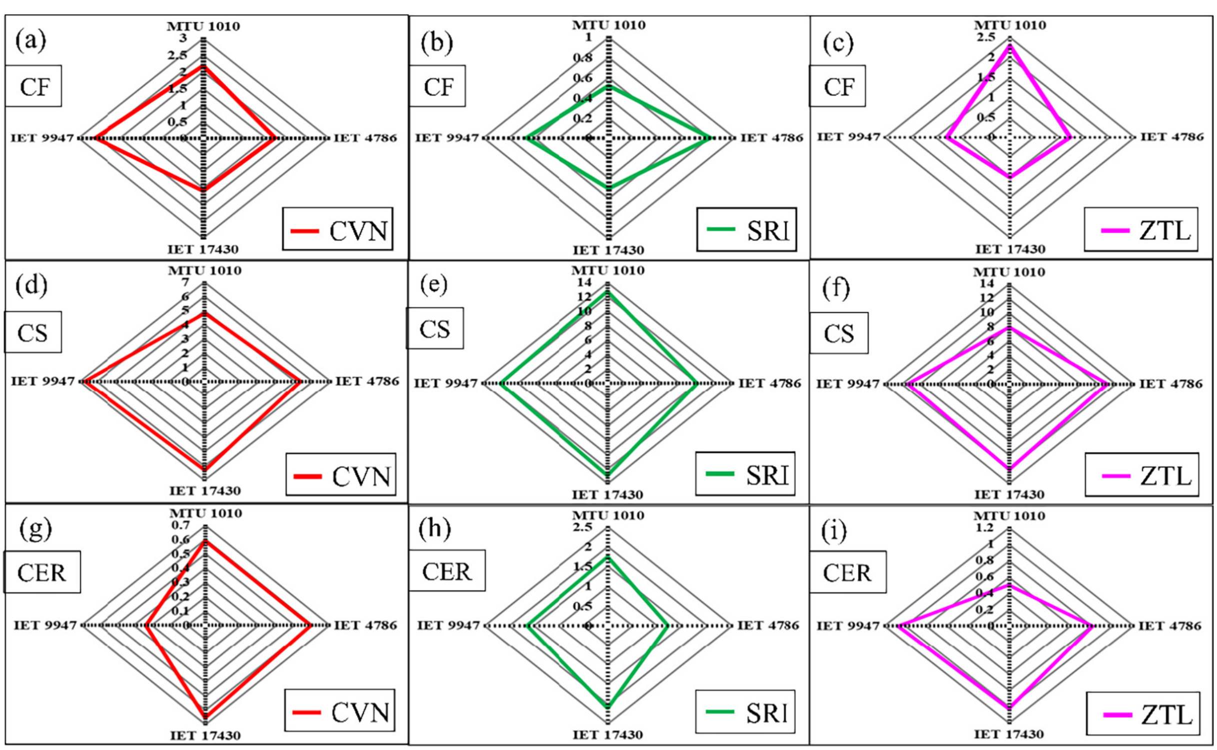

Fig. 6. Carbon indices (CF, CS, CER) for four rice varieties (viz. var. MTU 1010, var. IET 4786, var. IET 17430, var. IET 9947) during the Kharif season under three methods of cultivation (CVN-Conventional cultivation, SRI – System of rice intensification, ZTL- Zero tillage). CF- Carbon footprint, CS- Carbon sustainability index, CER – Carbon efficiency ratio. Fig. 6a- CF of CVN, 6b- CF of SRI, 6c- CF of ZTL, Fig. 6d-CS of CVN, 6e - CS of SRI, 6f - CS of ZTL, Fig. 6g-CER of CVN, Fig. 6h-CER of SRI and Fig. 6i-CER of ZTL.

4.6. The carbon balance between ecosystem service and disservice

Carbon sequestration, an exceptional ecosystem service rendered by the rice fields, was observed to be highest under SRI, followed by ZTL and CVN cultivation ($p < 0.05$). However, in terms of money, when the balance between carbon sequestration (service) and total GHG emission from rice fields (disservice) was analyzed, it was found that the values were higher for CVN followed by SRI and ZTL cultivation ($p < 0.05$), (Table 3). There was no statistically significant difference between SRI and ZTL, but both cultivations showed a substantial difference with CVN ($p < 0.05$).

The production cost of rice under three cultivations in the present study included all the farm operations per hectare of lands, such as fertilizer requirement, seed requirement, herbicide application, fuel consumption, irrigation and farm labour (men or women) involved in the farm operations. And the yield of rice and straw through marketing (price per hectare) was considered a profit by the farmers (Table S13). The results of the three-year study showed that in the CVN cultivation, either there was 2 % loss or gain throughout the study during Rabi and Kharif seasons. However, the average gain throughout the study was around 42 % in the SRI cultivation. In the ZTL cultivation, the average gain was four times compared to the cost of expenditure. Hence, it could be concluded that the highest return (in terms of money) by the farmer could be achieved if they adopt the ZTL cultivation. The remarkable difference between ZTL and CVN happened due to the process of cultivation through zero-tillage machines which involved no labour input and irrigation management. The two cost prices were extremely low for ZTL cultivation. However, in terms of soil health, it could be detrimental as chemical fertilizer was used during the cultivation. Moreover, SRI cultivation also showed a profit in terms of economy. Hence, the SRI could be a promising solution to promote sustainable agriculture and mitigation of GHGs.

The Swedish carbon tax is an internationally recognized measure in calculating the ecosystem service values of carbon sequestration of the rice field ecosystems (Jiang et al., 2019; Chen et al., 2020). In the present context, the Indian carbon tax is considered more appropriate when estimating ecosystem services and disservices (Table 3). Arunrat et al. (2022) employed the Swedish carbon tax to estimate the value of ecosystem service provided by carbon sequestration in rice fields. They observed that the value of carbon sequestration ecosystem services in organic farming was twofold higher than in conventional rice farming practice. Evaluation of ecosystem disservice from an Indian perspective using the Indian carbon tax was made by Rasheed et al. (2021). The results showed the economic value of the penalty rendered due to GHG emission was 16 US$ ha^{-1} yr^{-1}. This is in line with the results of the present study.

In ZTL techniques, the rice varieties var. IET 17430 > var. IET 9947 > var. IET 4786 > var. MTU 1010 was observed in decreasing order of returns per unit cost. In contrast, following the SRI technique, the rice varieties were var. IET 9947 > var. IET 17430 > var. IET 4786 > var. MTU 1010 in decreasing order of returns per unit cost. As a result, among the four rice varieties studied in this study, IET 17430 and IET 9947 are the only rice types cultivated under SRI and CVN.

4.7. Limitations and implications

In this study, GHG emissions were measured three times a day, and average emissions per day were presented throughout the study period. However, the GHG emissions at midnight were not included in the study, leading to uncertainties in estimating GHG emissions from the rice fields. In addition, the three cropping styles in the RCBD pattern were practised in the experimental field plots with similar soil types and textures. If the ZTL practice is done in the water-deficient regions of other parts of India, the results may differ from the present results. The rice varieties selected in the present study are widely accepted by farmers and have a good market value in this region. However, GHG emissions from other varieties (from other areas) are not tested and may produce different results. The data on transporting the raw materials to the rice mills and the post-harvest work were not included in the present study. It is expected that such a post-harvest operation would somewhat affect the total GHG emissions from operations of the procedures. This, in turn, underestimates the impact of the entire production and marketing chain on the carbon footprint and ecosystem services of C sequestration. On the other hand, agricultural inputs can be determined by future technical innovations, policy improvements and economic developments, which could lead to significant uncertainties in the estimated GHG emissions.

Carbon emissions and carbon sequestration affect the net carbon balance of agroecosystems. Farming operations were identified in this study as the primary regulator of carbon balance in field plots. The introduction of appropriate rice varieties and cultivation practices can balance increasing net carbon fixation in rice biomass and reducing carbon emissions. Using organic manure in SRI cultivation can increase carbon input from rice biomass and SOC sequestration. Using fertilizers in conjunction with proper irrigation management techniques in ZTL cultivation can potentially reduce greenhouse gas emissions from rice fields. This supports the conclusion that improved water management, tillage, and fertilizer application are critical strategies to achieve a trade-off between lowering carbon emissions and increasing net carbon sinks in rice agro-ecosystems.

5. Conclusions

The present study compares the contribution of different farm operations to net carbon equivalent emissions under CVN, SRI and ZTL cultivation practices. The highest contributor to GWP among all three cultivation was fertilizer application. The GWP for CH_4 and N_2O was found to be higher in the CVN and ZTL plots, respectively. However, the present showed gains in all the crop cycles examined for all the cultivation practices as well as the varieties, and higher sequestration levels were achieved for the SRI cultivation. Hence, it could be said that the ecosystem service rendered by total carbon sequestration in the rice field soils was always more significant than the total carbon emission due to rice cultivation. In the tropical climate, rice cultivation is practised in both the upland areas and the lowland areas. Hence, sustainable agriculture could be promoted by applying organic manure in the context of SRI cultivation in the water-deficient zones and ZTL cultivation in the tropical upland zones, where such cultivation has not yet started. These cultivation techniques should be encouraged among farmers as they are cheaper, have low carbon costs and are cleaner in terms of GHG emissions. The var. IET 4786 and var. IET17430 could be promoted under CVN and ZTL cultivation practices, respectively. IET 9947 and var. IET 17430 could be announced as part of SRI cultivation in this region.

Table 3
Evaluation of carbon sequestration (service) and carbon emission (disservice) of farm emissions under Conventional (CVN), System of Rice Intensification (SRI) and Zero-Tillage (ZTL) cultivations during Rabi (sowing: January–February; harvest: March–April) and Kharif (sowing: July–August; harvest: October–November) seasons.

	Rabi season		Kharif season		
	CVN	SRI	CVN	SRI	ZTL
Ecosystem service (US$ ha^{-1})	468.66 ± 21.41	1500.04 ± 101.75	853.62 ± 49.91	1502.24 ± 51.28	1173.40 ± 28.09
Ecosystem disservice (US$ ha^{-1})	43.54 ± 0.47	31.95 ± 0.34	46.68 ± 1.23	30.59 ± 0.56	24.35 ± 0.23

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Not applicable.

Consent to participate

Not applicable.

Consent for publication

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Availability of data and material

Not applicable.

Code availability

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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