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Diversification of rice growing areas in Eastern India with integrated soil–crop system management for GHGs mitigation and higher productivity

A. K. Singh[a], A. K. Ghorai[a] and G. Kar[b]

[a]Crop Production Division, ICAR-Central Research Institute for Jute and Allied Fibres, Barrackpore, India; [b]ICAR-Central Research Institute for Jute and Allied Fibres, Barrackpore, India

ABSTRACT
Mono-cropping, burning of crop residues, imbalanced fertilization and limited use of farm manure are resulting in loss of soil organic carbon (SOC). In this study, integrated soil-crop management (ILM_{soil}), improved management (IM_{soil}) and conventional management (CM_{soil}) was studied to enhance the soil carbon sequestration for mitigation of greenhouse gas (GHG) emissions. The life cycle assessment (LCA) approach was used to estimate carbon footprint from successive crops of rice, mustard and jute with or without intercrops or mixed crops. The adoption of ILM_{soil} helped in reducing the carbon footprint by 78%. The overall economic yield increased by 25% over IM_{soil} as well. Net CO_2-eq emission was 68% less under ILM_{soil} as compared to other systems. The reduction in net LCA-GHG emission was mainly due to high SOC sequestration by jute crop and leguminous intercrops and mixed crops. Improved crop diversification and agronomic productivity as used in ILM_{soil} system may decrease the inputs of non-renewable energy and consequently reduce the emission of GHGs from agroecosystems. Improvement of soil health, minimization in nutrient and water losses, and application of the increased amount of organic fertilizers were found helpful in reducing the carbon footprint. ILM_{soil} method of cultivation in 0.70 million hectare of jute growing area may reduce about 0.40 million tonnes of CO_2-eq from atmosphere every year and provide carbon credit of 1.22 million US$to the farmers of eastern India.

KEYWORDS
Integrated soil-crop system; rice-mustard-jute cropping system; carbon footprint; carbon sequestration; nitrogen and water productivity

Introduction

Carbon dioxide (CO_2) is a major greenhouse gas (GHG) emitted from the soil surface into the atmosphere. Increasing GHG concentration in the atmosphere has increased the average air temperature. The worldwide mean surface temperature (GMST) reached 0.87 °C in 2006–2015 compared with pre-industrial age period (1850–1900). Climate models project a robust difference in regional temperature somewhere in the range of 1.5 °C and 2 °C [1]. Recorded climate data of the recent 40 years (1972–2012) show a noticeable increase in ambient temperature in the lower Indo-Gangetic Plain (IGP) of India where jute and rice are grown. An increase of 0.8–1.4 °C in annual average surface air temperature has been recorded [2], and by the 2050s, average ambient temperature is expected to rise by another 2 °C [3]. Precipitation pattern has also changed in which extreme events such as La-Niña and El-Niño frequently occur during the last decades [4]. Variations in air temperature and rainfall pattern are affecting the planting season and water availability in the agricultural fields. In order to cope with this climate change problem, adaptation and mitigation strategies are required to be adopted.

Rice (*Oryza sativa*) is the most extensively grown crop in South Asia, occupying nearly 50 million hectare of land area [5]. Rice-based crop rotations have complex effects on GHG emissions due to variation in energy use efficiencies, temperature and water regimes, carbon returns, nutrient inputs, fossil fuel use for machinery and pesticides, varied duration of crop growth as well as differences in crop yields [6]. Rice is grown mainly in submerged soils and emits methane (CH_4), and nitrous oxide (N_2O) from nitrogen fertilizers [7], resulting in higher GHG emissions than other crops [8]. Annual GHG emissions of rice-based crop production systems are ~18.4% of CO_2-eq (98 Mt) in India from ~43 Mha rice cultivating area, at a rate of 10.3%

CONTACT A. K. Singh singhak30@gmail.com Crop Production Division, ICAR-Central Research Institute for Jute and Allied Fibres, Barrackpore 700121, India
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(532 Mt CO_2-eq per year) of total agricultural emission globally [9]. However, improved management practices such as double cropping system, system of rice intensification (SRI) and crop residue management can increase soil organic carbon (SOC) in the rice ecosystem [10–12]. SRI can make a net contribution to the reduction of CH_4 production from rice fields by about 30 to 60% due to the reduction in inorganic nitrogen for aerobic soil organisms [13,14]. In the face of these environmental challenges, it is necessary to strengthen soil carbon sequestration because the emissions of crop inputs can be partially offset by the conversion of atmospheric carbon dioxide into plant biomass and eventually sequestration in the soil. Adoption of crop residue retention on annual basis to increase soil organic carbon, reduction in use of inorganic fertilizer, improvement of nitrogen (N) fertilizer use efficiency including N_2-fixing leguminous crops in rotations to lower the carbon footprints (CF), use of diversified cropping systems, and integration of suitable cropping practices with intercrops or mixed crops which can increase crop yield, reduce emissions and lower the CF of cereal crops are viable option to mitigate the risk of climate change [15].

Crop diversification has been considered as an important agriculture practices for improving agro-ecosystem productivity and lowering the CF [16]. In West Bengal, about 40% area remains fallow after wet season rice cultivation [17]. Such a fallow period emits more N_2O, thereby reducing the C:N ratio in soil and has high global warming potential (GWP) [18,19]. Proper crop diversification of such land with short duration pulse or oilseed crops followed by jute cultivation can reduce the GHG emission by making a good trade-off between system productivity and GWP in the study areas. Crop diversification helps in controlling weeds [16], suppressing plant diseases [20], and thereby increases economic yield [21]. Researchers found that the total emissions per unit of land varied significantly among the various cropping systems. Average GHG emission and the CF of biomass based cropping system were found maximum in cereal based cropping system [22]. In designing a diverse cropping system, there is a need to examine the overall greenhouse gas emissions (CO_2, N_2O, CH_4) and the CF of individual crops. Crops requiring low farm inputs and produce high yield of crop residues for incorporation into the soil to build carbon are keys to reducing the overall CF of the systems. Under various cropping system, carbon build-up rate was maximum under jute-rice-wheat (1.45–3.33 t C_{eq} ha^{-1}) and maize-soybean-wheat (0.43–3.82 t C_{eq} ha^{-1}) cropping systems [23–25]. Incorporation of pulse crops in the crop rotation even as intercrops helped in reducing the total GHG and CF.

Jute (*Corchorous olitorius*) is predominantly a rainfed fibre crop and the normal cultivation time is the summer season (March–July) when no other crops are grown without irrigation. Global production overview (FAO 1962–2018 data) shows that jute has always been the main bast fiber crop grown under various climatic conditions, mainly distributed in India, Bangladesh, Myanmar, Nepal, Taiwan, Thailand, Vietnam, China, Cambodia and Brazil. Eastern Indian states account for 98.41% area under jute cultivation, as well as 98.43% of total raw jute production [26]. The jute plant gets pre-monsoon showers during April-May for its normal growth and is not affected seriously by temporary drought or water stagnation. Life cycle assessment (LCA) study reveals that the most significant impact is carbon sequestration by green jute plants during the growth stages. On an average, as much as 0.97–2.8 tonnes ha^{-1} of the left over above- and below-ground biomass of jute (leaves, stubbles and roots) can be added annually to the soils under jute cultivation [27]. Approximately 4.88 to 5.30 tonnes of CO_2 get sequestered per hectare of raw jute fibre production which is much higher than many tree species [28].

Integrated cropping systems coupled with the adoption of the best agronomic practices such as line sowing, optimum plant establishment methods (e.g. SRI in rice), use of soil test based fertilizer and proper crop sequencing can increase crop productivity without increasing farm inputs or GHG emissions [29–31]. The CF of individual crop species is highly associated with crop biomass and the N concentration of plant parts like leaves, straw, stubbles and roots. Integration of agronomical practices can significantly improve the net productivity of crops by improving the water and nitrogen use efficiencies. Compared with a single cultivation system, the increase in net productivity of the integrated crop system is due to the increase in the diversity of the microbial population and the function of the microbial community in the soil [32,33]. Leguminous crop based intercropping systems help in minimising the loss of soil organic carbon and nitrogen and reduce the CF [34]. Many studies across the world demonstrate that use of integrated agronomical practices can increase the system productivity by 15 to 50%, reduce the carbon emissions associated with the

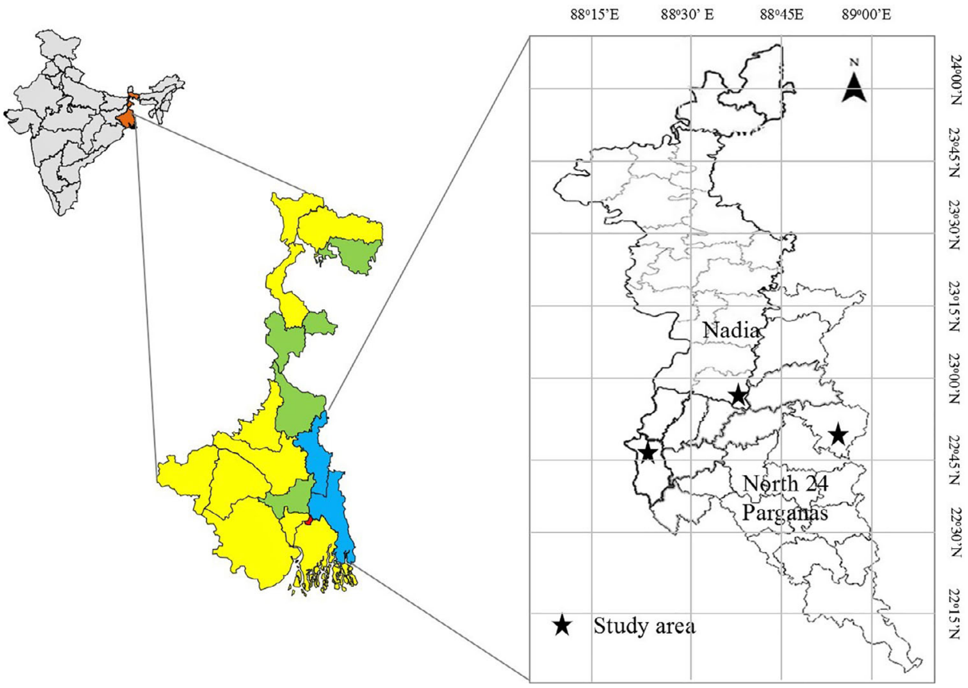

Figure 1. **Study location in Nadia and North 24 Parganas district of West Bengal (India).**

crop inputs by 25 to 50%, and lower the footprint CF of cereal crops by 25 to 35% [35–39].

Considering the rice-based production systems is one of the potential sources of annual GHG emission of global agriculture [40], an accounting of net life cycle GHG fluxes together with C sequestration in soil, is needed to evaluate strategies of GWP mitigation for rice-dominant cropping system. In this study, we aimed to achieve two important objectives, (i) to what extent can an integrated management practice and crop diversification can improve the economic yield and lower the CF in prevailing climatic, agronomic and economic condition, and (ii) how rice-mustard-jute agrosystem at both crop rotation and intercropping scale contributes most to reducing the annual emissions of GHGs within the cropping system LCA?

Materials and methods

Experimental site and weather

The study was conducted by the Central Research Institute for Jute and Allied Fibres (ICAR-CRIJAF) during the years 2018 to 2020 at three locations (Figure 1), viz. Barrackpore (88° 44.4′ E longitude, 22° 44.7′ N latitude, 15 m altitude), Swarupnagar (88° 51′ E longitude, 22° 46′ N latitude, 9 m altitude) and Haringhata (88° 34′ E longitude, 22° 55′ N latitude, 10 m altitude) situated in West Bengal (India). According to the National Agricultural Research Project classification [41] of Agriculture Climatic Zone (India), the study area belongs to the New Alluvial Zone (WB-4) consists of two soil groups (Dystrochrepts-Udifluvents) with Gitaldaha and Balrampur soil series. Jute-rice is the dominant cropping system followed at experimental locations. The mean annual rainfall was in the range of 1100 to 1200 mm with maximum temperature 34.0 °C in May and minimum 10.0 °C in January. The soil of the study area was clay loam to silty clay loam, moderately alkaline (pH 7.72) having low organic carbon (4.40 g kg^{-1}), available nitrogen (178 kg ha^{-1}) and available potassium (75 kg ha^{-1}) with high available phosphorus (52.6 kg ha^{-1}).

Experimental details and crop management

The study included three management systems, (i) integrated soil-crop management (ILM_{soil}) and (ii) improved management with the optimized crop and nutrient procedures (IM_{soil}). To compare the results of ILM_{soil} and IM_{soil}, conventional management (CM_{soil}) practices as followed by farmers was also included as control. Rice was grown during the rainy season (July–November), followed by mustard (*Brassica nigra*) in winter (December–March), while jute as fibre crop grown in summer (April–July). The details of fertilizer dose and farm yard manure (FYM), inter or mixed crops, crop varieties, plant density, date of sowing or transplanting, weeding practices and residue management under ILM_{soil}, IM_{soil} and CM_{soil} systems are given in Table 1. Seeds of mustard and jute were sown while rice was transplanted as

Table 1. Crop management including annual application of manure and fertilizer under different soil management treatments.

Treatment	N ($kg\ ha^{-1}$) Basal	N ($kg\ ha^{-1}$) Top dressing	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Manure ($kg\ ha^{-1}$)	Cultivar	Inter/ mixed crop (cultivar)	Density (plant m^{-2})	Sowing /Transplanting month	Weeding	Residue Management
ILM_{soil}											
Jute	20	50	30	40	2000	NJ 7010	Green Gram (cv. TMB37)	50–60	25–30 Mar	Mechanical	Return
Rice	30	30	30	30	2000	Khitish	Pumpkin (cv. Bravo)	25	5–10 Aug (SRI)	Mechanical	Return
Mustard	25	25	40	40	1000	B-9	Lentil (cv. WBL58)		10–15 Dec	Manual	Return
IM_{soil}											
Jute	50	40	50	50	1000	JRO 204	–	50–60	5–10 Apr	Mechanical	Remove
Rice	40	40	40	40	1000	Pratikshya	–	54	5–10 Aug	Manual	Remove
Mustard	30	30	50	40	500	B-9	–		10–15 Dec	Manual	Remove
CM_{soil}											
Jute	30	30	40	35	750	JRO 524	–	90–100	5–10 Apr	Manual	Remove
Rice	55	40	40	40	750	IET 4094	–	54	10–15 Aug	Manual	Remove
Mustard	15	15	40	40	500	B-9	–		15–20 Dec	Manual	Remove

ILM_{soil}: Integrated soil-crop Management; IM_{soil}: Improved management; CM_{soil}: Conventional management; SRI: System of rice intensification. Return: biomass of weeds and intercrops after harvesting of pulse and pumpkin mixed in the soil; Remove: removal of weeds from cultivated field without mixing in soil.

seedlings. Crops under IM_{soil} were grown as per recommended practices while CM_{soil} system was as per traditional practices of farmers. Under ILM_{soil} system, rice was grown following the SRI method [42]. In SRI (ILM_{soil}), 12-day-old seedlings were transplanted at 25 cm × 25 cm spacing keeping one seedling per hill, while in IM_{soil} and CM_{soil} system, 30-days-old seedlings were transplanted at 20 cm x 15 cm spacing keeping 2–3 seedlings per hill. The soil was kept near saturated moisture condition throughout the vegetative phase in SRI system. A thin layer of 1–3 cm rainwater was maintained during the reproductive phase of rice. However in IM_{soil} and CM_{soil}, 5–6 cm rainwater was maintained from transplanting to grain filling stage. Pumpkin (*Cucurbita pepo*) and green gram (*Vigna radiata*) were grown as intercrop in rice and jute fields of ILM_{soil}, respectively. Lentil (*Lens culinaris*) was grown as a mixed crop with mustard in 25%:75% seed ratio. Chemical fertilizer application rates were based on initial soil test value and percentages of the recommended doses for rice, mustard and jute crops. Each crop was managed by using appropriate crop varieties and by optimizing sowing dates, plant densities, and split N fertilization procedures. Keeping in view of the socio-economic conditions of the farmers and availability of manure in the rural areas, about 50% of the recommended dose of farm yard manure (FYM) was applied in ILM_{soil} treatment. For growing pumpkins in submerged rice fields of ILM_{soil} system, a reinforced soil column was made using biodegradable jute gunny bags. These gunny bags were filled up with a mixture of FYM and soils (1:1). About 1450 numbers of such reinforced columns were placed within the rice field on each drainage channel at a distance of 2.5 m after 10 rows of rice plants (Figure 2). About 4 or 5 pumpkin seeds were sown on each soil column after 15 days when excess water drained out from upper wet soil. Pumpkin plants are short lived annual vines (100–150 days) normally produce 3 to 5 fruits in each plant. Unlike vining gourds and cucumbers, they do not require trellis for support. It can be grown easily in such reinforced soil column or grow bags with small stakes support under submerged rice field during September to January months [43]. Pumpkins produce male and female flowers on the same plant and are naturally pollinated by insects. The harvested fruits of pumpkin are not perishable like gourds or cucumber and can be stored in cool and dry place for 3 to 4 months. For crop residue management in ILM_{soil} and IM_{soil} treatments, the shredded leaves, stubbles and roots of previous crop were mixed in soil during the first tillage operation of each crop. In case of ILM_{soil} treatment, the crop residues of inter crops (green gram) or mixed crops (lentil) were left in the field after harvesting (60–70 days after sowing) with main crop to decompose naturally. Need-based irrigation, weeding, and plant protection measures as per three treatments were taken for all crops. The field experiment was laid out in a randomised block design.

Agronomic assessment of nitrogen and water use efficiency

Nitrogen use efficiency (NUE) from applied N fertilizer was calculated as given by Cassman et al. [44]. The water use efficiency (WUE) was computed using CROPWAT 8.0 model [45]. Reference evapotranspiration (ETo) was estimated with local climatic data of the study area to validate CROPWAT

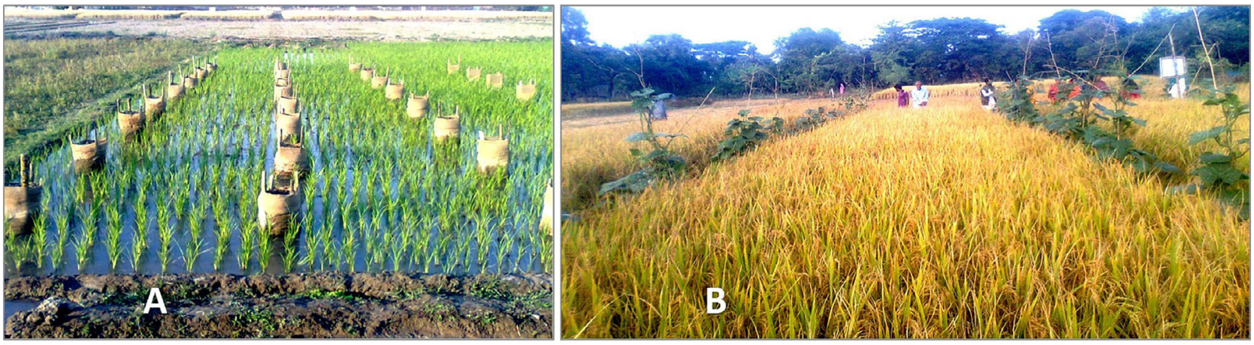

Figure 2. **Intercropping of pumpkin with rice (SRI) under ILM_{soil} system. A: After 15 days of Transplantation; B: At maturity stage of rice.**

Table 2. **Greenhouse gas (GHG) emission coefficient of farm inputs used in the study.**

Input	Unit	GHG coefficient (kg CO_2-eq ha^{-1})	Data source/Reference
Mouldboard ploughing	MJ	15.2	[48]
Field cultivation	MJ	4.0	[25]
Seed sowing	MJ	3.20	[25]
Machinery	MJ	0.071	[49]
Diesel fuel	L	2.76	[50]
Manure	kg	0.0032	[25]
Nitrogen (N) fertilizer	kg	1.30	[25,51]
Phosphorus (P_2O_5) fertilizer	kg	0.20	[25,51]
Potassium (K_2O) fertilizer	kg	0.20	[25,51]
Herbicide	kg	6.30	[25,51]
Insecticide	kg	5.10	[25,51]
Fungicide	kg	3.90	[25,51]
Water for irrigation	mm	0.05	[25]
Harvesting	MJ	10	[25]

model [46]. The overall water productivity was determined by dividing the grain or fibre yield by the water used by the crop and expressed as kg $ha^{-1}mm^{-1}$. For achieving higher efficiency of nitrogen fertilizers, split doses of urea were applied.

Estimation of GHG emission and carbon footprint

The amounts of GHG emissions from inputs in all crops were calculated by using CO_2, N_2O and CH_4 emissions coefficient of inputs. GHG emission is calculated and represented per unit of the land used in crop production, per unit weight of the produced yield and per unit of the energy input or output [47]. The amount of CO_2 produced was calculated by multiplying the input application rate per hectare (e.g. labour, diesel fuels, chemical fertilizers, herbicides and pesticides) by its corresponding coefficient enumerated in Table 2. The emissions were measured in terms of reference gas, CO_2 [52]. Emissions from farm inputs (diesel, nitrogen, phosphate, potash) were converted to kg CO_2-eq. The total emissions of greenhouse gases were determined using the following Equation (1) [53]:

$$\text{GHG emission} = \sum GWP_i x\ M_i \quad (1)$$

where, M_i is the mass (kg) of the emission gas, and GWP_i is the Global warming potential. The GWP of CO_2 is 1, CH_4 is 21 and N_2O is 310. The score was expressed in terms of kilogram carbon dioxide equivalent (kg CO_2-eq).

Stored carbon dioxide was used for the calculation of the CF for each crop separately. Net life cycle GHGs (LCA-GHG) were calculated by subtracting the CO_2-eq for SOC sequestered annually from the total CF of the product.

The carbon based sustainability index (Cs) was calculated [51] as Equation (2),

$$Cs = (Co - Ci)/Ci \quad (2)$$

where, Cs is sustainability index, Co is carbon output (kg CO_2-eq ha^{-1}), and Ci is carbon input (kg CO_2-eq ha^{-1}). The total GWP (in kg CO_2-eq) was integrated which determined the GWPs per hectare of fibre production.

Representative soil samples (0–30 cm) were collected from each of the plots every year during 2018 to 2020 and analyzed following standard procedures for their physical and chemical analyses [54] such as pH (1:2 soil–water suspension), texture (hydrometer method), soil organic matter (Walkley and Black method), extractable N (alkaline $KMnO_4$ method), extractable P (Olsen's $NaHCO_3$ method) and extractable K (NH_4OAc method. The IPCC (2006) guidelines recommend using a default

Table 3. Change in soil nutrient content during the experimental three-year period (2018–2020).

		Soil characteristics* (0–30 cm)								
		2018			2019			2020		
Soil parameters	Initial	ILM	IM	CM	ILM	IM	CM	ILM	IM	CM
pH	7.72^{a}	7.38^{b}	7.73^{a}	7.48^{a}	6.70^{c}	7.77^{a}	7.41^{a}	6.84^{c}	7.52^{a}	7.28^{a}
Org C (g kg^{-1})	4.40^{a}	4.80^{b}	4.60^{a}	4.10^{a}	5.80^{c}	4.90^{a}	4.20^{a}	7.10^{c}	5.10^{a}	4.70^{a}
Avail. N (kg ha^{-1})	178^{a}	201^{c}	184^{a}	174^{a}	214^{c}	184^{a}	164^{a}	247^{c}	184^{a}	169^{a}
Avail. P_2O_5 (kg ha^{-1})	52.60^{a}	40.81^{b}	54.14^{a}	49.7 1^{a}	43.64^{b}	57.18^{a}	49.22^{a}	43.96^{b}	56.27^{a}	53.31^{a}
Avail. K_2O (kg ha^{-1})	75.27^{a}	89.85^{b}	77.86^{a}	69.3^{a}	105.48^{c}	80.21^{a}	81.03^{a}	121.61^{c}	83.66^{a}	77.86^{a}

*Mean values followed by a common letter are not significantly different by DMRT at 5% level.

Table 4. Production, economics, carbon sequestration, water productivity and nitrogen use efficiency under ILM_{soil}, IM_{soil} and CM_{soil} system.

Treatment	Yield (kg ha^{-1})	EY (kg ha^{-1})	LER	CC (US$)	BCR	Total water use (mm)	WP** (kg ha^{-1} mm^{-1})	N-applied (kg ha^{-1})	NUE* (kg grain or fibre kg^{-1} N added)
Rice grain									
ILM_{soil}	4920	9050	2.26	462*	3.17	861.1	5.74^{c}	60.00	83.20^{c}
IM_{soil}	3755	3755	1.00	289	2.56	682.2	5.56^{a}	80.00	47.30^{a}
CM_{soil}	3300	3300	1.00	276	2.36	785.7	4.22^{b}	95.00	35.45^{b}
Mustard seeds									
ILM_{soil}	960	1231	1.19	239*	2.71	152.3	6.35^{a}	50.00	19.20^{d}
IM_{soil}	740	740	1.00	223	1.74	162.2	4.55^{b}	60.00	12.40^{e}
CM_{soil}	607	607	1.00	213	1.50	171.1	3.57^{d}	30.00	20.30^{d}
Jute fibre									
ILM_{soil}	3216	3733	1.10	889*	2.04	540.5	5.96^{a}	75.00	42.80^{a}
IM_{soil}	2796	2796	1.00	912	1.49	578.3	4.85^{b}	90.00	31.10^{b}
CM_{soil}	2174	2174	1.00	901	1.17	389.8	5.60^{c}	60.00	36.20^{b}

EY: Equivalent yield; LER: Land equivalent ratio; CC: Cost of cultivation; BCR: Benefit:Cost ratio; WP: Water productivity.
*Cost of cultivation and B/C ratio of main crop plus inter/mixed crops; **Mean values followed by a common letter are not significantly different by DMRT at 5% level.

0–30 cm layer. Within this layer, the changes in the organic carbon content due to different management practices are more pronounced [55]. The monthly mean air temperature, monthly precipitation and open-pan evaporation data were obtained from the Meteorological Unit of Research Farm provided by the ICAR-CRIJAF for the period of 2018–2020.

Data analysis

Data recorded in 2018, 2019 and 2020 cropping seasons were pooled together on account of non-significant interaction between years, locations and treatments. The data were then subjected to ANOVA with each year of sampling. Average value of treatments was separated using the least significant difference (LSD) at 0.05 probability level.

Results

Economic yield

Economic yield under ILM_{soil} practice increased by 52.6% in rice, 53.3% in mustard and 47.5% in jute over CM_{soil}. Under IM_{soil}, the yield of rice grain, mustard seeds, and jute fibre increased by 20.8, 24.9, and 31.5% of CM_{soil}, respectively. The yield under ILM_{soil} was 31.8, 28.4, and 15.9%, higher than IM_{soil} in rice, mustard and jute, respectively. When ILM_{soil} practice was adopted, an additional crop yield of pumpkin (6195 kg ha^{-1}), lentil (180 kg ha^{-1}) and green gram (320 kg ha^{-1}) was harvested. Maximum equivalent yield (EY) was recorded in rice followed by jute and mustard. The EY and benefit: cost ratio (BCR) of rice was found maximum due to higher yield of pumpkin (Table 4). Yield advantage in terms of LER was the greatest in the rice-pumpkin (2.26) and the lowest in mustard-lentil association (1.19) and jute-green gram (1.10). Price index of the produce (per kg) was US$0.48, US$0.78, US$0.13, US$0.13, US$0.53, US$0.78 for jute, green gram, rice, pumpkin, mustard and lentil, respectively.

Soil nutrient content, nitrogen use efficiency and water productivity

The fertility indices prior to conversion to integrated soil-plant management system differed between the treatments as per initial nutrient content (Table 3). Under ILM_{soil} system, the content of available nitrogen (N) and readily available K (K_2O) increased in soil but there was a negative balance for phosphorus (P, P_2O_5). The P-balance was negative due to application of lower amount of P-fertilizer during each crop season. As per initial soil

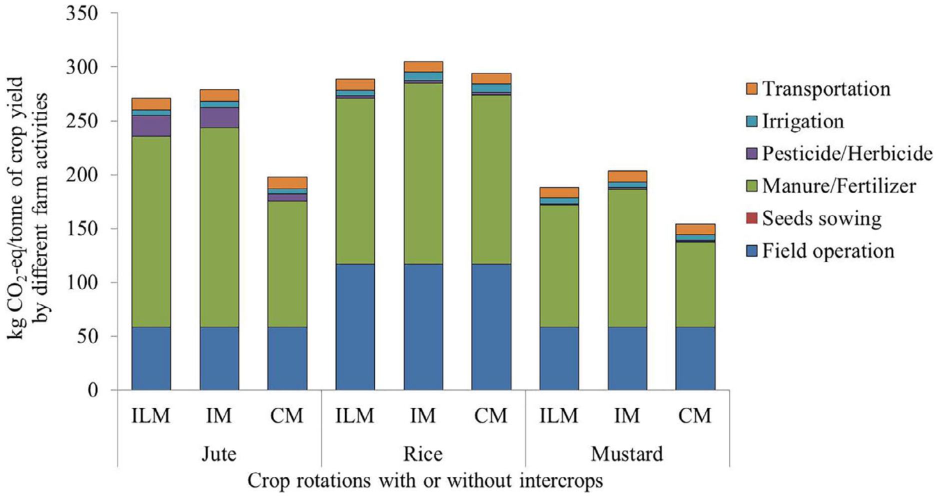

Figure 3. On-farm life cycle greenhouse gas emissions produced per season per hectare for rice-mustard-jute crop rotations with and without intercrops as influenced by integrated soil-crop management (ILM_{soil}), improved management with optimized crop and nutrient procedures (IM_{soil}), and conventional system (CMsoil) ($p < 0.05$).

test, P_2O_5 content was high at all experimental sites. In IM_{soil} and CM_{soil} system, non-significant change in soil nutrient content was observed.

Higher nitrogen use efficiency (NUE) is required to maintain N supply to fulfil crop N demand during crop growth period, which in turn resulted in a significant increase in economic yield of all main crops (Table 4). On an average, NUE were higher in ILM_{soil} by about 68% in rice, 54.8% in mustard, and 37.6% in jute over IM_{soil}. Maximum recovery of fertilizer was under ILM_{soil} as compared to IM_{soil}. About 17% (jute and mustard) to 25% (rice) of N-fertilizer could be saved in ILM_{soil} with about 16–32% of additional crop yield. Incorporation of 5000 kg ha^{-1} per year of FYM along with N-P-K fertilizers helped in improving the crop yield and soil health. Higher levels of NUE suggest changes in management could increase crop response or reduce input costs.

As per rainwater availability during the crop growth period, jute crop utilised only 40%, whereas rice and mustard crop could utilize about 100% of their water demand. The water productivity was significantly higher in the ILM_{soil} as compared to IM_{soil} and CM_{soil} for all crops (Table 4). Timely sowing and reducing soil moisture loss through intercropping or mixed cropping of leguminous crops in jute and mustard crops especially during mid-season crop development phase helped in improving the water productivity. SRI techniques significantly influence rice productivity and rice grain yields which were approximately 31–49% higher in ILM_{soil} system.

On-farm LCA-GHG emission

The life cycle assessment (LCA) approach was used to estimate GWP with the inclusion of GHG emissions of different soil-crop management systems. The data on analysis of emission of LCA-GHG during cultivation of each crop indicated that chemical fertilizer use contributed the maximum CO_2-eq emissions followed by the mechanised field operations (Figure 3). Irrespective of the crops and growing seasons, CM_{soil} system emitted the lowest annual LCA-GHG production, followed by ILM_{soil} and IM_{soil}. The difference in CF between ILM_{soil}/IM_{soil} and CM_{soil} was attributed to the emission from fuel and the input of fertilizer and plant protection chemicals. Use of low chemical fertilizer and pesticides helped in minimising the CF of jute and mustard crops under CM_{soil} system. In the rice crop, changes in CF were non-significant between all systems.

Contributions of jute and intercrops in reducing the overall LCA-GHG

The data on total CO_2-eq $tonne^{-1}$ of crop yield indicated that CM_{soil} emitted only ∼10% less GHGs than those emitted under the ILM_{soil} and IM_{soil} system (Table 5). However, this CO_2-eq emission under CM_{soil} was at the cost of about 50% low crop production as compared to those under ILM_{soil}. The value of total CO_2-eq emission was almost the same for both ILM_{soil} and IM_{soil}. However, the equivalent yield difference was about 25% higher under ILM_{soil} as compared to those under IM_{soil}. For the production of rice, mustard and jute fibre per hectare after accounting for soil sequestered C, net LCA-GHG emissions followed the sequence of $ILM_{soil} < IM_{soil} < CM_{soil}$ practices (Figure 4). In the case of ILM_{soil} practice, about 78% of net LCA-GHG emissions saving were estimated. In case of IM_{soil} and CM_{soil}, the

Table 5. **CO_2-eq emissions during cultivation and processing including labour use in the study.**

	kg CO_2-eq tonne^{-1} of crop yield per hectare											
	Jute			Rice			Mustard			Total		
Farm activities*	ILM	IM	CM	ILM	IM	CM	ILM	IM	CM	ILM	IM	CM
Cultivation	271	279	198	289	305	294	188	203	154	748	787	646
Processing	316	289	215	540	422	346	91	78	61	947	789	622
Labour	556	676	676	540	540	540	380	380	380	1476	1596	1596
Total	1143	1244	1089	1369	1267	1180	659	661	595	3171	3172	2864

*Cultivation: land preparation, ploughing, seed sowing, weeding, machinery and fuel used for ploughing and transportation, manure, fertilizer and pesticides application, irrigation and harvesting; Processing: extraction of fibre, threshing of paddy, green gram, mustard and lentil. Labour: sowing, farm input application, weeding, threshing, harvesting and drying.

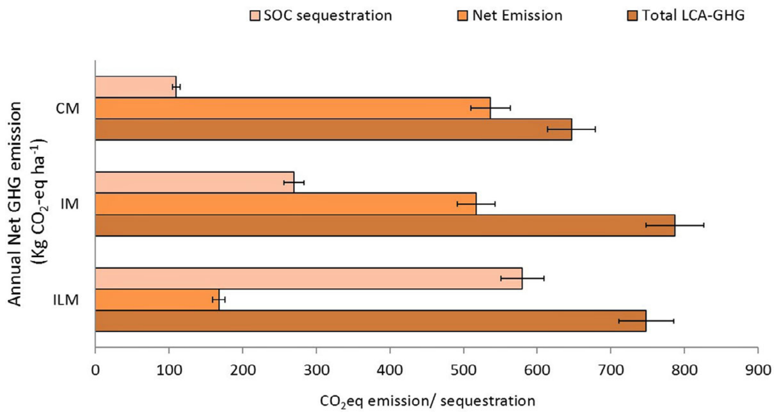

Figure 4. **SOC sequestration, average total (LCA-GHG) and net life cycle greenhouse gas emitted for the production of per hectare area in the rice-mustard-jute crop rotations with and without intercrops as influenced by integrated soil-crop management (ILM_{soil}), improved management with optimized crop and nutrient procedures (IM_{soil}), and conventional system (CM_{soil}) ($p < 0.05$).**

reduction in net LCA-GHG emission was 34 and 17%, respectively. Relative contributions of component crops to the LCA-GHG of the rice-based cropping system varied due to different crop establishment, residue retention practices and high soil organic carbon (SOC) sequestration by jute and intercrops. Rice crops contributed the highest portion of the net cropping system LCA-GHG (289–305 kg CO_2-eq tonne^{-1}). The reduction in net LCA-GHG emission was mainly due to high SOC sequestration by jute crop and leguminous intercrops. About 580 kg CO_2-eq ha^{-1} was sequestered in the soil under ILM_{soil} followed by IM_{soil} (270 kg CO_2-eq ha^{-1}) and CM_{soil} (110 kg CO_2-eq ha^{-1}) system (Figure 4). Considering the average global carbon price of around US$3.0 per tonne of CO_2-eq, ILM_{soil} can provide carbon credit of US$1.74 per hectare which is much higher than IM_{soil} (US$0.81) and CM_{soil} (US$0.33) system.

Carbon based sustainability index

The C-based inputs considered in this study were annual rates of manures and fertilizers (N, P, K), herbicides, pesticides consumed, irrigation-management practices, labour and farm power used for various operations, and total production of each crop (on dry basis). These data were used to calculate CO_2-eq per hectare of input and output and sustainability indices. The CF value of each three systems were used from a total period of 3 years. The annual production and total biomass were used to calculate the C output. Average data over three years, C input and output differed among three crop-soil management systems. ILM_{soil} system required lower C input (719 kg ha^{-1}) and produced more C output (2978 kg ha^{-1}) as compared to those under the IM_{soil} and CM_{soil} (Figure 4). The carbon based sustainability index (CSI) for ILM_{soil} (7.03) was also found the highest while CM_{soil} recorded the lowest value (3.54). The high C-sustainability index in ILM_{soil} may be because of the high economic yield with less application of C based inputs farm inputs as compared to other two systems (Figure 5). In the context of the global climate change and anthropogenic emissions of GHG into the atmosphere, sustainability of a production system increases with increasing in use efficiency of C based inputs [51].

Discussion

Appropriate soil and crop management practices integrate a series of cropping options and nutrient management strategies based on local

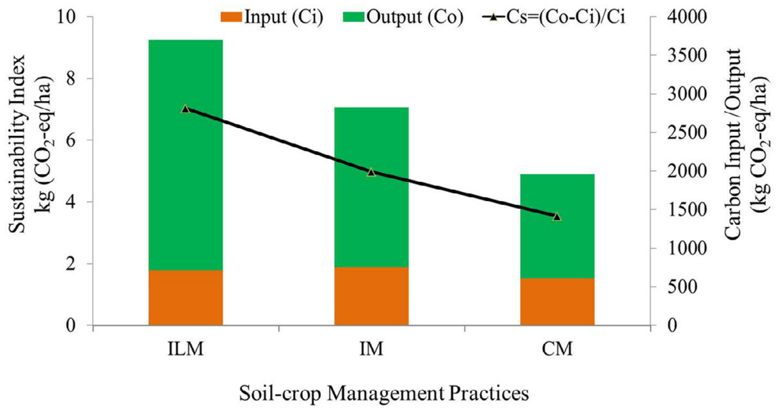

Figure 5. Carbon based sustainability index (Cs) in the rice-mustard-jute crop rotations with and without intercrops as influenced by integrated soil-crop management practices.

environments. As expected, the yield of all crops improved under ILM_{soil}, reaching about additional 32% in rice, 28% in mustard and 16% in jute over the recommended improved method of cultivation (IM_{soil}). Inclusion of green gram as intercrop in jute and lentil as mixed crop in mustard helped to enhance ground cover, thereby reducing weeds and also provided nitrogen for subsequent crops [26,56]. The combination of a non-leguminous crop with a leguminous one generates yield advantages over sole cropping system and curtailed overall weeding and irrigation costs [57]. Growing of pumpkin as intercrop in wet rice fields helped in generating an additional farm income to farmers [43]. NUE was significantly increased in ILM_{soil} over IM_{soil} and $CM_{soil.}$ The higher NUE may also be attributed to a reduction in N application at the basal and early vegetative stages and a delayed in-season N application [58]. Fertilizer management systems which include FYM along with crop residues (roots, stubbles, shredded leaves, weeds, etc.) helped to recover the soil carbon [26]. SRI improves WUE and yield by reducing fertilizer and water requirements and curtailed harvesting time up to 15 days [59]. Hence, this method increased the availability of residual moisture to post-rainy season crops (mustard and lentil) under ILM_{soil} system [5].

After accounting for sequestrated C in soil, net LCA-GHG produced by the cropping system amounted to 0.17, 0.52 and 0.54 tonne for ILM_{soil}, IM_{soil} and CM_{soil}, respectively. The economically valuable crop jute and mustard in the rice-based system comprised only 29 and 22% of net cropping system LCA-GHG emission. On the other hand, rice crops alone emitted about 44% of LCA-GHG. The jute crop contributed maximum to the soil carbon sequestration which helped in reducing the LCA-GHG to a great extent (78%). SRI (rice) helped in reducing the LCA-GHG (37%) as compared to other systems of rice cultivation. Soil carbon sequestration plays a key role in reducing the CF of crop cultivation, because a per unit farmland GHG emission represents the balance between CO_2-eq emissions and carbon sequestration during the cultivation of crops per year [15]. GHG emissions associated with the crop production inputs can be offset by greater carbon conversion from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil [60–62]. The higher CSI in ILM_{soil} was due to higher C output (grain and fibre yield) even with lower C input [63]. Integration of intercrops or mixed crops increased the C output in the system as compared to IM_{soil} and CM_{soil}. The application of crop residues of jute and leguminous intercrops (leaves, roots and stables) also helped in increasing the C output [64]. Increase in cropping intensity and inclusion of intercropping in the crop rotation could effectively lower carbon emissions by improving overall biomass production and it also decreases organic matter decomposition rate and mineralization/oxidation of SOC [65,66]. Growing legumes as intercrop can substantially reduce the chemical N fertilizer application, suppress weeds and insects, control plant disease, and to increase the overall productivity with limited resources [67]. Increased fertilizer N application as required for rice and jute under IM_{soil} application commonly increases N_2O emissions and, that, N_2O production increases LCA-GHG [68,69]. Through ILM_{soil} method of cultivation in 0.70 million hectare of jute growing area, India may reduce about 0.40 million tonnes of CO_2-eq from atmosphere every year and provide carbon credit of 1.22 million US$ to the farmers.

Conclusion

Agriculture is an important sector in most developing nations, contributes to climate change by emitting GHG and is suffering from the variations in air temperature and rainfall pattern. Adopting a sustainable crop production practices which decreases the inputs of non-renewable energy and consequently reduce the emission of GHG by increasing soil C sequestration would be helpful in reducing the carbon footprint and GWP mitigation. In this study, crop diversification through integrated crop and nutrient management practices increases the cropping intensity, generates additional farm income, saves about 78% of net LCA-GHG emissions, and reduces water and nutrient requirements of each crop in the rotation. Adoption of jute and leguminous based intercrop rotation, practising crop residue retention, improvement of nitrogen use efficiency, and enhancement of carbon sequestration into the soil together enhances agronomic productivity per unit consumption of C-based input. Water productivity of the rice field increased as remunerative pumpkin crop was grown in the wet rice fields. Hence, crop production practices which lead to less carbon emission as observed in ILM_{soil} are more desirable for sustainability and environmental safety from any production system. It can give better return and pay 53 to 81% higher carbon credit in comparison to improved (IM) and conventional system (CM) of crop production. Rice-mustard-jute production system with a low CF can be a double win in the form of enhanced adaptation, increased GWP mitigation and stability in the rice and jute based farming system and sustainability.

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Disclosure statement

No potential conflict of interest was reported by the author.

Data availability statement

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

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