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Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation

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ABSTRACT

Identification of a suitable cultivation method with low energy use, GWP and high productivity is the need of the hour. A 16-year old field study in the Indo-Gangetic Plains (IGP) with different methods of rice cultivation *viz.,* zero tillage (ZT), happy turbo seeder (HTS), bed planting (BP), reduced tillage (RT), conventional sowing (CS), direct sowing (DS), broadcast method of sowing (BS), manual transplanting (HT) and selected transplanting methods like, manual transplanter (MT) and mechanical transplanter (MaT) was used to evaluate the energy input and GWP. HT method of rice cultivation recorded higher energy use than ZT, HTS, BP, RT, CS, DS and BS methods, respectively. Whereas HTS method recorded highest net grain energy (NEg) and this was followed by ZT and MaT, The PTR method recorded 61–66% higher GWP compared with direct sown unpuddled method of rice cultivation. Among direct sown unpuddled methods of rice cultivation, HTS, BP, RT and ZT had lower GWP than farmers' practice. MaT recorded higher carbon output than ZT, HTS, BP, RT, CS, DS and BS methods. The study indicated that direct seeded method of rice cultivation is energy efficient with lower GWP and thus may be recommended.

1. Introduction

Rice (*Oryza sativa* L.) is one of the important staple food crops, feeding more than half of world's population. Globally, rice fields cover around 153 Mha comprising about 11% of the world's arable lands [1]. India and China are main producers of rice. The cultivated area under rice in India was highest, but China was the highest producer of rice, contributing >28% of total global rice production [2]. Rice is cultivated under a wide variety of climate, soil and hydrological conditions. In India, 44% of rice area is under traditional puddled transplanted method (PTR). Puddling is advantageous in rice systems as it reduces weeds, soil permeability by creating hardpans and reduces water losses through percolation. However, repeated puddling has a negative effect on the succeeding upland crop [3]. In PTR, puddling operation alone requires about 30% of the total water requirement [4] (3000–5000 L water to produce 1 kg rice). This higher water requirement is due to higher water losses through puddling, surface evaporation and percolation.

In recent years, depleting ground water resources along with climate change and labour shortage are major threats to the sustainable productivity of PTR. In Asia, 39 Mha irrigated rice may suffer from “physical water scarcity” or “economic water scarcity” by 2025 [5]. Besides these disadvantages, the conventional PTR requires higher energy inputs due to use of fuel for puddling operations, electricity, coal and diesel for pumping irrigation water [6–8]. This method also has adverse environmental impacts through soil and water pollution [9] and increased greenhouse gas (GHGs) emissions, which in turn contribute to higher global warming potential (GWP) [10]. The GWP with rice cultivation is 467 and 169% higher than wheat and maize [11], respectively. This higher GWP in rice cultivation is due to increased CH_4 and N_2O emissions. About 73% of CH_4 emission in agriculture is from rice cultivation [12]. But N_2O emissions from PTR are generally lower, since CH_4 in the rice field reduces the nitrification process.

The global demand for rice is predicted to increase by 24% in the

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next 20 years. This increase in rice demand is a major concern, since rice cultivation aggravates GWP [13]. Hence, there is a need to reduce GHG emissions, thereby GWP. Changes in management regime offer possibilities for mitigation of GHG emissions. The different methods of rice cultivation like, direct-seeded rice (DSR), zero tillage (ZT), bed planting (BP) etc, which do not need puddling and transplanting as the seeds are directly sown in tilled or no-tilled soils, are viable alternatives to save water and labour with low environmental impacts compared to conventional PTR method (farmers' practice in the Indo-Gangetic Plains). Moreover, these methods have better adaptive capacity to climate change, which is predicted to increase the variability of rainfall and the risks of water stress. Additionally, these methods of rice cultivation reduce CH_4 emissions, but may contribute considerably to N_2O emissions [14]. It has been reported that CH_4 emission mitigation practices, like mid-season drainage and application of ammonium sulphate lead to increased N_2O emission by increasing the redox potential of soils. Hence, the mitigation options differ for CH_4 and N_2O gases and minimizing one of these gases may increase the emission of the other, since the production of these two gases take place under different conditions. Thus, there is a need to develop a set of mitigation options, which may optimize this emission trade-off so that the GWP of the rice production is minimum with greater environmental sustainability. Hence, developing technologies and practices for sustainable and productive rice-based systems with low GHG emissions are needed to be revisited [15]. In this study, an attempt was made to estimate the GHG emissions in different rice cultivation methods in the Indo-Gangetic Plains (IGP).

The energy analysis of agricultural ecosystems is a promising approach to assess the energy efficiency, and their impact on environment [16]. Studies on this aspect help in identifying or developing more energy efficient technologies, with low adverse environmental impacts and improvement in natural resource conservation [17–19]. To date, many studies were devoted on exploring yield performance and nitrogen use efficiency of different methods of rice cultivation based on aerobic soil conditions (both under rainfed and controlled irrigation). Nonetheless, few studies have been conducted to unravel the crop performance, energy efficiency and GWP of different methods of rice cultivation individually in the IGP and similar agro ecologies. But very few studies compared PTR with un puddled transplanted and direct sown methods of rice cultivation. In this study, we hypothesized that rice cultivation without puddling reduces the energy use and impacts on environment. The objective of this study was to identify a suitable method of rice cultivation (among a set of novel agronomic management practices) in the IGP that had maximum productivity, energy use efficiency and low environmental impacts.

2. Materials and methods

2.1. Study area, climate and soil

A long-term field experiment was conducted for 16 years (from 1998 to 2014) at the experimental farm of ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut (UP), India, (29°4′ N latitude and 77°46′ E longitude, 237 m above mean sea level), located at Upper IGP. Agriculture in this zone is intensively irrigated, mechanized and input-intensive. The climate of this zone is semi-arid subtropical with extreme summers and severe cold winters. The average monthly minimum and maximum temperatures in January (the coolest month) were 7.2 and 20.1 °C, respectively. The corresponding temperatures in May (the hottest month) were 24.2 and 39.8 °C, respectively. The average annual rainfall of the region is 823 mm, of which around 75% of the rainfall is received through north-west monsoon during July–September. The soil (0–15 cm layer) of the experimental site was sandy loam (63.7% sand, 19.1% silt and 17.2% clay) in texture (Typic Ustochrept), slightly alkaline (pH 8.20), non-saline (EC 0.27 dS m^{-1}), low in oxidizable SOC (4.4 g kg^{-1}), available N (74 kg ha^{-1}), medium in P and K (0.5 M $NaHCO_3$ extractable P 14.1 kg ha^{-1} and neutral normal NH_4OAC-extractable K 125 kg ha^{-1}) and deficient in available Zn (DTPA-extractable Zn 0.73 mg kg^{-1}).

2.2. Crops and treatments

A replicated field experiment was conducted in a randomized block design (RBD) to study the impact of different rice crop establishment methods on yield and energy use by rice. The details of the land preparation treatments, method of planting, inputs applied in different treatments (seed rate, quantity of irrigation water, fertilizer etc.), weed control methods etc, are presented in Table 1. The experimental plots were 48 m × 5 m in size. The tillage systems were maintained in the same plots throughout the study (from 1998 to 2014) with the same layout. Tillage operations were repeated in each rice growing season using the same tractor and machinery and these are still in use in the region and many other parts of India. Field speed, field efficiency and working widths were obtained from the machines commonly used in the region (Table 2). The treatments included: zero tillage (ZT), happy turbo seeder (HTS), bed planting (BP), reduced tillage (RT), conventional sowing (CS), direct sowing (DS), broadcast method of sowing (BS), manual transplanting (HT), manual transplanter (MT) and mechanical transplanter (MaT). In ZT and HTS, sowing was performed in zero-tilled fields without residues and with residues, respectively. In CS, land was prepared with two passes of harrow followed by two passes of tiller and one passes of rotovator, and sowing was done using a zero-till drill. In DS, BS, HT, MT and MaT methods, plots were tilled with one pass of harrow, followed by tiller and rotovator in dry field. The sprouted seeds were sown in DS and BS treatments in puddled fields with use of a drum seeder and broadcasting, respectively. Whereas, in HT, MT and MaT plots, puddling was performed with two passes of rotovator before transplanting. Every year, the crop was sown in the second week of June in nursery and transplanting of rice seedlings was done in the first week July. The spacing adopted in all treatments was 22 cm between the lines. Each year harvesting of the crop was done in mid-October.

The recommended doses of mineral fertilizers, i.e. 120 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1} were applied in all treatments. About 50% of the recommended nitrogen (N), entire phosphorous (P) and potassium (K) were applied as basal and the remaining 50% N was top-dressed in two split doses, at tillering and milking stages. Zn and Fe were applied in the form of $ZnSO_4$ and $FeSO_4$ at 25 and 20 kg ha^{-1}, respectively. The grain and biomass yields were recorded at 12% moisture content in all treatments.

2.3. Energy balance

Energy inputs of different rice establishment methods were estimated using direct and indirect energy inputs. Direct energy inputs include total quantity of fossil fuel used in land preparation, establishment methods, harvesting, human labour, bullock labour and electricity. The indirect energy inputs are: energy used in production of machinery and raw materials, like mineral fertilizers, pesticides, seed energy inputs and transportation. A complete inventory of all inputs (fertilizers, seeds, plant protection chemicals, fuels, human labour, irrigation water and, machinery power) and outputs of both grain and straw yields were recorded. Energy inputs in different treatments were computed by multiplying the inputs with the corresponding energy coefficients and summation of all these components. The direct and indirect energy coefficients

Table 1
Package of practices/cultural practices of different resource conservation technologies (RCTs) in the rice crop.

S. No.	Operation	Month	Direct seeded rice					Sprouted seeded		Transplanted rice		
			ZT	HTS	BP	RT	CS	DS	BS	HT	MT	MaT
1.	Land preparation	May–June	No- tillage	No- tillage	Re-shaped bed	Rotary tilling followed by seeding	2H + 2T + R and seeding with ZT	1H + 1T + 1R		1H + 1T + 1R and followed by pudling with two pass of rotavator		
2.	Nursery & seeding	June	Seeding with ZT drill at seed rate 50 kg ha^{-1} Direct seeding with various seed drill in line spacing of 22 cm at seed rate of 50 kg/ha	Seeding happy –turbo seeder at seed rate 50 kg ha^{-1}	Seeding by bed planter at seed rate 50 kg ha^{-1}	Seeding rotary till drill at seed rate 50 kg ha^{-1}	Seeding with ZT drill at seed rate 50 kg ha^{-1}	Seeding of sprouted seed at rate 40 kg ha^{-1} with drum seeder of 22 cm line spacing	Broad casting of sprouted seed at seed rate 40 kg ha^{-1}	Conventional method of nursery raising at seed rate of 30 kg ha^{-1}		Mat type of nursery raising at seed rate of 25 kg ha^{-1}
3.	Transplanting	July	–	–	–	–	–	–	–	Transplanted manually, 2-3seedling per hill, 25 days old seedlings	Transplanted by manual transplanter, 2-3seedling per hill, 25 days old seedlings	Mechanical transplanting, 2–3 seedlings per hill, 20 days old seedlings
4.	Fertilizer application	June to September	Recommended dose of fertilizer (i.e. N:P:K:: 120:60:40) Basal dose applied - 50% N & full dose of P & K at the time of sowing and 25 kg ha^{-1} zinc sulphate and 20 kg ha^{-1} ferrous sulphate Topdressing application- two split dose of 50% N at tillering and milking stage					Recommended dose of fertilizer (i.e. N:P:K:: 120:60:40) Basal dose applied - 50% N & full dose of P & K at the time of sowing and 25 kg ha^{-1} zinc sulphate Topdressing application- two split dose of 50% N at tillering and milking stage				
5.	Weedicides	June	Pre-emergence herbicide- Glyphosate@ 6 lit ha^{-1} 360 gm/lit Post-emergence herbicide- Pendimethalin 30% EC at 4.5 kg/ha (1.50 kg a.i.ha^{-1})				–	–	–	–	–	–
		July	Post-emergence herbicide- Bisbiribac sodium (nomani glod) @ 300 ml/ha or 40 g ha^{-1} 10% a.i. Followed by one manual spot weeding									
6.	Pesticides		Insecticides- Insecticide Furadan (carbofuran) @20 kg ha^{-1} @ content 19 mg kg^{-1} available Pesticides- Carbenzin + mancozeb @4 kg ha^{-1}									
7.	Irrigation	June to September	wet & dry method					wet & dry method		Flooding about 5 cm depth		
	Total water quantity (m^3 ha^{-1})		8000	7000	6400	7500	7500	9000	9000	12,600	12,600	12,600
8.	Harvesting		Manually harvested									
9.	Threshing & winnowing		Tractor operated thresher									

H- Harrowing, T- Tiller (cultivator), R- Rotavator. Zero tillage (ZT), happy turbo seeder (HTS), bed planting (BP), reduced tillage (RT), conventional sowing (CS), direct sowing (DS), broadcast method of sowing (BS), manual transplanting (HT), manual transplanter (MT) and mechanical transplanter (MaT).

Table 2
Machinery equipment used in different mechanical operations and commonly available in farms of the regions.

Implements	Working width (mm)	Weight (kg)	Field efficiency (%)	Life (h)	Field speed/operating speed (km ha^{-1})	Effective field capacity (ha h^{-1})	Time for each operation (h ha^{-1})	Working depth (cm)
Harrow (14 disc)	1850	250	64.66	2500	3.80	0.45	2.20	10–12
Cultivator (9-tyne spring)	2000	220	58.48	3000	3.80	0.44	2.25	10–15
Rotovator	1500	500	68.38	4000	3.90	0.40	2.50	8–10
Zero till drill	1980	300	70	3000	5.18	0.5	2.50	3
Happy turbo seeder	2000	400	55.80	2400	3.20	0.27	2.80	2
Bed planter	1500	300	51.48	2500	3.70	0.29	3.50	–
Rotary tiller	1980	400	43.17	3000	3.60	0.31	3.25	8–10
Drum seeder	1425	16	60	1000	1.5	0.17	6.67	–
Manual transplanter	1000	20	55	2000	0.8–1.0	0.04	29.40	2–3
Self-propelled rice transplanter	1904	320	70.0	3000	1.57 to 1.97	0.2	2.50	3

were taken from the literature. These are presented in Table 3 [20–23]. Energy coefficients reported in different studies varied; these differential coefficients were due to differences in calculations and spatial and temporal system boundaries [24]. Due to this, the results of different studies are not comparable. However, in this study, energy coefficient values from Indian studies were used.

2.3.1. Energy use in machinery

Indirect energy use of agricultural machineries was calculated using the following equation:

$$E_{im} = (MTR \times M)/(L \times C_e) \quad (1)$$

where, E_{im} = Machinery input energy, MJ ha^{-1},

MTR = Energy used to manufacture, transport and repair (for tractor, 76 MJ kg^{-1} and farm machinery, 111 MJ kg^{-1}),
M = Mass of machinery, kg,
L = Life of machinery, h and
C_e = Effective field capacity of farm machinery, h ha^{-1}

Fuel consumption in different tillage operations depends on depth and width of ploughing, soil type, moisture content, tractor size, and the implement used. So, fuel consumptions in different tillage operations, which were done with different tillage implements drawn by a 45 HP two-wheel drive tractor, were estimated. Diesel energy was estimated from the total fuel used in different farm operations for rice crop production.

In this study, only the energy inputs used in crop production were included, but the renewable/built-in source of energy (solar radiation, wind, inbuilt fertility in the soil) was not considered since it has no opportunity cost. Moreover, these inputs are independent of the management practices. Manual labour and bullock power inputs were considered in this study, unlike in the other studies of developed countries, since significant amounts of human labour were used for weeding and intercultural operations. These values correspond to the biochemical energy potentially consumed by a person.

2.3.2. Irrigation energy

The energy required for pumping water from a well was calculated using the following equation:

$$DE = r \times g \times H \times Q/\ Ep \times Eq \quad (2)$$

where, DE direct energy (MJ ha^{-1}), r is water density (1000 kg m^{-3}), g is acceleration due to gravity (9.80 m s^{-2}), H is total depth of dynamic head (m), Q indicates volume of water required for one season (m^3 ha^{-1}), Ep is pump efficiency (80%) and Eq is total power conservation efficiency (20%) [25]. Transmission and production efficiencies were also considered for estimation of irrigation energy.

2.4. Output energy

Rice grain and straw yields were determined from the total plot area by harvesting all plants in the net plot area after excluding the plants bordering the individual plots. Sub-samples of grain and straw yields of rice were oven-dried at 65 °C for 48 h and weighed after 12% moisture content was attained during all years. The average grain and straw yields of all years were considered for calculating output energy. Energy outputs were calculated by multiplying the grain and straw yields with corresponding energy coefficients.

Energy efficiencies or intensities of the different rice crop establishment methods were estimated as: i) net energy, ii) ratio of output to energy input (energy use efficiency, EUE) and iii) specific energy (energy use per kg production). The formulae used for estimation of the energy efficiency variables (energy use efficiency, energy productivity and net energy) are presented in Table 5.

2.5. Greenhouse gas (GHG) emissions in different methods of rice cultivation

2.5.1. Carbon input data

Environmental impact of different rice cultivation methods was assessed by estimating the spatial and yield-scaled C foot print. Spatial C footprint is the total amount of GHG emissions (CO_2, N_2O and CH_4) released directly and indirectly during crop production in terms of CO_2 equivalents. The CO_2, CH_4 and N_2O emissions were converted into CO_2 equivalents using GWP equivalent factors of 1, 34, 298 for CO_2, CH_4 and N_2O, respectively. The C foot print was estimated considering the GHG emissions from fossil fuel used for different cultural operations (tillage, herbicide application, insecticide, planting and fertilizer application and harvesting) (operation GHG flux) and the production of fertilizers and seeds (input GHG flux). The amounts of GHG emissions in terms of CO_2 equivalent associated with agronomic inputs and farming operations were estimated by multiplying the inputs (diesel fuel, mineral fertilizers and biocide) with their corresponding C emission coefficients (Tables 3 and 4) [26,27]. However, the emission coefficients are unavailable for individual pesticide and herbicide application. Hence, it was assumed that the emissions during the processes of production, transportation, storage, and field applications were same for a similar group of pesticides [26]. Apart from the GHG emissions from farm operations and input uses, the N_2O emissions

Table 3
Energy and carbon coefficients of different input and output used in agriculture input.

Particulars	Energy coefficients (MJ unit^{-1})	Units	Source	GHG coefficients (kg CO_2 eq unit^{-1})	Units	Source
A. Inputs						
1. Labour						
(a) Adult man	1.96	MJ man h^{-1}	[20]	–		
(b) Woman	1.57	MJ man h^{-1}	[20]	–		
2. Diesel	56.31	Litre	[20]	0.94	Litre	[25]
3. Electricity	11.93	kWh	[20]	0.523	kWh	[26]
4. Machinery						
a) Farm machinery (Including self-propelled machines)	68.4	MJ kg^{-1c}	[20]			
b) Farm machinery (Excluding self-propelled machines)	62.7	MJ kg^{-1c}	[20]			
5. Chemical fertilizers						
(i) Nitrogen	60.6	MJ kg^{-1}	[19]	1.35	kg	[25]
(ii) Phosphate (P_2O_5)	11.1	MJ kg^{-1}	[19]	0.2	kg	[25]
(iii) Zinc sulphate	20.9	MJ kg^{-1}		4.18	kg	
(iv) Fe So_4	20	MJ kg^{-1}		0.18	kg	
6. Manure	0.47	MJ kg^{-1}	[21]			
7. Organic Fertilizer	2.02	MJ kg^{-1}	[21]			
8. Pesticides						
(i) Fungicides	97	MJ kg^{-1}	[21]			
(ii) Insecticides	184.63	MJ kg^{-1}	[21]			
Nuvan	120	MJ kg^{-1}	[21]	4.65	MJ kg^{-1}	[25]
(iii) Herbicides						
a) Pendimethalin	421	MJ kg^{-1}	[22]	3.00	MJ kg^{-1}	[25]
b) 2, 4-D	85	MJ kg^{-1}	[22]	1.70	MJ kg^{-1}	[25]
c) Quizalofop-p-ethyl	561	MJ kg^{-1}	[22]	10.4	MJ kg^{-1}	[25]
9. Seed						
(i) Rice	14.7	MJ kg^{-1}	[21]			
(ii) Straw (Rice)	13.4	MJ kg^{-1}	[21]			

Table 4
Precipitation, PET, parameters and emission factors used in the calculation of greenhouse gas emission.

Description	Revised coefficients	Source
Emission factor (EF), (%)	0.7	[26]
Leaching factor of N ($FRAC_{Leach}$) (%)	0.5	
Volatilization of NH_3 and NOx ($FRAC_{gasf}$), %	0.5	
Leaching emission factor (EF_{Leach}), $^{(\%)}$	0.5	
Volatilization emission factor (EF_{volat}), (%)	0.5	
FracGASF (gas loss through volatilization from inorganic fertilizer); (%)	15	
FracGASF–AM (gas loss through volatilization from manure); (%)	20	
Fracleach (leaching loss of N from applied fertilizer and manure); (%)	10	
Methane emissions		
Transplanted (kg CH_4 ha^{-1})	162	[27]
Direct sown (kg CH_4 ha $^{-1}$)	18	

from applied mineral fertilizers and residues and CH_4 emissions from different methods of rice cultivation were estimated using the emission factors (Table 4) [27,28]. The biomass left in soils and root biomass of the rice crop was calculated from the shoot: root ratios [26]. The total above ground biomass is estimated as the sum of grain and straw yields of the rice crop.

The direct (emission factor) and indirect N_2O emission (fraction of leaching and volatilization) factors are variable, uncertain and moreover they depend on method of rice cultivation, amount of mineral fertilizer addition, soil type, etc. [29]. In spite of the variations in direct emission factors of N_2O emissions, the Intergovernmental Panel on Climate Change (IPCC) recommended use of a common default emission factor of 1.25 kg N_2O emitted per 100 kg N applied to soils. But, in India, some studies have reported a specific emission factor of 0.76 kg of N_2O-N for 100 kg mineral fertilizer applied [30] for rice. This factor is lower than the IPCC default factor [27,31]. Hence, in this study, the GHGs emission factors for different techniques of rice cultivation were adapted from various published works in India [32,33]. Here, the N_2O and CH_4 emission from conventional methods of rice i.e. continuous flooded PTR was considered 0.75 kg and 162 kg, respectively (Table 4). While emission factors for other methods of cultivation were derived by comparing these emission factors. The N_2O emission factors 1.13 and 1.19, and CH_4 emission factors 0.6 and 0.07, respectively, were used for simulating GHGs emission from intermittent wetting and drying methods and direct seeded rice (DSR), respectively [34].

2.5.2. Indirect emission

The indirect soil N_2O emissions ($N_2O_{Indirect}$) are the N_2O emissions from nitrate leaching and volatilization of NH_3 and NO_x. These were calculated as:

N_2O from atmospheric deposition of N volatilized from managed soils

$$N_2O\ (ATD){-}N = (F_{SN} \times Frac\mathit{GASF}) \times EF_2 \tag{3}$$

N_2O (ATD)–N = annual amount of N_2O-N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O-N yr^{-1} (4)

F_{SN} = amount of mineral fertilizer N applied to soils, kg N yr^{-1}.
Frac $_{GASF}$ = Fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, kg N volatilized kg N applied^{-1}.
EF_2 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces [kg N-N_2O (kg NH_3-N + NOx-N volatilized)$^{-1}$. Default value 0.01.

N_2O from N leaching/runoff from managed soils in regions where leaching/runoff occurs

$$N_2O\ (L){-}N = (FSN + FON + FCR) \times Frac\ _{LEACH} \times EF_3 \tag{5}$$

N_2O (L)−N = Annual amount of N_2O-N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O-N yr^{-1}.
FSN = Annual amount of mineral fertilizer N applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}.
FON = Annual amount of compost and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}.
FCR = Amount of N in crop residues, kg N yr^{-1}.
$Frac_{LEACH}$ = Fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg N additions)$^{-1}$
EF_3 = Emission factor for N_2O emissions from N leaching and runoff, kg N_2O-N (kg N leached and runoff)$^{-1}$.

2.6. *Carbon output, carbon efficiency and carbon sustainability index*

Total C output is the sum of the carbon equivalent of grain, straw and root biomass produced by the crop. The below-ground root biomass was estimated from shoot: root ratio of paddy rice. Total C present in biomass was estimated by multiplying the yield with 40% C, as it was assumed that biomass contains 40% C. Carbon efficiency was calculated as ratio of C output to C input, whereas C sustainability index (CSI) was calculated by deriving difference between C output and C input and divided by C input. Carbon efficiency ratio (CER) was calculated following the equation:

CER = Grain yield (in terms of C)/CEE

where CEE = Carbon equivalent emissions.

2.7. *Statistical analyses*

The experiment was laid in randomized block design (RBD) with three replications. The data on energy input and output, carbon foot print were subjected to analysis of variance as per the procedure [35] and treatment means were compared using least significant difference (LSD) at 5%.

3. Results and discussion

3.1. *Energy balance*

In the present study, the energy analysis of different methods of rice cultivation was estimated and compared. The total energy used for different agricultural operations in different paddy cultivation methods ranged from 25,724 to 38,879 MJ ha^{-1} and were significantly influenced by the method of rice cultivation (Table 5). In general, transplanted method of rice cultivation recorded higher energy input than the direct sowing methods. These findings were in agreement with Islam et al., 2013 [36]. Among different transplanted methods, HT and MT recorded higher energy input than MaT. But, the energy inputs in different transplanting methods were similar to each other. Human labour transplanted method (HT) recorded 43, 51, 49, 43, 33, 25 and 25% higher energy use over ZT, HTS, BP, RT, CS, DS and BS, respectively. The lowest energy input was recorded in HTS and this was followed by BP, ZT, RT, CS, DS and BS treatments. However, the energy inputs of HTS, BP and ZT were similar and were lower than CS, DS and BS (Table 6). The higher energy use in different puddled transplanting methods (i.e. MaT, HT and MT) over direct sowing methods was due to higher energy use for nursery raising, land preparation and irrigation. The higher irrigation water energy was due to water use for puddling and cultivation of the transplanted rice compared with direct sowing methods. Similar results were reported by Pathak et al. [33] and liu et al. [37]. The DS method recorded 85% higher energy use for weed control and inter-cultivation compared with transplanted method of rice cultivation. This was due to use of higher quantity of herbicide use in direct methods of rice cultivation (Table 7). In transplanted method, flooding reduced the weed burden, which contributed to lower use of herbicides. Ozpinar and Ozpinar [38,39] established that shallow rootling increased the total weed density compared to mouldboard ploughing. But energy saving in interculture operation and weed control under transplanted rice could not compensate the higher energy use in nursery raising, puddling and irrigation. These observations supported several investigations that the energy input for fuel consumption can be decreased by reducing tillage operations [40].

The operation wise energy contributed by human, animal and machinery were also calculated in terms of MJ ha^{-1}. Crop management practices recorded higher share of energy in all methods of rice cultivation (Table 6). Higher share of energy in crop

Table 5
Description and units of energy and carbon parameters used in this study.

Parameters	Description	Abbreviation	Unit
Direct energy	Diesel + labour + bullock + electricity	DE	MJ ha^{-1}
Indirect energy	Machinery + fertilizers + pesticides + seeds	IDE	MJ ha^{-1}
Renewable energy	Labour + bullock + seed	E_R	MJ ha^{-1}
Non-renewable energy	Machinery + diesel + electricity + chemical fertilizer + pesticides	E_{NR}	MJ ha^{-1}
Total energy input	Sum of direct and indirect energy or sum of renewable energy and non-renewable energy	EI	MJ ha^{-1}
Grain energy output	Energy in the harvested grain (grain)	EO_g	MJ ha^{-1}
Total energy output	Energy in the harvested total biomass (grain + straw)	EO_t	MJ ha^{-1}
Grain net energy	Grain energy output − energy input	NE_g	MJ ha^{-1}
Total net energy	Total energy output − energy input	NE_t	MJ ha^{-1}
Grain energy use efficiency	Grain energy output/energy input	EUE_g	–
Total energy use efficiency	Total energy output/energy input	EUE_t	–
Grain specific energy	Grain yield/energy input	SE_g	MJ kg^{-1}
Total specific energy	Total biomass yield/energy input	SE_t	MJ kg^{-1}
Global warming potential	Sum of total CO_2 and N_2O emission converted into CO_2 eq.	GWP	kgCO_2 eq ha^{-1}
Greenhouse gas (GHG) emission	Sum of total CO_2 and N_2O emission converted into CO_2 eq.	GHG	Kg CO_2 eq ha^{-1}
Carbon Input	(Sum of total GHG emission in co_2 eq.)* 12/44	CI	kg C eq ha^{-1}
Carbon output	Total biomass * 0.4	CO	kg C eq ha^{-1}
Carbon sustainability index	(C output − C input)/C input	CSI	–
Carbon efficiency	C output/C input	CE	–

Table 6
Input/source wise energy (MJ ha^{-1}) use different resource conservation techniques.

Parameters	ZT[a]	HTS	BP	RT	CS	DS	BS	HT	MT	MaT
Fossil Fuel (diesel)	516	1036	2371	1352	3290	1951	1951	3408	3344	3475
Manual labour	770	739	764	739	786	1225	1256	1272	895	816
Electricity	6437	5632	5149	6034	6035	7243	7243	10,379	10,331	10,192
Machinery	394	384	570	455	665	586	586	859	879	904
Fertilizers	9140	9140	9140	9140	9140	9140	9140	9140	9140	9140
Pesticides	211	211	211	211	211	211	211	211	211	211
Herbicides	707	707	707	707	707	707	707	707	11	11
Seed	735	735	735	735	735	735	735	441	441	368
Water energy	8160	7140	6528	7650	7650	9180	9180	13,158	13,097	12,886
Total Energy (MJ ha^{-1})	27,069	25,724	26,174	27,023	29,218	30,986	31,009	38,879	38,348	37,992

[a] Refer to Table 1 for treatment details.

Table 7
Operation wise energy (MJ ha-1) use in different rice crop establishments under different conservation techniques.

Parameters	ZT[a]	HTS	BP	RT	CS	DS	BS	HT	MT	MaT
Nursery	0	0	0	0	0	0	0	1007	824	185
Land preparation, sowing and transplanting	1255	1334	2871	1636	3815	2740	2763	3714	3366	3621
Fertilizer	9250	9250	9250	9250	9250	9250	9250	9250	9250	9250
Herbicides/Intercultural	927	927	927	927	927	927	927	134	134	134
Pesticides	282	282	282	282	282	282	282	282	282	282
Irrigation	15,153	13,259	12,173	14,191	14,206	17,049	17,049	23,753	23,753	23,781
Harvesting and threshing, winnowing	203	673	673	738	738	738	738	738	738	738
Total	27,069	25,725	26,174	27,023	29,218	30,986	31,009	38,879	3835	37,992

[a] Refer to Table 1 for treatment details.

management was due to higher energy use for irrigation and fertilizers. The irrigation energy in different methods of cultivation was maximum. Alipour [41] also reported higher irrigation energy in rice production. But these findings differed with Agha-Alikhani et al. [42], who reported higher energy use with mineral fertilizers (43%).

The irrigation energy use in different methods of rice cultivation ranged from 46 to 61%. The share of irrigation energy to the total energy was about 61% in transplanting methods of rice cultivation. Contrarily, in direct methods of cultivation, it ranged between 46 and 55%. Among different methods of rice cultivation, the lowest irrigation energy was recorded in BP and CS (46%). The higher irrigation energy in transplanting compared with direct sowing was due to electricity use for pumping of irrigation water for puddling, nursery raising and continuous flooding of water for the crop growth [43]. Puddled transplanting consumed 36, 44, 48, 40, 40, 28 and 28% higher irrigation energy over ZT, HTS, BP, RT, CS, DS and BS, respectively. However, saving of irrigation energy especially in terms of irrigation water would depend on the rainfall patterns. The share of mineral fertilizers ranged between 14 and 21% of total input energy across different treatments. The fertilizer energy was 21% of total input energy in ZT, HTS and BP. However, in puddled transplanting the fertilizer energy was 14%. The share of weed control and inter-culture operations were higher in direct methods of rice cultivation. The energy consumed for weed control through herbicides and inter-culture in direct sowing methods (ZT, HTS, BP, RT, DS, BS) of rice was 84% higher over HT, MT and MAT. Similarly, higher weed infestation in direct seeded methods of rice cultivation (ZT, HTS, BP, RT, CS, DS, BS), than transplanted puddled method was reported by many researchers.

Among different sources of energy uses, the electricity used for pumping irrigation water recorded the highest energy over other sources of energy. In transplanting method, the share of electricity was the highest. The fossil fuel (i.e. diesel) energy use varied from 516 to 3475 MJ ha^{-1} in different treatments (Table 6). The highest fossil fuel energy input was recorded in MaT. This higher fossil fuel

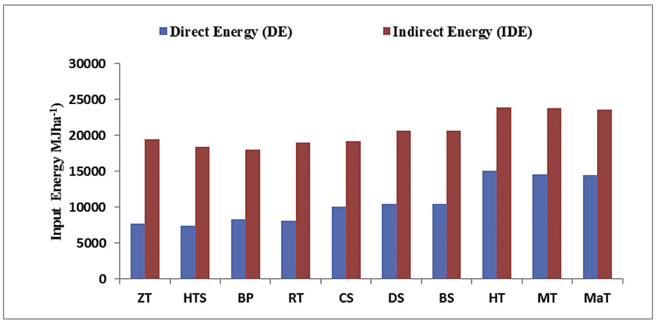

Fig. 1. Direct, Indirect energy (MJ ha^{-1}) under different paddy establishment techniques. zero tillage (ZT), happy turbo seeder (HTS), bed planting (BP), reduced tillage (RT), conventional sowing (CS), direct sowing (DS), broadcast method of sowing (BS), manual transplanting (HT), manual transplanter (MT) and mechanical transplanter (MaT).

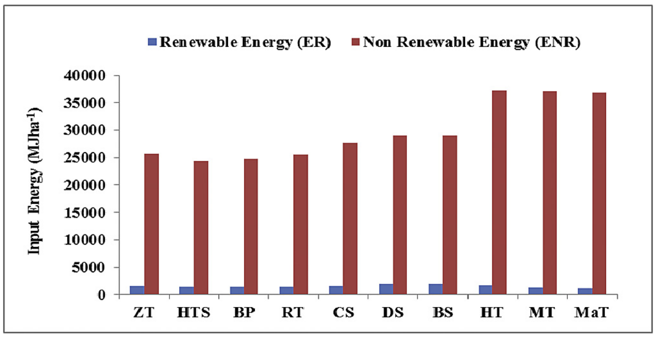

Fig. 2. Renewable and non-renewable energy (MJ ha^{-1}) under different paddy establishment techniques. zero tillage (ZT), happy turbo seeder (HTS), bed planting (BP), reduced tillage (RT), conventional sowing (CS), direct sowing (DS), broadcast method of sowing (BS), manual transplanting (HT), manual transplanter (MT) and mechanical transplanter (MaT).

Table 8
Energy (MJ ha^{-1}) balance in different rice crop establishment under resource conservation techniques.

Treatments[a]	EI (MJ ha^{-1})	EO_g (MJ ha^{-1})	EO_t (MJ ha^{-1})	NE_g (MJ ha^{-1})	NE_t (MJ ha^{-1})	EUE_g	EUE_t	SE_g (MJ kg^{-1})	SE_t (MJ kg^{-1})
ZT	27069^{b}	69178^{b}	132614^{c}	42109^{ab}	105545^{bc}	2.55^{ab}	4.89^{a}	5.75^{e}	2.87^{d}
HT/ST	25724^{a}	69531^{b}	131680^{c}	43807^{a}	105956^{bc}	2.7^{a}	5.11^{a}	5.44^{e}	2.75^{d}
BP	26174^{a}	64739^{cd}	115176^{d}	38565^{bc}	89002^{e}	2.47^{b}	4.4^{b}	5.94^{e}	3.2^{c}
RT	27023^{b}	63680^{d}	131833^{c}	36657^{c}	104809^{bcd}	2.36^{c}	4.87^{a}	6.23^{d}	2.87^{d}
CS	29218^{c}	68208^{bc}	127302^{c}	38990^{bc}	98084^{d}	2.33^{cd}	4.35^{cd}	6.29^{bcd}	3.22^{ab}
DS	30986^{d}	68237^{bc}	128886^{c}	37251^{bc}	97900^{cd}	2.2^{c}	4.16^{bc}	6.67^{cd}	3.38^{bc}
BS	31009^{e}	65092^{cd}	126678^{c}	34082^{c}	95669^{d}	2.09^{cde}	4.08^{bc}	7.00^{bc}	3.44^{bc}
HT	38879^{f}	77322^{a}	145957^{b}	38443^{ab}	107078^{d}	1.98^{e}	3.75^{d}	7.39^{a}	3.74^{a}
MT	38348^{f}	76469^{a}	146096^{b}	38122^{ab}	107747^{b}	1.99^{de}	3.81^{d}	7.37^{ab}	3.68^{a}
MaT	37992^{f}	79645^{a}	155033^{a}	41653^{a}	117041^{a}	2.09^{de}	4.08^{cd}	7.01^{ab}	3.44^{ab}

Letters in the superscript indicate significance levels. Means followed by same letter are not significantly different.

[a] Refer to Table 4 for treatment details.

energy consumption in MaT was due to more number of field operations for land preparation and puddling. Human labour energy consumption for various field operations in different treatments ranged from 739 to 1272 MJ ha^{-1}. Mechanization had significant share of input energy in conventional transplanted method. More tillage operations in transplanted method of cultivation used more energy, which varied from 384 to 904 MJ ha^{-1}. The seed energy was lower in transplanting methods of rice cultivation than DSR, since the seed rate used was lower in transplanting methods.

In all methods of rice cultivation, indirect and non-renewable energy consumption was higher than direct and renewable energy (Figs. 1 and 2). Irrigation water energy in all methods of rice cultivation was the highest indirect energy consumption, which indicated that rice cultivation methods with low water use might be required. Direct energy in different methods of rice cultivation was between 28 and 39%, while indirect energy was 59–71% of total energy consumption. The ZT, HTS, BP and RT methods recorded the lowest direct energy whereas, the transplanting methods had higher direct energy over direct sowing methods. This was due to more number of irrigations and electricity used for irrigation and fossil fuel use for the land preparation and puddling operations in the transplanting methods. Renewable energy systems in all rice cultivation methods were very low and showed that rice production was based on non-renewable resources.

3.2. *Output energy*

Grain energy output (EO_g) was directly related to the productivity. Hence, the highest energy output was observed in the treatment with the highest yield. Among different rice establishment methods, MaT recorded higher EO_g (79,645 MJ ha^{-1}), but this value was similar to MT and HT. This value was significantly ($P < 0.05$) superior to other direct sowing methods. The higher EO_g in PTR was due to higher rice grain yield. Similar grain yield decline of dry DSR compared to transplanted-flooded rice was reported from farmers' participatory trials [5]. The EO_g in transplanting method was followed by ZT (69,178 MJ ha^{-1}), HTS (69,531 MJ ha^{-1}), DS (68,237 MJ ha^{-1}) and CS (68,208 MJ ha^{-1}), were similar but were significantly higher than BP (64,739 MJ ha^{-1}), RT (63,680 MJ ha^{-1}) and BS (65,092 MJ ha^{-1}) methods (Table 8). The lowest EOg was recorded in RT (63,680 MJ ha^{-1}) and BP (64,739 MJ ha^{-1}) methods. Similar results were observed in total energy output (EO_t). Crop residue left over in the field was not included in estimation of total energy output, since these were returned to the land at the end of a crop season [40]. Highest total energy output was recorded in MaT method and the value was significantly superior to all other treatments. All direct sowing methods had similar total energy outputs, except BP method. ZT (42,109 MJ ha^{-1}) and HTS (43,807 MJ ha^{-1}) recorded higher grain net energy gain (NE_g) and the values were comparable. Lower NEg was recorded in BS and RT methods. But the total net energy (NE_t) had a different trend than NE_g. This was due to higher biomass in transplanted puddled fields compared with other methods of rice cultivation. The highest value of NE_t was recorded in MaT (116,143 MJ ha^{-1}). However, MT, HT, ZT, CS and HTS had similar NE_t values to that in MaT.

Grain energy use efficiency (EUE_g) and total energy use efficiency (EUE_t) were significantly influenced by different establishment methods adopted for rice cultivation (Table 8). The transplanting methods of rice cultivation recorded lower EUE than direct sown methods. MaT (2.09), MT (1.99), HT (1.98) recorded significantly lower EUE than other methods of rice cultivation. Among direct sown methods, HTS recorded significantly higher EUE (2.70) and this was similar to ZT (2.55) and BP (2.47) methods. Comparable rice yield in the DSR system with transplanted rice, and less energy use in former methods justifies higher energy use efficiency in direct sowing methods than transplanted methods of rice cultivation.

Specific energy is an index which indicates the energy used to produce one unit of the product. Higher grain specific energy (SE_g) was observed in transplanting methods of rice cultivation than direct methods. Highest SE_g was recorded in HT (7.39 MJ kg^{-1}) and this was followed by MT (7.37 MJ kg^{-1}) and MaT (7.01 MJ kg^{-1}). These SEg values were significantly higher than other treatments. The lowest SEg was recorded in HTS (5.44 MJ kg^{-1}), ZT (5.75 MJ kg^{-1}) and BP (5.94 MJ kg^{-1}) methods. However, SE_t was not affected by the studied treatments. The higher specific energy indicated poor energy output to the energy use in the transplanted method of rice cultivation compared to DSR (Table 8).

3.3. *Greenhouse gas emissions and global warming potential*

The GHG emissions (CO_2, CH_4 and N_2O emissions) revealed that 70–75% of the total emissions under direct seeded un-puddled rice were CO_2 emissions only, mainly due to field operations. This was followed by N_2O-based CO_2 equivalent emissions (14-13%), due to fertilizer application and rest (10%) was CH_4 emissions [45,46]. Whereas, in the puddled transplanted method of cultivation, CH_4 emissions based CO_2 equivalent emissions were highest (57%). This was followed by farm operations based CO_2 emissions (39%) and the N_2O emissions were negligible (~4%).

Among different methods, the puddled transplanting method of rice cultivation recorded 61–66% higher GWP (CO_2 equivalent GHG emissions) compared with direct sown un puddled methods of rice cultivation. This higher GWP in puddled transplanting method was because of higher CH_4 emissions and field-based CO_2 emissions. Puddling and continuous flooding of rice fields promote methanogenesis, thereby increase CH_4 emission. Contrarily, DSR has been reported to reduce CH_4 emission effectively due to aerobic

Table 9
Greenhouse gas (GHG) emissions as influenced by different paddy establishment techniques.

Treatments[a]	Input emission					Tillage and product application	GHG emission			CO_2 equivalents
	Diesel fuel	Fertilizer production	Herbicide production	Pesticides production	Electricity (kWh)		CO_2	CH_4	N_2O	
ZT	31.56	762	14.14	4.12	1735	28.17	2574	612	488	3674.1
HTS	63.4	761.7	14.14	4.12	1517.6	10.59	2371	612	488	3472.5
BP	190.8	761.7	14.14	4.12	1387.5	25.29	2384	612	488	3484
RT	82.7	761.7	14.14	4.12	1626.0	9.62	2498	612	488	3598.1
CS	201.3	761.7	14.14	4.12	1626.0	25.1	2632	612.0	488	3732
DS	119.4	761.7	14.14	4.12	1951.6	19.39	2870	612	488	3970
BS	119.4	761.7	14.14	4.12	1951.6	14.99	2865	612	488	3966
HT	189.0	761.7	0.22	4.12	2796.6	25.58	3777	5508	320	9605
MT	189.0	761.7	0.22	4.12	2783.6	33.37	3772	5508	320	9600
MaT	210.5	761.7	0.22	4.12	2738.7	37.7	3753	5508	320	9581

[a] Refer to Table 1 for treatment details.

Table 10
Carbon (C) input (kg ha^{-1}), C output (kg ha^{-1}), carbon sustainability index (CSI), C efficiency and kg CO_2 equivalent kg^{-1} grain under different paddy establishment techniques.

Treatments[a]	C input	C output	CSI	C efficiency ratio (CER)	kg CO_2 e kg^{-1} grain
ZT	1002	3776	2.77	3.77	0.78
HTS	947	3747	2.96	3.95	0.73
BP	950	3267	2.43	3.43	0.79
RT	981	3767	2.83	3.84	0.83
CS	1018	3620	2.55	3.55	0.80
DS	1083	3667	2.39	3.38	0.85
BS	1082	3610	2.33	3.33	0.90
HT	2619	4153	0.59	1.58	1.82
MT	2618	4159	0.59	1.59	1.84
MaT	2613	4417	0.69	1.69	1.77

[a] Refer to Table 1 for treatment details.

conditions [46]. In direct seeded un puddled method of rice cultivation, foregoing puddling and tillage in rice-based production systems of IGP coupled with improved water management reduced CH_4 emission. However, in the puddled transplanted method, high power and energy requirements due to higher number of tillage operations and puddling translated into higher fuel consumption. Additionally, more working time of implements could lead to faster depreciation rate of equipments, This could lead to increased emissions from farm operations and from the machinery manufacturing processes. Apart from fuel use, consumption of electricity for water pumping (with electric pumps) contributed to higher CO_2 emissions. This higher emission (due to fuel use and irrigation water) was owing to more number of tillage operations for land preparation and higher water requirement in transplanted rice. Gupta et al. [33] reported higher GWP in rice due to the indirect emissions as a result of farm operations, such as continuous flooded transplanted rice, use of electric pump, application of high amount of nitrogenous fertilizer and conventional tillage using a tractor. But, CO_2 equivalent N_2O emissions were negligible, like the results of this study.

The un puddled DSR method recorded lower GHG emissions. Among different direct sown un puddled methods of rice cultivation, HTS, BP, RT and ZT recorded lower CO_2 equivalent emissions than PTR method and the values of these direct sown methods were comparable. These differential GHG emissions in different direct sown un puddled methods were due to reduced fossil fuel consumption [47] and less indirect emissions associated with energy consumed in manufacture, transport, repair and use of machines (due to reduced number of operations and lower irrigation water use under DSR than PTR).

Analysis of different factors to the GHG emissions was done to assess the contribution of different sources and agronomic inputs to GHG emissions in different methods of rice cultivation. The results revealed that in direct sown un puddled method of rice cultivation, electricity was the major source of GHG emissions (Table 9). This higher emission was due to pumping of irrigation water. In un puddled direct sown method, CO_2 equivalent CH_4 emissions decreased significantly, although CO_2 equivalent N_2O emissions increased [45]. However in puddled transplanting method, CO_2 equivalent CH_4 emissions were higher than CO_2 and CO_2 equivalent N_2O emissions (although the CO_2 equivalent N_2O emissions were negligible). Similar results were reported by Hulsbergen [23].

The pooled yield data of 16 years revealed that C output of different method of rice cultivation was significantly influenced by methods of rice cultivation. Plots under MaT had higher total C output and was similar to MT and HT plots (Table 10). The MaT method recorded 14, 15, 26, 15, 18, 17 and 18% higher yield than ZT, HTS, BP, RT, CS, DS and BS methods of rice cultivation, respectively. Transplanting method had lower CSI and CER than direct sown un puddled conditions. Among direct sown un puddled method of rice cultivations, HTS and ZT had higher CSI and CER than other methods. The higher CSI in HTS and ZT was due to reduced C input and reduced number of tillage operations. Higher CER indicated more C efficiency in these treatments. Transplanting method had higher GHG emission than the direct sown methods of rice cultivation. This study thus indicated that DSR could be an important practice to reduce GWP of rice cultivation.

3.4. Uncertainty in assessment

The CH_4 and N_2O emission from agricultural soils are the chief sources of emissions in puddled transplanted and direct sown rice, respectively. But the estimations of these emissions may be of major uncertainty. The large doubt may be due to uncertainties related to the emission factors, natural variability, activity data, lack of coverage of measurements and spatial aggregation [48]. The N_2O emission factors depend mostly on the amount of mineral fertilizer applied and, to a lesser extent, on the specific characteristics of the site, such as temperature, soil or crop type. The emission factors also depend on the method of rice cultivation, soil moisture conditions, rainfall and temperature [28]. In spite of the variations, the IPCC recommends the use of a default emission factor for direct emissions from N inputs in managed agricultural soils of 1.25% (EF1 in IPCC tier 1 methodology). However, some authors recommend Indian-specific emission factor which is lower by almost 44% than the IPCC default emission factor [26,29]. In Indian scenarios, the EF ranged from 0.14 to 12.8%. The discrepancy for Indian values seems to be related to limited locations for data collection, as most values are derived from very controlled experimental conditions. Consequently, the methodology exclude factors that are crucial in determining the emissions, and have no means to assess the potential impact of future climate and land use change.s In addition, to CH_4 and N_2O emissions, the uncertainty may also exist in field operations based emissions. The emissions from N, P and K fertilizers and from use of pesticides were estimated using those reported by Refs. [44,45] as Indian factors are not available.

Most studies in the past were not as comprehensive as this was. In this study, a novel attempt was done to assess GWP (by measuring CO_2, N_2O and CH_4 emission) of the major rice cultivation methods of irrigated agriculture, based on GHGs emissions from soils and all field operations followed to cultivate rice under a tropical climate. In addition, energy balance and C sustainability index of all rice cultivation methods were appraised. Based on all information it was evident that although transplanting methods of rice cultivation yielded higher productivity, the energy input and GWP of some DSR plots (HTS, ZT and BP) were much less than the former method (farmers' practice).

4. Conclusions

Of the total rice cultivated area in India 44% is under TPR. Results of this study revealed that TPR method had 14–26% higher grain yield (C output) than DSR. However, TPR method of rice cultivation (HT, MT and MaT plots) consumed about 47% higher energy than some DSR plots (HTS and BP). Additionally, the GWP of TPR methods of cultivation was about 170% higher than best DSR practices (HTS and BP plots). Interestingly, N_2O emissions from the DSR practices were significantly higher compared with transplanting methods of rice cultivation and future research is needed to counter this problem under DSR. Thus, despite higher productivity under transplanting methods of rice cultivation, the energy input and GWP of some DSR plots (HTS, ZT and BP) were much less than the former practice. Analyzing all impacts, un puddled direct-seeded rice cultivation methods (mainly HTS) is a sustainable and very feasible alternative to TPR in the region, as it requires low energy input, higher EUE and reduced GHG emissions due to fuel saving and decreased CH_4 emissions.

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