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RESEARCH

Conservation Tillage Enhances Energy Efficiency and Mitigates Carbon Footprint and Greenhouse Gas Emissions in Long-Term Wheat Production Trials in the Western Indo-Gangetic Plain of India

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Abstract

Traditional rice and wheat cropping system (RWCS) of the western Indo-Gangetic Plains (IGP) is not only less productive, but also unsustainable owing to its elevated energy demands and environmental carbon footprint. Transition towards the long-term adoption of conservation agriculture (CA) technologies can possibility overcomes these constraints and making it a crucial component of modern farming systems. Therefore, the effects of conservation tillage and residue retention on wheat cultivation were evaluated from 2015–2016 to 2019–2020 under RWCS on CA fields maintained for twenty one years. Five tillage treatments viz., zero tillage without residue retention (ZT-R), zero tillage with residue retention (ZT+R), permanent bed planting without residue retention (PBP-R), rotary tillage without residue retention (RT-R) and conventional tillage without residue retention (CT-R) were evaluated in four times replicated randomised complete block design. The CT-R recorded 28%, 25%, 24%, and 16% higher energy inputs than those of the ZT+R, ZT-R, PRB-R, and RT-R, respectively. Nevertheless, the lowest grain energy output was recorded in RT-R (86,769 MJ ha^{-1}) and CT-R (86,926 MJ ha^{-1}). Under CT-R, greenhouse gas (GHG) emissions were approximately 20%, 19%, 17%, and 10% greater than those under ZT-R, ZT+R, PRB-R, and RT-R, respectively. Compared to ZT-R, ZT+R, PRB-R, and RT-R plots, CT-R exhibited significantly lower carbon efficiency ratio and carbon sustainability index. The long-term study revealed that ZT+R represent a promising step towards sustainability, characterized by low global warming potential and high energy use efficiency. This makes it an appealing agricultural technique for wheat production in the sub-tropical IGP regions under irrigated RWCS.

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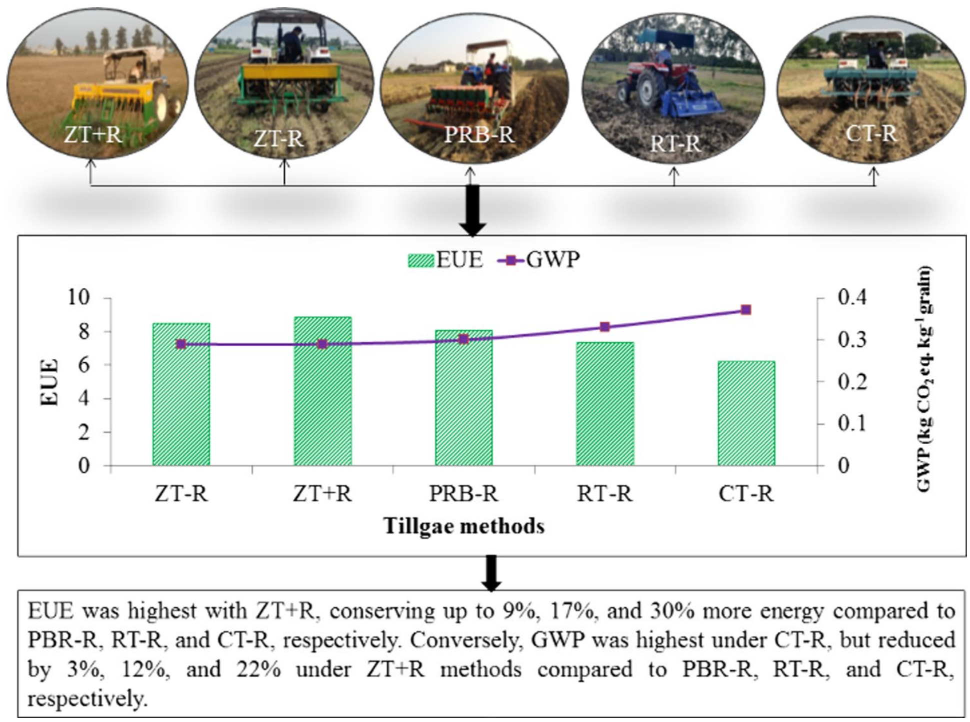
Graphical Abstract



Keywords Conservation agriculture · Energy budgeting · GHG emissions · Rice–wheat cropping system · Tillage methods

Introduction

Over 217 million hectares (Mha) of wheat (*Triticum aestivum* L.) are grown worldwide, yielding 731 million tons (Mt) of grain (USDA, 2018). Wheat, an indispensable food for approximately 2500 million people worldwide (FAO, 2024), is a key component of the largest rice and wheat cropping system (RWCS), which covers ~85% (Dhanda et al., 2022) and 13.5 Mha of area (Brar et al., 2023) of the Indo Gangetic Plains (IGP). With an average productivity of 3371 kg ha^{-1}, RWCS ranks second in the world's food production (MoA & FW, 2018). RWCS is cultivated over 9.2 Mha in India, representing 35.38% of the world's area (26 Mha) under RWCS (Dhanda et al., 2022; Jat et al., 2020) and together, these crops accounted for approximately 74.7% and 46.7% of total grain production of the India and the world, respectively (PIB, 2023; FAO, 2024). Wheat is the third most significant cereal crop in India following rice and maize. Wheat grows with intensive tillage practices by majority of farmers in the IGP in the traditional RWCS, which enhances crop productivity by reducing weed infestation. However, conventional tillage operations increase greenhouse gas (GHG) emissions and energy input due to burning of fuels and natural oxidation of organic matters in the soil (Chakrabarti et al., 2015). Furthermore, intensive tillage operation delays wheat sowing, as it takes time to prepare the field. Delayed sowing reduces the wheat yield owing to terminal heat stress (Chhokar et al., 2023). The rice residues burning in the IGP is a major cause of worry, causing pollution and GHG emissions. Therefore, retaining rice residues and planting wheat with ZT could be an alternative for environmental protection. Additionally, ZT in wheat with or without crop residue retention (CRR) reduces the input energy (EI) (Honnali et al., 2021), improves soil organic carbon (SOC) (Sawant et al., 2023), total nitrogen content (Rani et al., 2017) and also decreases the GHG emissions. Inappropriate and intense tillage are the main causes for soil degradation, which in turn led to low productivity of agricultural crops. Furthermore, the residue burning and higher usage of machines for tillage resulted in higher carbon and energy inputs and higher cost of cultivation (Das et al., 2021). Cultivating crops involves various practices like tillage, manuring, fertilization, irrigation, and inter-cultural operations. Furthermore, these activities contribute to increased GHG emissions per unit area, negatively impacting the environment. Maraseni et al. (2018) reported that in RWCS, rice alone produces approximately 10% of total agricultural GHG emissions worldwide accounts for 1.3–1.8% of human-induced GHG emissions. In India, puddled rice adds approximately 24% of overall agricultural methane emissions (3.37 Mt). Moreover, the nitrogenous fertilizer application in crops like rice and wheat results in about 0.14 Mt of N_2O emissions (Bhatia et al., 2013). Among different agro-techniques in wheat cultivation, 25−30% of the total cost is due to soil tillage for land preparation alone (Uri, 2000). Besides cultivation cost, soil tillage is a substantial cause of GHG emissions in agricultural production (Tjandra et al., 2016). Conservation agriculture (CA) has the potential to decrease overall energy need by 13.2%, lower CO_2-equivalent emissions by 13.9%, and enhance energy use efficiency (EUE) and energy productivity (EP) by 17% in RWCS (Gathala et al., 2020). Given these findings, it becomes imperative to identify a crop sowing method that not only increases yield and energy output but also enhances energy efficiency while minimizing energy input and carbon footprint (CF). The pressing need is to adopt sustainable practices that strike a balance among agricultural productivity and environmental management. The CRR on the soil is a major investment to the future and it can increase the system productivity due to decrease in the amount of water and soil lost by erosion, increased soil moisture retention and improvement in SOC (Meena et al., 2016).

Despite GHG emission by rice was systematically and extensively studied at various levels (Chaudhary et al., 2017), very few studies assessed CF and energy balance of wheat in the RWCS, especially in the sub-tropical IGP. Hence, the current study was undertaken from 2015–2016 to 2019–2020 under RWCS in the IGP, with the goal of developing an environmentally acceptable tillage practices aligned with increased crop productivity, and reduced GHG emissions and energy usage for small farmers. The impact of tillage practices on the energy balance and carbon usage efficiency of wheat in a long-term RWCS was assessed.

Material and Methods

Site, Soil and Climatic Description

The CA field was maintained for 21 years during 1998–2019 in the experimental farm of ICAR-Indian Institute of Farming Systems Research (ICAR-IIFSR), Modipuram, Meerut (UP), India (29°84′N, 77°46′E, 237 m altitude) situated in the IGP. In the same field, experiment was conducted for wheat cultivation using conservation tillage for 5 years during 2015–2016 to 2019–2020 to check the effect of various tillage methods on crop growth and yield attributes, energetics, GHG emission and GWP. The soil of an experimental location was Typic Ustochrept, exhibited a sandy loam texture (17% clay, 19% silt and 64% sand). The soil at 0–15 cm layer was slightly alkaline and non-saline with pH of 8.2 and EC of 0.27 dS m^{-1}, respectively. Available nitrogen content in the soil was measured at 154 kg ha^{-1}, while oxidizable SOC was found to be 4.4 g kg^{-1}. Furthermore, the soil displayed medium levels of phosphorus (0.5 M $NaHCO_3$ with 14.1 kg ha^{-1} available P) and potassium (neutral normal NH_4OAC extractable 125 kg ha^{-1}) and deficit in available Zn (DTPA-extractable Zn 0.73 mg kg^{-1}). The climate of the experimental location was categorized as semi-arid and sub-tropical. The maximum temperatures of the location was ranging from 26.4 to 33.7 °C and minimum temperatures ranging from 10.9 to 23.4 °C recorded at the farm's meteorological observatory. The rainy season (July–October) experienced a mean seasonal rainfall of 583 mm, while the wheat growing season (November to April) had a mean seasonal rainfall of 80 mm.

Treatments and Experimental Design

The investigation utilized a randomized complete block design featuring five distinct treatments viz., zero tillage with 6 t ha^{-1} rice residue retention (ZT+R), zero tillage without CRR (ZT-R), permanent bed planting without CRR (PBP-R), rotary tillage without CRR (RT-R), and conventional tillage without CRR (CT-R), each with four replications. The plots size of experiment was measured as 4.0 m × 15.0 m. The field layout and treatments were maintained throughout the study period (from 2015–2016 to 2019–2020). In ZT+R, wheat was directly sown in rice crop residues (6 t ha^{-1}) using a turbo happy seeder, while in ZT-R, wheat was sown without tillage and CRR using a zero-till planter. The quantity of retained rice residue, measured at 6 t ha^{-1}, was determined by collecting and oven-drying both the loose and anchored rice straw above the ground surface left behind by the combine harvester. The height of the anchored rice straw left behind by the combine harvester was 300 ± 100 mm. In case of PRB-R, tillage (twice harrowing + once tiller + once rotavator) was done and beds were formed only in first year of experiment and sowing was done using raised bed shaper-cum-planter. In experimental plots following RT-R, wheat was sown using a single pass of a rotary till drill, whereas in CT-R, the standard regional farming practice involving two passes of cultivator followed by one pass of disc harrow, one pass of rotavator and planting with a drill. The machinery used for plant protection (e.g., sprayer), harvesting (combine harvester), and irrigation (electrically operated submersible pump) were same and remained consistent across all tillage treatments. The wheat cultivar of PBW-343 was cultivated in accordance with recommended agronomic practices (Chaudhary et al., 2006) in all treatments. An even application of 120 kg N, 80 kg P_2O_5, and 60 kg K_2O per hectare was administered in all tillage treatments. The N was applied through urea in three splits: 50% as a basal application and 25% each in two top dressings at the crown root initiation stage, approximately

20–25 days after sowing (DAS), and at the tillering stage, around 40–45 DAS. The K_2O and P_2O_5 fertilizers were applied at sowing in the form of muriate of potash (KCl) and single superphosphate, respectively. The CA influences weed infestation due to adoption of no tillage practice; therefore timely herbicide application is crucial for uniform plant growth (Sharma & Singh, 2014). In this study, weed management was accomplished through the utilization of glyphosate (*N*-(phosphonomethyl)-glycine), a non-selective herbicide @ 1.5 kg a.i. ha^{-1} and sulfosulfuron and metsulfuron methyl as a post-emergence herbicides @ 25 g a.i. ha^{-1} and 4.00 g a.i. ha^{-1}, respectively 30 days after sowing (DAS), followed by manual weeding of any remaining weeds at 45 DAS. Approximately 50 ± 20 mm of water was applied to all treatments using the open channel irrigation method. Four to five irrigations were given to wheat each year, as per the need. Harvesting of wheat was done at maturity during the month of April using combine harvester. The grain and straw yields were noted at 12% moisture content, and the yields were averaged over 5 years. Crop residues were removed from all treatments, except ZT+R.

Energy Budgeting

The EI, output, net energy (NE), EUE and specific grain energy were calculated for various treatments using energy equivalent factors. Each treatment involved the assessment of human labour (h), machinery usage (h), diesel fuel consumption (L), irrigation water usage (m^3), electricity consumption (kWh), mineral fertilizer application (kg), insecticide usage (kg), pesticide usage (kg), herbicide usage (kg), and seed usage (kg) per hectare as crop input sources. Additionally, wheat crop biomass, including grain and straw yields, was evaluated per hectare as total output. Energy equivalents were estimated as input and output energy by multiplying their corresponding energy coefficients (Table 1). Coefficients of energy reported in diverse research findings exhibited variation owing to differences in calculation methods and constraints related to spatial

Table 1 Coefficients of energy and carbon for various agricultural inputs and outputs

Particulars	Energy coefficients (MJ $unit^{-1}$)	Source	GHG coefficients, CE (kg carbon eq. $unit^{-1}$)	Units	Source
1. Labour (MJ h^{-1})		Singh et al. (2008)			Tabatabaie et al. (2012)
(a) Adult man	1.96		–		
(b) Woman	1.57		–		
2. Diesel (l)	56.31		0.94	l	
3. Electricity (kWh)	11.93	Erdal et al. (2007)	0.523	kWh	Lal (2004)
4.Water energy (MJ m^{-3})	1.02				
5. Machinery (MJ kg^{-1})		Singh et al. (2008)			
(a) Farm machinery (including self-propelled machines)					
(b) Farm machinery (excluding self-propelled machines)	62.7				
6. Chemical fertilizers (MJ kg^{-1})		Toader and Lăzăroiu (2014)			Tabatabaie et al. (2012)
(a) Nitrogen	60.6		1.35	kg	
(b) Phosphate (P_2O_5)	11.1		0.20	kg	
(c) Potassium (K_2O)	6.6		0.15	kg	
7. Pesticides (MJ kg^{-1})		Surendra Singh and Mittal (1992)			
(a) Fungicides	97				
(b) Insecticides	184.63				
(c) Diclrovos 76% Ec NuvanInsecticide	120		4.65	MJ kg^{-1}	
8. Herbicides (MJ kg^{-1})		Nassiri and Singh (2009)			
(a) Glyphosate	454.4		3.00	MJ kg^{-1}	
(b) Metsulfuron methyl + sulfosulfuron	254.40		1.70	MJ kg^{-1}	
9. Output (MJ kg^{-1})		Surendra Singh and Mittal (1992)			
(a) Wheat grain	15.7				
(b) Wheat straw	12.5				

and sequential systems (Hülsbergen et al., 2001). The discrepancies in results across global studies can be attributed to the utilization of different coefficients. In present study, coefficients tailored to the Indian context were employed for estimating energy input and output, direct and indirect emissions, and carbon fluxes as suggested by Surendra Singh and Mittal (1992), Nassiri and Singh (2009), and Toader and Lăzăroiu (2014). The total energy input for various treatments was computed, encompassing energy from direct and indirect sources. In addition to electricity and human labour, direct energy sources included fossil fuels used by agricultural machinery for tilling, planting, and harvesting. Indirect energy sources encompassed energy used in manufacturing agricultural machinery (for tasks such as land preparation, sowing, spraying, pumping, and harvesting) and the production of seeds, insecticides, herbicides, mineral fertilizers, and irrigation water energy, etc. Energy from renewable sources, such as wind, solar radiation and inherent soil fertility, were excluded from the calculation, as these involve no opportunity costs and are independent of management practices. In developing countries, including Asia, significant human labour, particularly in small and marginal farmlands, was employed for activities like weeding, in contrast to developed countries. The value of human labour aligns with the biochemical energy potentially consumed by an individual, as outlined by Sartori et al. (2005).

Total input energy was estimated using following Eq. 1 (Pratibha et al., 2019),

$$EI = EI_{\mathrm{d}} + EI_{\mathrm{id}} \quad (1)$$

where EI = Total input energy (MJ ha^{-1}), EI_d = Direct input energy (MJ ha^{-1}) and EI_{id} = Indirect input energy (MJ ha^{-1}).

$$\mathrm{EI_d} = \mathrm{EI_{df}} + \mathrm{EI_{hl}} + \mathrm{EI_{elect}} \quad (2)$$

where EI_d = total direct input energy, EI_{df} = total energy from diesel spent for farm machinery operation, EI_h = total energy used by human for different operations and EI_{elect} = total energy used in electricity for irrigation of crops.

The full tank method was used to compute the quantity of diesel fuel consumed per hectare (EI_{df} in MJ ha^{-1}) in farm machinery operation by a tractor and other related parameters. Energy indices, such as EUE, EP, specific energy (SE) and net return energy (NRE) were calculated by established methodologies (Asgharipour et al., 2012).

Energy Output

The mean wheat yields (grain and above-ground biomass per hectare) were measured at 12% moisture content after a 48-h of oven drying at 65 °C. Output energy values for wheat seed and above-ground biomass in various treatments were computed by multiplying the energy coefficient with total biomass and grain yields (Eq. 3).

$$\mathrm{EO_t}\left(\mathrm{MJ}\ ha^{-1}\right) = GY \times E_g + BY \times E_s \quad (3)$$

where EO_t = total output energy (MJ ha^{-1}), GY = grain yield (kg ha^{-1}), E_g = energy coefficient for wheat grain (MJ kg^{-1}), BY = wheat straw yield (kg ha^{-1}). The energy coefficients for wheat grain and straw (E_g and E_s) were set at 15.7 MJ kg^{-1} and 12.5 MJ kg^{-1}, respectively, for estimating energy outputs under different wheat cultivation methods (Surendra Singh & Mittal, 1992).

Greenhouse Gas Emission and Global Warming Potential

The environmental impact of different tillage methods in wheat cultivation was assessed by computing the yield-scaled and spatial CF. Spatial CF represents the cumulative GHG emissions (CO_2, N_2O, and CH_4) released during crop cultivation. These emissions were converted into CO_2 equivalents multiplying with their GWP equivalent factors of 1 and 298 for CO_2 and N_2O, respectively. In present study the CH_4 emissions were not considered due to their absence in wheat cultivation, this might be due to anaerobic conditions lead to the formation of CH_4 in soil. One major aspect that may be suppressing methane gas emissions is the sowing of wheat under dry soil conditions without submergence (Jain et al., 2016; Kumar et al., 2021). The GHG emissions in terms of CO_2 equivalent (CF values) were assessed by multiplying the inputs used (farm operations, use of diesel fuel, electricity and mineral fertilizers), in wheat crop production, with the corresponding emission coefficients reported in the literature (Lal, 2004). Nevertheless, specific emission coefficients for specific pesticides and herbicides were not available, so equivalent coefficients were assumed based on similar groups of insecticides, and comparable coefficients were applied to various applications (Tabatabaie et al., 2012).

Direct N_2O Emissions

Inclusive of agronomic inputs, the total CO_2 equivalent calculations encompassed direct and indirect N_2O emissions from fertilizers, crop biomass (Bhatia et al., 2004; Lal, 2004) as detailed in Table 2. The direct sources of N_2O emissions include rice roots, crop leftovers (previous anchored rice biomass left on the surface), and the nitrification and denitrification of N mineral fertilizer. The root shoot ratio was used to calculate the biomass of rice roots (Tabatabaie et al., 2012).

$$N_2O_{direct} = (N_{SNF} + N_{CR} + N_{root}) \times EF \times {}^{44}/_{28} \times 298 \quad (4)$$

Table 2 Factors and parameters employed in computing carbon footprint for wheat cultivation

Parameters	IPCC coefficient	Revised coefficient for Indian scenario	References
EF (N_2O emitted from applied fertilizer; %)	1.25	0.53	Jain et al. (2016)
EF_{LEACH} (N_2O emitted from leaching and run-off of fertilizer; %)	2.5	0.5	Lal (2004)
EF_{VD} (N_2O emitted from volatilized N from fertilizer, %)	1	0.5	Bhatia et al. (2004)
$Frac_{GASF}$ (Volatilization of gases from inorganic fertilizer; (%))	10	15	
$Frac_{GASF}$–AM (Volatilization of gases from manure; %)	20	20	
$Frac_{LEACH}$ (loss of N from leaching of fertilizer and manure; %)	30	10	

$$N_{CR} = CR_{st} \times Frac_{NCRST} \tag{5}$$

where N_{SNF} = Fertilizer quantity (N) applied to the crop per unit area; N_{CR} = Nitrogen content in crop residue left-over soil surface; CR_{st} = amount of crop residue left on the soil surface; $Frac_{NCRST}$ = nitrogen content of crop residues; EF = emission factor for N_2O–N released from nitrogen add-ons to the soil.

The Intergovernmental Panel on Climate Change (IPCC) advocates 1.25 kg N_2O–N emitted per 100 kg N applied to soils as a standard default emission factor. However, this study employs 0.53% as a specific emission factor, aligning with the recommendation for wheat in northwest India (Jain et al., 2016).

Indirect Soil N_2O Emissions

It arises from leaching and volatilization, exhibit diverse and indefinite variables and they are influenced by different treatments, mineral fertilizer additions, soil type, and other factors (Sharma et al., 2011). Methods to compute the indirect soil N_2O emissions are given by Fagodiya et al. (2023).

Carbon Indices

The computed spatial CF, in CO_2 equivalent is converted to carbon equivalent. The carbon output, carbon sustainability index (CSI) and carbon efficiency ratio (CER) estimated as per Chaudhary et al. (2017).

$$Carbon\ input = (Sum\ of\ the\ total\ carbon\ equivalents) \times {}^{12}/_{44} \tag{6}$$

$$Carbon\ output = Total\ biomass \times 0.40 \tag{7}$$

$$Carbon\ sustainability\ Index = \frac{\left(Carbon_{output} - Carbon_{input}\right)}{Carbon_{input}} \tag{8}$$

$$Carbon\ efficiency\ ratio = \frac{\left(Carbon_{output}\right)}{Carbon_{input}} \tag{9}$$

CO_2 Equivalent

The CO_2 equivalent emissions (kg CO_2 eq. ha^{-1}) from each treatment were computed as per given expression:

$$\begin{aligned} CO_2eq. = \big[&EI; fuel \times CO_2eq. \\ &+ (EI; fram\ machinery \times CO_2eq.) \\ &+ (EI; fertilizers \times CO_2eq.) \\ &+ (EI; agrochemicals \times CO_2eq.) \\ &+ (EI; eletricity \times CO_2eq.)\big] \end{aligned} \tag{10}$$

where EI = total energy used (MJ ha^{-1}) multiplied by relevant CO_2-equivalent.

Global Warming Potential

The GWP with a 100-year time span transformed into CO_2-equivalent emissions by multiplying cumulative CH_4 and N_2O emissions by 34 and 298, respectively.

$$GWP = CO_2eq. + 34 \times CH_4emission + 298 \times total\ N_2O\ emission \tag{11}$$

Statistical Analysis

The energy indices and carbon footprint data were analysed following the methodology outlined by Freund et al. (1986), and treatment averages were compared using the least significant difference (LSD) test at a significance level of 5%. Statistical analysis for energy indices and CF was performed using proc glm of SAS software version 9.2. Tukey's honestly significant difference test (HSD) was used to perform multiple comparisons. *P* values less than 0.05 were used to reject the null hypothesis of equal means (Gomez & Gomez, 1984).

Results

Machine Performance Parameters

The five tillage methods viz., ZT-R, ZT+R, PRB-R, RT-R and CT-R were employed for wheat cultivation under rice harvested field during the experimental period of 5 years (2015–2016 to 2019–2020). The operational parameters of the tillage methods showed in Table 3. The working width and depth of operation of sowing equipment were 1.5–2.0 m and 20–120 mm, respectively. The highest fuel consumption of tillage equipment recorded under CT-R (38.40 l ha^{-1}) followed by PRB-R (31.16 l ha^{-1}), whereas for sowing operation lowest fuel was consumed by zero till drill under ZT-R (8 l ha^{-1}), followed by seed-cum-fertilizer drill under CT-R (8.5 l ha^{-1}), happy seeder under ZT+R (9 l ha^{-1}), raised bed shaper-cum-planter (12.5 l ha^{-1}) and rotary till dill (16 l ha^{-1}). The effective field capacity of zero till drill (0.37 ha h^{-1}) was reported to be greater compared happy seeder (0.36 ha h^{-1}), rotary till drill (0.31 ha h^{-1}) and raised bed shaper-cum-planter (0.29 ha h^{-1}) while operating at average operating speeds of 1.0–1.5 m s^{-1}. The field capacity of machine is actual average rate of coverage by the machine and it is expressed as ha h^{-1}.

Crop Growth Parameters and Yield Attributes

The analysis of variance revealed that there was a substantial influence of tillage methods on wheat crop growth and yield attributes at 5% significance level (Table 4). In case of tillers per square meter, CT-R has reported highest number of tillers which were at par with ZT-R and ZT+R, while the latter were comparable to PRB-R and RT-R. The CT-R has reported 2.8% more number of tillers compared to PRB-R and RT-R. The mean plant height was superior in case of ZT-R (1016 mm) and ZT+R (1014 mm) than that of PRB-R (1001 mm), RT-R (1004 mm) and CT-R (1005 mm). However, the number of grains per spike and

Table 3 Technical specifications and performance parameters of implements used in different tillage treatments adopted in wheat cultivation

Tillage methods	Operation details	Working width (m)	Working depth (mm)	Fuel consumption (l ha^{-1})		Effective field capacity (ha h^{-1})
				Tillage	Sowing	
ZT-R	Sowing with zero till drill	1.98	30–40	–	8.0	0.37
ZT+R	Sowing with happy seeder in rice residue of 6 t ha^{-1}	2.00	20–30	–	9.0	0.36
PRB-R	Bed is formed in the first year and sowing using raised bed shaper-cum-planter	1.50	30–40	31.16[a]	12.5	0.29
RT-R	Sowing with rotary till drill	1.98	80–100	–	16.0	0.31
CT-R	Two harrowing + two cultivating + one rotavating and seeding	2.00	100–120	38.40	8.5	0.070[b]

ZT+R zero tillage with residue (sowing with happy turbo seeder in presence of 6 t ha^{-1} rice residue), *ZT-R* zero tillage without residue, *PRB-R* permanent raised bed planter without residue, *RT-R* rotary tillage without residue, *CT-R* conventional tillage without residue

[a]Ist year—Tillage operation (twice harrowing + once tiller + once rotavator) and reshaped bed

[b]Total time all field operation including sowing

Table 4 Crop growth and yield attributes under various conversation tillage methods in wheat cultivation (pooled data)

Treatment	Number of tillers m^{-2}	Plant height (mm)	Spike length (mm)	Number of grain $spike^{-1}$	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Total Biomass (t ha^{-1})
ZT-R	355^{AB}	1016^{A}	105^{A}	72.5^{A}	5.63^{A}	7.20^{A}	12.83^{A}
ZT+R	354^{AB}	1014^{A}	104^{A}	72.6^{A}	5.68^{A}	7.15^{AB}	12.83^{A}
PRB-R	350^{B}	1001^{B}	103^{AB}	70.2^{AB}	5.58^{AB}	7.10^{B}	12.68^{B}
RT-R	351^{B}	1004^{B}	100^{AB}	72.0^{AB}	5.53^{AB}	7.11^{B}	12.64^{B}
CT-R	360^{A}	1005^{B}	98^{B}	69.8^{B}	5.47^{B}	7.20^{A}	12.67^{B}

ZT-R zero tillage without residue, *ZT+R* zero tillage with residue (sowing with happy turbo seeder in presence of 6 t ha^{-1} rice residue), *PRB-R* permanent raised bed planter without residue, *RT-R* rotary tillage without residue, *CT-R* conventional tillage without residue

Significance levels are indicated by the letters in the superscript. The same-letter means are not statistically different at $P < 0.05$ (LSD) spike length were found to be significantly lowest under CT-R than remaining treatments. Highest wheat grain yield was found under ZT+R (5.68 t ha^{-1}) compared to CT-R (5.47 t ha^{-1}), which was equivalent to PRB-R (5.58 t ha^{-1}) and RT-R (5.53 t ha^{-1}). The yield of wheat straw was reported to be highest under ZT-R (7.20 t ha^{-1}) and CT-R (7.20 t ha^{-1}), which were considerably higher than that of PRB-R (7.10 t ha^{-1}) and RT-R (7.11 t ha^{-1}). There was difference in the wheat biomass yield as ZT-R and ZT+R reported to be higher values than that of PRB-R, RT-R and CT-R at 5% significance level.

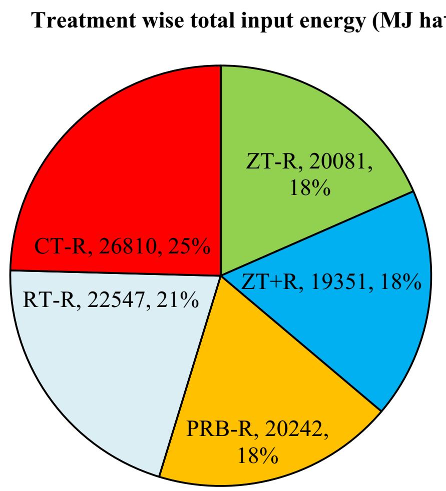


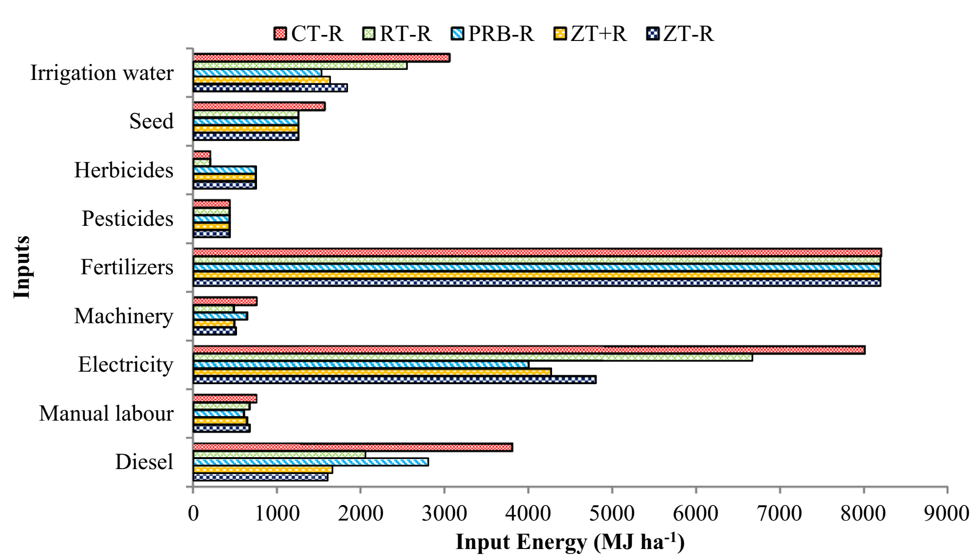
Fig. 1 Treatment wise total input energy (MJ ha^{-1}) use under selected tillage practices in wheat cultivation. ZT+R = zero tillage with residue; ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue

Energy Budgeting

This study compares energy balances across various tillage practices in wheat cultivation. The tillage methods exerted a significant influence on energy inputs for land preparation. CT-R exhibited higher energy intensity, registering an input of 26,810 MJ ha^{-1} followed by RT-R (22,547 MJ ha^{-1}). The ZT+R showcased 39% and 17% reduction in total energy input than that of CT-R and RT-R, respectively, closely succeeded by ZT-R (20,081 MJ ha^{-1}). Notably, ZT-R demonstrated approximately 34% and 12% lower energy input than CT-R and RT-R, respectively. The CT-R exhibited approximately 50, 47, 40 and 17% higher electricity requirement than plots using PRB-R, ZT+R, ZT-R, and RT-R, respectively (Fig. 1).

The changes in energy inputs between various treatments were from the variations in energy obtained from various input parameters such as diesel, labour, electricity, machinery, agrochemicals, irrigation water and seeds (Fig. 2). Based on source of energy, fertilizers (40.8%) have major share in total input energy followed by electricity (19.7–30%), irrigation water (7.5–11.4%), diesel (7.9–14.2%), seeds (5.5–6.5%), herbicide (0.7–3.8%), manual labour (2.8–3.3%), machinery (2.1–3.1%) and pesticide (1.6–2.3%). The fertilizer and pesticide inputs remained consistent across all tillage treatments, thus ensuring uniform input energy levels. The energy from remaining input factors was highest under CT-R except herbicides (204 MJ ha^{-1}), which was comparable to RT-R. Lowest energy consumption was reported under PRB-R for manual labour (608 MJ ha^{-1}), electricity (4006 MJ ha^{-1}) and irrigation water (1530 MJ ha^{-1}). Input energy from diesel was lowest under ZT-R (1604 MJ ha^{-1}) succeeded by ZT+R (1660 MJ ha^{-1}), RT-R (2055 MJ ha^{-1}), PRB-R (2805 MJ ha^{-1}) and CT-R (3809 MJ ha^{-1}).

Fig. 2 Input energy utilization based on source under different tillage practices in wheat cultivation. ZT+R = zero tillage with residue ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue

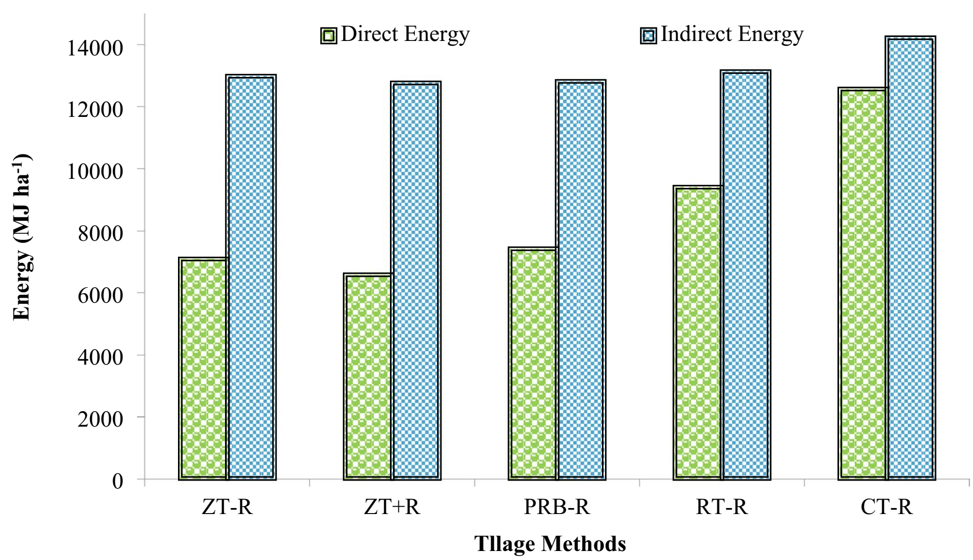


The share of input energy for fertilizer application (31–43%) was higher across all tillage treatments followed by irrigation (28.4–41.4%), sowing (9.0–15.4%), harvesting and threshing (5.95–8.23%), herbicide application (0.99–4.19%), insecticide application (1.89–2.63%) and weeding (0.56–0.78%). The energy input for irrigation significantly varied among different tillage systems. The PRB-R exhibited the lowest irrigation input energy approximately 49%, 46%, 39%, and 17% lower than CT-R, ZT+R, ZT-R and RT-R, respectively. In terms of sowing, CT-R (4602 MJ ha^{-1}) plots registered the uppermost input energy amongst selected tillage methods, followed by PRB-R (3115 MJ ha^{-1}) RT-R (2237 MJ ha^{-1}), ZT+R (1883 MJ ha^{-1}) and ZT-R (1807 MJ ha^{-1}). Energy consumption in fertilizers application, insecticide spraying, weeding and harvesting and threshing is similar under selected tillage treatments, which were approximately 8316, 508, 150 and 1592 MJ ha^{-1}, respectively. Since the weeds were mainly controlled by herbicide application under ZT+R, ZT-R, PB-R plots, which reported the energy consumption of about 811 MJ ha^{-1}, whereas the energy consumption for herbicide application was less under RT-R (266 MJ ha^{-1}), which was comparable to CT-R.

Apart from various sources of energy input, it is further divided into non-renewable and renewable energy sources and indirect and direct energy inputs. The renewable sources of energy involve manual labour and seed, whereas non-renewable sources of energy involve diesel, electricity, machinery, fertilizers, agrochemicals, and water. Similarly, the direct energy sources involve diesel, manual labour, electricity and the indirect energy sources involve machinery, agrochemicals, seed and water. Figure 3 showed that the direct energy inputs were reported to be highest under CT-R followed by RT-R, PRB-R, ZT-R, and ZT+R, whereas the indirect energy input were highest in case of CT-R followed by RT-R, ZT-R, PRB-R and ZT+R. ZT+R and ZT-R exhibited the lowest direct energy share (34–35% of total energy source), followed by PRB-R (37%), RT-R (42%), and CT-R (47%). This lower direct energy share in zero tillage plots resulted from reduced diesel usage in tillage, sowing, and intercultural practices compared to CT-R. Indirect energy use constituted a substantial portion, ranging from 53 to 66% of the total input energy. Similarly, Fig. 4 depicted that renewable energy inputs were in order of CT-R > RT-R = ZT-R > ZT+R > PRB-R and non-renewable energy inputs were in order of ZT+R < ZT-R < PRB-R < RT-R < CT-R. Non-renewable energy sources dominated, accounting for approximately 90–91% of the total input energy across all five tillage practices in wheat. Conversely, renewable energy sources, like solar or wind power and organic fertilizer, contributed only 9–10% to the total input energy, indicating a limited reliance on renewable sources in wheat cultivation practices.

Table 5 presented the grain output energy (EO_g) was substantially highest in ZT+R and this is superior to all other tillage treatments. The EO_g values followed the trend of ZT+R > ZT-R > PRB-R > CT-R > RT-R, which had significant difference among each other except RT-R and CT-R. The EO_g value in PRB-R was considerably lower than ZT+R and ZT-R by 1.8 and 1.3%, respectively. ZT+R plots (4.59 and 8.85) revealed the highest values for grain and total EUEs surpassing those of ZT-R (4.40 and 8.49), PRB-R (4.31 and 8.02), RT-R (3.85 and 7.31), and CT-R plots (3.24 and 6.16). The trend in EUE_g and EUE_t values followed the order ZT+R > ZT-R > PRB-R > RT-R > CT-R, with significant differences. The SE, representing the energy required to produce one kilogram of wheat, was considerably higher in CT-R plots (4.84 and 2.27 MJ kg^{-1}) compared to ZT+R, ZT-R, PRB-R, and RT-R treatments at 5% level of significance.

Fig. 3 Indirect and direct energy in selected tillage practices in wheat cultivation. ZT+R = zero tillage with residue; ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue



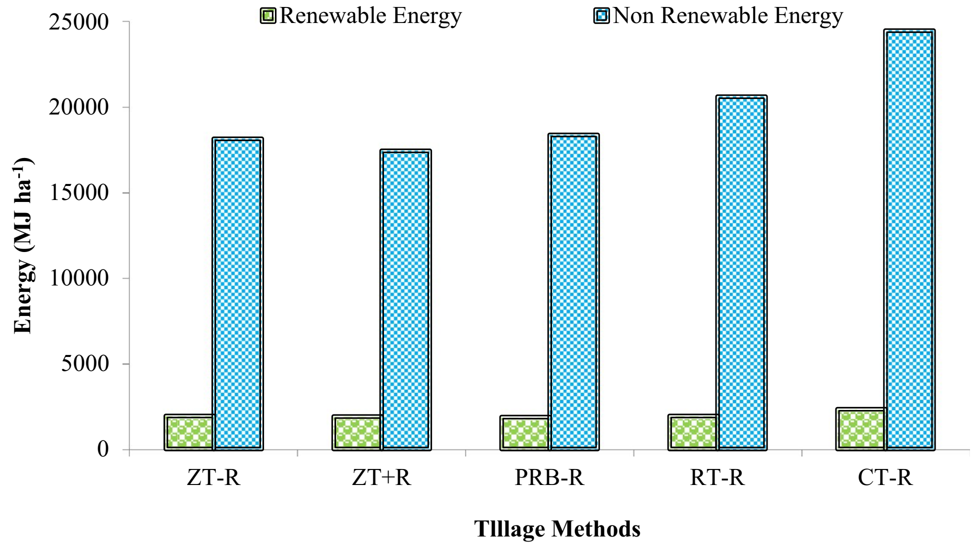


Fig. 4 Non-renewable and renewable energy in selected tillage practices in wheat cultivation. ZT+R = zero tillage with residue; ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue

Table 5 Energy indices under selected tillage practices in wheat cultivation

Treatments	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+R	19356^{D}	88757^{A}	171299^{A}	69406^{A}	151948^{A}	4.59^{A}	8.85^{A}	3.61^{B}	1.58^{E}
ZT-R	20080^{C}	88339^{B}	170380^{B}	68259^{B}	150300^{B}	4.40^{B}	8.49^{B}	3.58^{B}	1.65^{D}
PRB-R	20242^{C}	87187^{C}	162396^{D}	66946^{C}	142154^{C}	4.31^{C}	8.02^{C}	4.04^{B}	1.75^{C}
RT-R	22547^{B}	86769^{D}	16489^{C}	64222^{D}	142347^{C}	3.85^{D}	7.31^{D}	4.08^{B}	1.91^{B}
CT-R	26809^{A}	86926^{D}	165092^{C}	60117^{E}	138284^{D}	3.24^{E}	6.16^{E}	4.84^{A}	2.27^{A}

ZT+R zero tillage with residue, *ZT-R* zero tillage without residue, *PRB-R* permanent raised bed planter without residue, *RT-R* rotary tillage without residue, *CT-R* conventional tillage without residue, *EI* energy input, EO_g grain energy output, EO_t total energy output, NE_g net energy from grain, NE_t total net energy, EUE_g grain energy use efficiency, EUE_t total energy use efficiency, SE_g specific energy from grain, SE_t total specific energy

Significance levels are indicated by the letters in the superscript. The means that are indicated by the same letter do not differ significantly at $P < 0.05$ (LSD)

Greenhouse Gases Emission and Global Warming Potential

The GHG emissions (kg CO_2 eq. ha^{-1}) were assessed for selected tillage practices and the results presented that the farm operations were key contributors to GHG emissions. The share of diesel fuel for CO_2 emission was highest in case of PBR-R (17%) followed by CT-R (14.3%), whereas lowest in case of ZT-R (8.0%). Fertilizer application accounted for the highest contributor for CO_2 emission irrespective of tillage treatments. The share of fertilizer application in CO_2 emission was highest for ZT+R (55.4%) followed by ZT-R (53.6%), PRB-R (51.1%), RT-R (47.2%) and CT-R (40.4%). Electricity used for irrigation (25.2–39.8%) was the second major contributor for GHG emissions. The CO_2 emission through electricity used for irrigation was 50.0, 46.6, 40.0, and 16.6% higher for CT-R compared to PBR-R, ZT+R, ZT-R and RT-R, respectively. The herbicide application, insecticide application and sowing were the minor contributors in CO_2 emissions across all the treatments with 0.4–1.4, 1.8–2.4 and 2.6–3.4% share, respectively. Field operations accounted for 72–80% of the total GHG emissions in various treatments during wheat production. The inorganic fertilizers used for wheat production were the prime source of N_2O emissions, which made a comparatively modest contribution, ranging from 20 to 28% of the total GHG emissions and it was succeeded by existing crop residue and crop roots (Fig. 6). The direct sources of N_2O emissions includes existing crop residue, roots and the nitrification and denitrification of mineral fertilizers, whereas the leaching and volatilization of mineral fertilizers are the main sources indirect N_2O emissions. The direct and indirect N_2O emission were reported to higher under ZT+R (395 MJ ha^{-1}), however it was lowest in instance of PRB-R (331 and 70 MJ ha^{-1}) (Fig. 5). The plots subjected to conventional tillage (CT-R) exhibited the 20, 19, 17, and 11% highest total GHG emissions compared to ZT-T, ZT+R, PRB-R, and RT-R, respectively (Table 6).

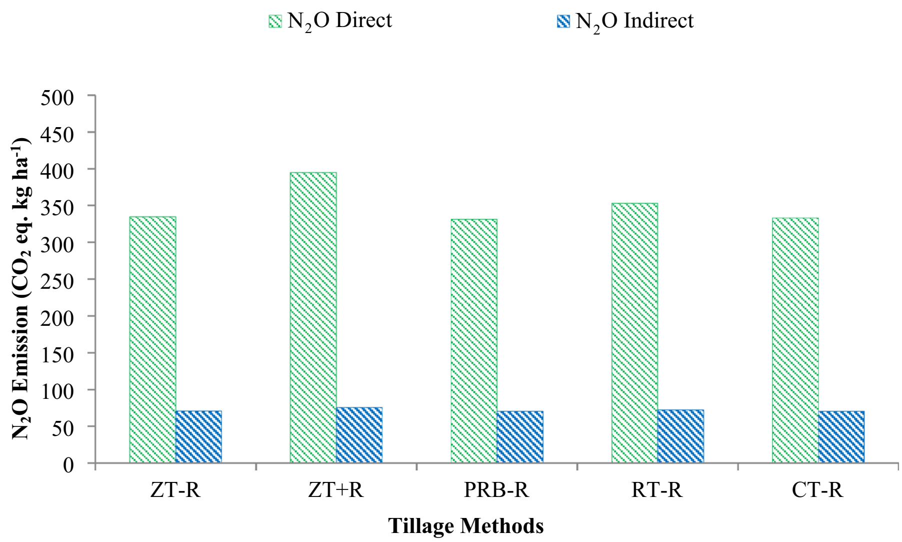


Fig. 5 Total N_2O emission (direct and indirect) from synthetic fertilizer, crop residues and previous crop root in selected tillage practices in wheat cultivation. ZT+R = zero tillage with residue; ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue

Table 6 GHG emissions (kg CO_2 eq. ha^{-1}) under selected tillage practices in wheat cultivation

Treatments	Farm operations								Total GHG emissions (kg CO_2 eq. ha^{-1})
	Diesel	Fertilizers application	Herbicides application	Pesticides	Electricity for irrigation (kWh)	Sowing	CO_2	N_2O	
ZT-R	98.1	660.0	16.8	29.0	390.2	37.9	1231.9	403.0	1635
ZT+R	101.5	660.0	16.8	29.0	346.9	36.5	1190.6	467.4	1658
PRB-R	219.3	660.0	16.8	29.0	325.2	40.4	1290.6	398.3	1689
RT-R	125.6	660.0	5.8	29.0	542.0	36.0	1398.4	424.0	1822
CT-R	233.0	660.0	5.8	29.0	650.4	56.0	1634.1	401.4	2036

ZT-R zero tillage with no residue, *ZT+R* zero tillage with residue (sowing with happy turbo seeder in presence of 6 t ha^{-1} rice residue), *PRB-R* permanent raised bed planter with no residue, *RT-R* rotary tillage with no residue, *CT-R* conventional tillage with no residue

Carbon Budgeting

Carbon output was computed by multiplying yields and carbon content (40%) in both grain and total biomass. The CSI and CER averaged over years were influenced by selected tillage methods. Carbon inputs were lower in ZT-R (446.27 kg $C_{eq.}$ ha^{-1}), which was comparable with ZT+R and PRB, whereas it was highest in case of CT-R (555.63 kg $C_{eq.}$ ha^{-1}) succeeded by RT-R (497.47 kg $C_{eq.}$ ha^{-1}). CT-R plots had approximately 20, 19, 17 and 10% higher carbon inputs than ZT-R, ZT+R, PRB-R, and RT-R plots, respectively. Carbon output estimation utilized the average yield data from five years of different wheat cultivation methods. Among the various treatments, ZT+R (4902.67 kg $C_{eq.}$ ha^{-1}) recorded the highest carbon output, followed by ZT-R (4876 kg $C_{eq.}$ ha^{-1}). The lowest carbon output was observed in PRB-R (4628 kg ha^{-1}), followed by RT-R (4710.67 kg $C_{eq.}$ ha^{-1}) and CT-R (4716 kg $C_{eq.}$ ha^{-1}) plots. The CSI and CER followed the similar trend of ZT-R > ZT+R > PRB-R > RT-R > CT-R. The kg CO_2 eq. kg^{-1} grain was significantly lowest in ZT+R (0.29 kg CO_2 eq. kg^{-1} grain), which was comparable to ZT-R, followed by PRB-R (0.30 kg CO_2 eq. kg^{-1} grain), RT-R (0.33 kg CO_2 eq. kg^{-1} grain) and CT-R (0.37 kg CO_2 eq. kg^{-1} grain) (Table 7). The kg CO2 eq. kg^{-1} grain was 21.6, 12.1 and 3.3% higher in case of CT-R, RT-R and PRB-R compared to ZT+R, respectively, which was comparable with ZT-R (Fig. 6).

Uncertainty in Assessment

The use of mineral fertilisers and tillage activities in wheat production are the main sources of N_2O emissions from the soils. Factors influencing N_2O emissions include the amount of fertilizer applied and site-specific variables such as temperature, soil moisture content, soil types, precipitation, and temperature (Sharma et al., 2011). Despite variations in soil pH, temperatures, and climatic conditions, the IPCC recommended a default emission factor of 1.25% for N input-based direct emissions from agricultural soils. However, studies in diverse locations in India have stated a specific EF is 44% lesser than the IPCC default EF (Dobbie & Smith, 2003; Lal, 2004). In Indian conditions, Jain et al. (2016)

Table 7 Carbon indices under selected tillage practices in wheat cultivation

Treatment	Carbon input (kg $C_{eq.}$ ha^{-1})	Carbon output (kg $C_{eq.}$ ha^{-1})	Carbon sustainability index	Carbon efficiency ratio	kg CO_2 eq. kg^{-1} grain
ZT+R	452.57^{CD}	4902.67^{A}	9.84^{B}	10.84^{B}	0.29^{D}
ZT-R	446.27^{D}	4876.00^{B}	9.94^{A}	10.94^{A}	0.29^{D}
PRB-R	461.03^{C}	4628.00^{D}	9.05^{C}	10.05^{C}	0.30^{C}
RT-R	497.47^{B}	4710.67^{C}	8.48^{D}	9.48^{D}	0.33^{B}
CT-R	555.63^{A}	4716.00^{C}	7.50^{E}	8.50^{E}	0.37^{A}

ZT-R zero tillage with no residue, *ZT+R* zero tillage with residue (sowing with happy turbo seeder in presence of 6 t ha^{-1} rice residue), *PRB-R* permanent raised bed planter with no residue, *RT-R* rotary tillage with no residue, *CT-R* conventional tillage with no residue

The superscript's letters represent the various significance levels. The same-letter means are not statistically different at $P < 0.05$ (LSD)

observed an EF of 0.53. This method excludes aspects that are major contributors to emissions. Similarly, uncertainties may arise owing to emissions from farm operations. In the absence of emission factors tailored to the Indian context, emissions from mineral fertilizers as well as insecticides and herbicides were computed using factors documented in the literature (Shang et al., 2011). A novel approach of the present research involved evaluating the GWP by quantifying CO_2 and N_2O emissions in the context of managing irrigated wheat production in the IGP. Additionally, the energy indices and CSI were calculated for various crop production techniques for wheat. The findings of the study indicate that zero tillage (ZT-R and ZT+R) not only resulted into superior yield, but also consumed less energy and reported low CF.

Discussions

In IGP of India, RWCS has been predominant. However, over the past several decades, it is resulted into degradation of land, depletion of ground water table, overexploitation of natural resources and exacerbated global warming (Khedwal et al., 2023; Kumar et al., 2022). In RWCS, management of rice residue is challenging, which is used to get burn to make field ready for wheat sowing due to short time interval (Dhanda et al., 2022). Furthermore, the conventional practice of wheat cultivation by performing intensive tillage operation followed by sowing by means of seed drill is energy intensive and contributes in GHG emissions (Chethan et al., 2020; Sharma et al., 2023). Hence, to address these issues a long term experiment (2015–2016

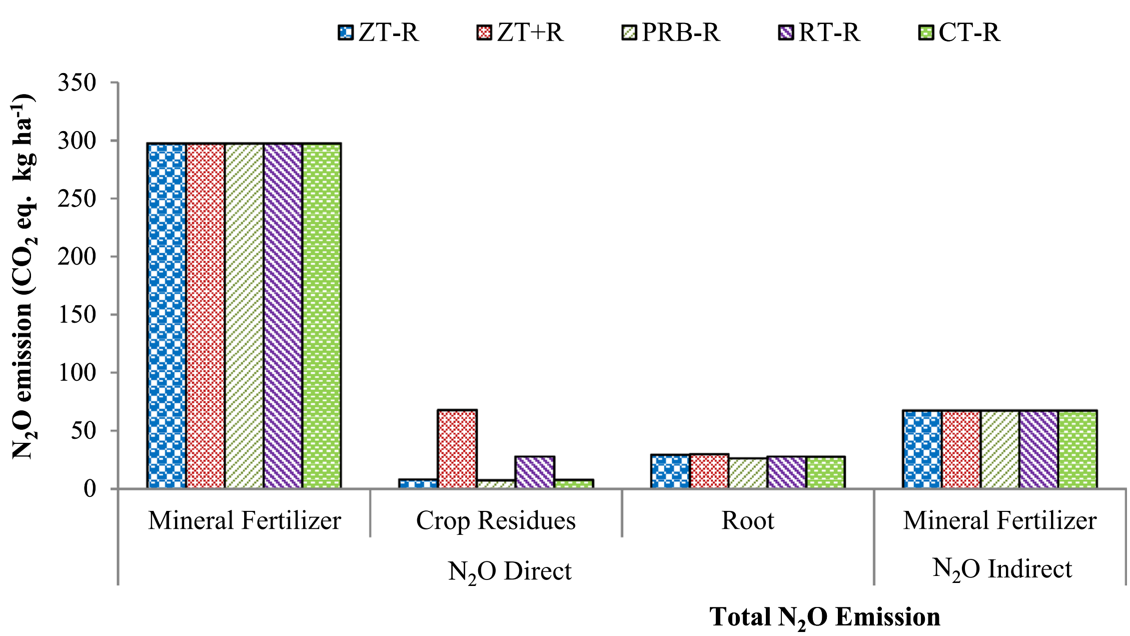


Fig. 6 N_2O emission sources from synthetic fertilizer, crop residues and previous crop roots in selected tillage practices in wheat cultivation. ZT+R = zero tillage with residue; ZT-R = zero tillage without residue; PRB-R = permanent raised bed planter without residue; RT-R = rotary tillage without residue; CT-R = conventional tillage without residue

to 2019–2020) was carried out to investigate the impact of various tillage methods on wheat crop productivity, energetics, GHG emissions and CSI. Thus, the rice residue was recycled to enhance crop productivity, EUE and to reduce GHG emissions and GWP.

Performance Parameters of Equipment and Their Influence on Crop Growth and Yield Attributes

Wheat cv PBW-343 was cultivated using ZT-R, ZT+R, PRB-R, RT-R and CT-R under rice harvested field during the experimental period (2015–2016 to 2019–2020) of 5 years. The effective field capacity of zero till drill was reported to be highest under ZT-R compared to remaining tillage methods, closely followed by happy seeder under ZT+R. Happy seeder could sowed wheat in presence of 6 t ha^{-1} rice residue without any prior field operation. The 18.85% higher fuel consumption was reported under CT-R compared to PRB-R (31.16 l ha^{-1}) for field preparations, which could be eliminated under other treatments. Zero till drill consumed comparatively less fuel than that under other conservation tillage methods. Raised bed shaper-cum-planter and rotary till drill consumed higher fuel due to higher draft and power consumption for rotating blades, respectively. Under CT-R, the seed-cum-fertilizer drill led to a higher number of tillers, but these did not necessarily convert into superior yields. In contrast, the use of the happy seeder under ZT+R and zero till drill under ZT-R resulted in taller plants, longer spikes, more grains per spike, and consequently, higher grain yield.

The tillers were more under CT-R than that of ZT-R, ZT+R, PRB-R and RT-R. This might have attributed to the higher plant stand establishment under no residue condition due to uniform seed placement (Ankit et al., 2022). However, the decline in grain yield was observed in CT-R in contrast to other treatments. The decrease in grain yield under CT-R might be result of reduced spike length and number of grains per spike, which revealed that there was significant effect of tillage treatments on wheat grain and straw yields. The highest grain yield of wheat was reported in ZT+R followed by ZT-R. The contrast analysis exhibited that wheat yield was greater under CT than that to minimum tillage and ZT (Woźniak & Gos, 2014; Woźniak & Rachoń, 2020). This possibility could arise from improved soil structure and favourable conditions for seed germination facilitated by CT, which may not occur under ZT conditions due to occasional lack of seed coverage (Sawant et al., 2019) and the presence of crop residue (Colecchia et al., 2015).

Impact of Tillage Methods on Energy Budgeting

The energy demand for a crop is intricately linked to inputs utilized in crop management. Evaluating energy balance provides insights into the system's production efficiency. A more efficient production system is characterized by higher EUE and productivity. The ZT methods have been found to conserve up to 9, 17, 30% more energy compared to PRB-R, RT-R and CT-R, respectively, notably in electricity and diesel consumption. ZT achieves energy savings by eliminating surplus irrigation, avoidable tillage and manual weeding (Lal et al., 2019). Despite higher fuel consumption, plots employing PRB-R exhibited lower energy input compared to RT-R and CT-R. This discrepancy is attributed to the reduced irrigation water requirement in PRB-R, as furrow irrigation replaced flood irrigation compared to other treatments (Jat et al., 2018). Additionally, PRB-R maintained higher soil moisture storage. He et al., (2008, 2015) also reported that the PRB increased wheat crop and water productivity than that to ZT and CT in arid northwest China. The machinery energy share was considerably greater in CT-R at 756 MJ ha^{-1} compared to ZT-R and ZT+R at 508 and 493 MJ ha^{-1}, respectively. This is attributed to the increased machinery usage in CT-R for land preparation, involving operations such as harrow (two passes), cultivator (two passes), and rotavator (one pass) (Singh et al., 2022). Conversely, in ZT-R and ZT+R, zero-till drill and turbo happy seed drill were adequate for sowing (Keil et al., 2021). Increased yields of grains and straw were the cause of increased energy outputs in ZT+R and ZT-R (Chaudhary et al., 2017). Energy output in the RT-R and CT-R were comparable but substantially higher than PRB-R. However, CT-R exhibited the lowest grain net energy and total net energy values. This discrepancy was attributed to diminished grain and biological yields in CT-R, coupled with higher input energy (Kumar et al., 2023). The output energy from grain and biomass was found to be increased in ZR + R and ZT-R than that of CT-R and RT-R, as reported by Chaudhary et al., (2006, 2017). The elevated specific energy in CT-R plots pointed to higher EI and lower output energy, highlighting the less efficient energy utilization in those plots. These outcomes concur with the earlier results of Pratibha et al. (2015) and Kumar et al. (2013), who stated that the zero tillage methods (ZT-R and ZT+R) are energy efficient for wheat production.

Impact of Tillage Methods on Greenhouse Gas Emission and Global Warming Potential

Differential GHG emissions in various tillage treatments of wheat crop production can be linked to deviations in diesel consumption associated with distinct tillage practices (Sadeghinezhad et al., 2014). Reduced GHG emissions in ZT+R and ZT-R resulted from lower fuel consumption and less indirect emissions related to energy expended in manufacturing, transportation, repair, and the use of equipment. This is also attributed to the reduced tillage operations and shallower irrigation depths. Conversely, the higher GHG emissions in CT-R were a consequence of increased diesel fuel consumption for tillage operations (47 l ha^{-1}), surpassing that of ZT-R (8 l ha^{-1}) and ZT+R (9 l ha^{-1}) (Stošić et al., 2021). Furthermore, CT-R exhibited higher electricity usage for irrigation compared to ZT-R and ZT+R (Busari et al., 2015; Choudhary et al., 2022). The ZT-R and ZT+R exhibited the 20% and 19% less GHG emission than that to CT-R, whereas PRB-R and RT-R emitted 17 and 11% lower GHG emissions than that under CT-R, respectively (Choudhary et al., 2022). PRB-R plots exhibited lower total GHG emissions compared to RT-R and CT-R, primarily due to reduced irrigation water use applied in furrows, as opposed to flood irrigation in other treatments (Jat et al., 2018). Additionally, N_2O emissions were lower in PRB-R due to the absence of residue application. In contrast, the reduced emissions in ZT-R and ZT+R were attributed to the prevention of tillage operations (Carbonell-Bojollo et al., 2019). Differences in N_2O emissions across treatments were influenced by residue retention, as reported by Bhatia et al. (2010) and Mutegi et al. (2010). ZT+R exhibited approximately 15%, 14%, 14%, and 9% higher estimated N_2O emissions compared to PRB-R, ZT-R, CT-R and RT-R, respectively. This elevated N_2O emission in ZT+R was likely a result of additional annual nitrogen inputs from rice residues (6 t ha^{-1}). However, in light of studies by Sapkota et al. (2015) and Aryal et al. (2015), the primary ways that CA technologies decreased GHG emissions were by reducing input consumption and altering the soil environment. Furthermore, Sapkota et al. (2015) concluded that CRR in one season had no impact on the next crop's GHG emissions.

Impact of Tillage Methods on Carbon Budgeting

The reduced carbon outputs in plots subjected to CT-R and RT-R were attributable to lower combined yields in these treatments (Silva-Olaya et al., 2013). Plots under ZT-R and ZT+R exhibited higher CSI and CER compared to other tillage methods. This elevation in CSI and CER values was a result of increased carbon output and decreased carbon input values. The lower carbon input values in ZT-R and ZT+R were attributed to less fuel consumption and reduced irrigation water demand (Kumar et al., 2022). It was also found that CF was lowest in plots under ZT-R and ZT+R (0.29), succeeded by PRB-R (0.30), RT-R (0.33) and CT-R (0.37) plots. This was due to more equivalent CO_2 emission from conventional wheat growing practices (Singh et al., 2022). Higher emission was observed in machinery operation during tillage and electricity used in irrigation. The conventional method of wheat sowing (CT-R) had lower CSI and CER values due to lower yields. The adaptation potential of zero tillage to drought and high temperature change was observed, since the wheat crop could be sown earlier than the other treatments. Thus wheat grown under ZT-R was more resilient, leading to higher yield over conventionally cultivated crops (Mishra et al., 2021). The potential benefits of ZT-R and ZT+R over other practices, such as soil mulching with crop residues, reduced carbon and nitrous-oxide emissions to the atmosphere (Iqbal et al., 2020). This study, thus, indicated that ZT+R were environmentally friendly practice, since it had lower kg CO_2 eq. kg^{-1} grain (Modak et al., 2020; Sapkota et al., 2019). The treatment performance especially under ZT+R and ZT-R improved soil health and ultimately enhanced crop yields (Das et al., 2021). The results of the study validate that employing conservation tillage presents energy and carbon efficient and eco-friendly approach for cultivating wheat in an IGP of India.

Conclusions

The large scale adoption of wheat sowing under zero tillage practice, combined with in-situ residue retention has the potential to significantly diminish ecological ways. The findings of present study revealed that the cultivation of wheat in zero-tilled plots, with or without retaining previous crop residues, proved to be an effective strategy for reducing both energy inputs and carbon footprints. Additionally, energy consumption varied across selected tillage treatments, spanning a spectrum from 19,351 MJ ha^{-1} (ZT+R) to 26,810 MJ ha^{-1} (CT-R) with highest share of EI for fertilizer application (31–43%) and irrigation (28.4–41.4%). The ZT+R reported highest values for total energy use efficiency (8.85) and lowest value for total specific energy (1.58 MJ kg^{-1}). Fertilizer application accounted for the highest contributor for GHGs emission irrespective of tillage treatments. The share of fertilizer application in GHGs emission varied from 40.4% (CT-R) to 55.4% (ZT+R). The total GHGs emissions reduced under ZT-R, ZR + R, PRB-R and RT-R to the tune of 19.7, 18.6, 17.0 and 10.5%, respectively compared to CT-R. The 19–20% lower CF exhibited in ZT+R (0.29 kg CO_2 eq. kg^{-1} grain) compared to CT-R (0.37 kg CO_2 eq. kg^{-1} grain). Similarly, ZT-R demonstrated lowest CSI (9.94) and CER (10.94). The findings of this study will be utilitarian to administrators while planning comprehensive approaches to reduce agricultural residue burning and develop energy and carbon efficient wheat cultivation practices to strengthen its adaptability in changing agro-ecological conditions.

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Data availability The data analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare that none of the work reported in this study could have been influenced by any known competing financial interests or personal relationships.

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