



OPEN ACCESS

EDITED BY

Dinesh Jinger,
Indian Institute of Soil and Water Conservation
(ICAR), India

REVIEWED BY

Kamlesh Kumar,
Indian Agricultural Research Institute
(ICAR), India
Mohammad Hasanain,
ICAR-Indian Agricultural Research
Institute, India
Shubhra Singhal,
Bundelkhand University, India

*CORRESPONDENCE

Chetankumar Prakash Sawant
✉ chetankumarsawant@gmail.com

RECEIVED 24 July 2025

ACCEPTED 29 August 2025

PUBLISHED 23 September 2025

CITATION

Chaudhary VP, Sawant CP, Gupta A,
Gautam R, Khadatkhar A, Magar AP,
Wakchaure GC, Kumar V and Chaudhary R
(2025) Long-term zero tillage with residue
retention boosts yield, enhances energy
efficiency, and mitigates greenhouse gas
emissions in the western Indo-Gangetic
rice–wheat systems.

Front. Sustain. Food Syst. 9:1672467.
doi: 10.3389/fsufs.2025.1672467

COPYRIGHT

© 2025 Chaudhary, Sawant, Gupta, Gautam,
Khadatkhar, Magar, Wakchaure, Kumar and
Chaudhary. This is an open-access article
distributed under the terms of the [Creative
Commons Attribution License \(CC BY\)](#). The
use, distribution or reproduction in other
forums is permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication in
this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Long-term zero tillage with residue retention boosts yield, enhances energy efficiency, and mitigates greenhouse gas emissions in the western Indo-Gangetic rice–wheat systems

Ved Prakash Chaudhary¹, Chetankumar Prakash Sawant ^{1*},
Ajita Gupta², Rahul Gautam¹, Abhijit Khadatkhar¹,
Ajit Pralhad Magar¹, Goraksha C. Wakchaure³, Vijay Kumar¹ and
Rahul Chaudhary⁴

¹Agricultural Mechanization Division, ICAR–Central Institute of Agricultural Engineering, Bhopal, MP, India, ²Irrigation and Drainage Engineering Division, ICAR–Central Institute of Agricultural Engineering, Bhopal, MP, India, ³School of Drought Stress Management, ICAR–National Institute of Abiotic Stress Management, Baramati, MH, India, ⁴VIAET, Sam Higginbottom University of Agriculture, Sciences and Technology, Prayagraj, UP, India

The rice–wheat cropping system (RWCS) in the Indo-Gangetic Plains (IGP) of India is a dominant food production model, but its conventional management practices, viz., puddled transplanted rice (PTR) and conventionally tilled wheat (CTW), are highly energy-intensive, leading to excessive greenhouse gas (GHG) emissions, lower energy use efficiency (EUE), and soil degradation. This 15-year field study, using a split–split plot design, evaluated the impact of various crop establishment methods on crop productivity, energy use, carbon indices, and GHG emissions under RWCS. Conservation agriculture (CA)-based practices such as zero-till direct-seeded rice (ZTDSR), dry-seeded rice (DSDSR), and zero-till wheat (ZTW) and wheat sown with a Turbo Happy Seeder with residue retention (THSW + R) were compared with conventional systems. The results showed that ZTDSR and THSW + R significantly reduced total input energy, fossil fuel use, and irrigation water demand, resulting in 14–21% energy savings compared to PTR-CTW systems. ZTDSR-THSW + R emerged as the most energy-efficient combination, recording the highest EUE (13.6) and the lowest system-specific grain energy (9.5 MJ kg^{−1}), reducing global warming potential by over 50%. Despite slightly lower rice yields under ZTDSR, system productivity remained comparable due to superior wheat performance. Carbon output (8,907 kg C ha^{−1}) and carbon efficiency ratio (11.43) were higher under CA-based treatments for wheat due to greater biomass returns and reduced carbon inputs (2,293 kg C ha^{−1}). Integrating zero-till and residue management practices in RWCS enhances energy efficiency, improves sustainability metrics, and reduces environmental footprints. These findings support a transition from conventional to CA-based systems for climate-resilient, resource-efficient agriculture in the IGP and similar agroclimatic zones.

KEYWORDS

clean environment, conservation agriculture, energy budgeting, energy use efficiency, global warming potential, rice–wheat cropping system

Highlights

- Long-term CA boosts energy use efficiency of RWCS by 32–38%.
- ZT in RWCS reduces GHG emission by 53%.
- CSI and CER of RWCS increase under long term CA practices.
- GWP of RWCS using ZTDSR-ZTW reduces to 5,354 kg CO₂ eq. ha⁻¹.

1 Introduction

In India, intensive agriculture is closely scrutinized to increase overall agricultural production and profitability, with the aim of meeting the increasing demands for food, fiber, shelter, and energy due to the rapidly growing population (Pata and Kumar, 2021). A substantial proportion of energy, primarily from expensive fossil fuels, is needed for mechanization, while other inputs such as improved seed varieties, agrochemicals, irrigation, and technological innovations are crucial for achieving agricultural goals (Kumar A. et al., 2018). Agricultural activities contribute significantly to greenhouse gas (GHG) emissions, accounting for approximately 18% of the total GHG emissions (Omotoso and Omotayo, 2024). The excessive use of agricultural inputs and intensive crop management practices aimed at boosting yields results in increased environmental pollution, depletion of natural resources, higher energy consumption, and increased GHG emissions from agriculture (Gupta et al., 2015; Kakraliya et al., 2021). The increasing concentration of GHGs in the atmosphere contributes to increased global warming potential (GWP) and poses significant environmental challenges (Pratibha et al., 2015). The rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system (RWCS) is characterized by high input use, essential for food, nutrition, and livelihood security (Kumar et al., 2019), which covers approximately 13.5 million hectares (Mha) in the Indo-Gangetic Plains (IGP), with a significant concentration of 9.2 Mha in India, supporting approximately 18% of the world's population (Dhanda et al., 2022; Brar et al., 2023). Conventional agricultural management practices, including the burning or removal of crop residues in RWCS, have led to the degradation of natural resources, reduced profitability, high input energy consumption, increased GWP, and deteriorating soil health and environmental quality (Samal et al., 2017). These challenges and declining water use efficiency are significant sustainability issues of the RWCS in IGP (Bhatt et al., 2016). In RWCS, rice transplanting typically requires intensive tillage and puddling of the soil, whereas wheat sowing demands well-prepared soil. These practices consume significant energy and contribute to increased GWP (Jat et al., 2014), severely impacting ecosystem sustainability (Lal, 2004; Chaudhary et al., 2017). Rice residue burning in the conventional RWCS from October to December remains a major contributor to poor air quality, adversely affecting human health and the atmosphere (Jain et al., 2014; Shyamsundar et al., 2019). Farmers have a limited window of 15–20 days for managing loose paddy straw in the field, which is mainly left behind by combine harvesters. Owing to this constraint, many opt to burn rice residue to clear the fields for wheat planting, as the residue can obstruct seeding (Lohan et al., 2018). In

contrast, wheat residue is typically collected and used as livestock feed. This scenario calls for using environmentally friendly energy sources and energy-efficient management techniques in agricultural production systems, making them highly desirable for climate-smart practices. Adopting climate-smart agricultural practices is crucial for mitigating climate change and enhancing production sustainability. This can be accomplished by conserving natural resources, decreasing dependence on fossil fuels, and increasing the use of renewable energy sources in agriculture (Acosta-Silva et al., 2019). In addition, one of the technological options to practice in place of conventional tillage (CT) is conservation agriculture (CA), which consists of minimum tillage, crop residue management, and crop diversification (Sawant et al., 2019). The CA practices are intended to conserve water and energy, enhance soil structure, decrease cultivation cost (Derpsch et al., 2024), and support the development of beneficial soil microflora and fauna (Kumar V. et al., 2018). According to Chaudhary et al. (2012) and Singh et al. (2022), implementing minimum tillage with crop residue retention has reduced GHG emissions by 8–10% from land preparation, 40–45% from irrigation application, and 60% from overall crop cultivation compared to conventional practices. This approach has also improved energy use efficiency, resulting in reduced specific energy consumption per kilogram of grain production. Minimum tillage in CA has been shown to reduce carbon dioxide (CO₂) emissions, the primary GHG contributing to global warming (Hobbs et al., 2008). Crop residue mulching in no-tilled fields helps maintain soil moisture and temperature, enhances soil fertility (Singh et al., 2011), and increases productivity and energy output (Gathala et al., 2015) while also reducing GWP (Sapkota et al., 2015). Therefore, CA-based RWCS are promising technological strategies for reducing GHG emissions, thereby mitigating the adverse effects of climate change on sustainable agricultural production.

Extensive region-specific studies evaluating crop production methods concerning energetics, economics, and GHG emissions in RWCS have been conducted in the eastern Himalayas (Babu et al., 2020) and the IGP (Chaudhary et al., 2017) for up to 10 years. Therefore, a long-term 15-year (2006–07 to 2020–21) field experiment was conducted in a CA field maintained for 23 years (1998–2021) in western IGP to identify suitable crop establishment methods (CEMs) for RWCS under long-term CA, with a focus on energy efficiency and climate-smart benefits over CT.

2 Materials and methods

2.1 Details of experimental site

The long-term (2006–07 to 2020–21) field study was conducted at the experimental farm of the ICAR-Indian Institute for Farming Systems Research (IIFSR), Modipuram, UP, India, located at 29°84'N, 77°46'E, 237 m elevation in the upper IGP. The experimental farm had been maintained under CA for 23 years (1998–2021). The climate of this subtropical semi-arid region is marked by very hot summers and cold winters. May and June are the hottest months with maximum temperatures reaching 45–46 °C; however, the coldest months are December and January with temperatures frequently falling below 5 °C. The average

yearly rainfall is 865 mm, with approximately 75–80% occurring during the northwest monsoon from July to September. The investigational field soil (0–0.15 m) was typic Ustochrept (Sobhapur sandy loam), containing 165 g kg⁻¹ silt, 205 g kg⁻¹ clay, and 620 g kg⁻¹ sand. The soil retained 18% and 7% water (mass basis) at 30 and 1,500 kPa water potential, respectively. Other soil attributes encompassed a bulk density of 1,590 kg m⁻³, a mean soil clod diameter of 1.54 mm, a pH of 8.2, an organic carbon content of 5.4 g kg⁻¹, nitrogen (N) content of 154 kg ha⁻¹, phosphorus levels of 16.7 kg ha⁻¹, potassium content of 124.34 kg ha⁻¹, and zinc concentration of 60 mg kg⁻¹ in the 0–100-mm soil depth.

2.2 Experimental design and crop management

The experimental field was established in 1998 and was retained under CA for 23 years until the winter season of 2020–21. In 2006–07, the experiment was laid out for RWCS in a split-split plot design with three replications. The experiment involved four main plots of rice CEM: (i) zero-tilled direct-seeded rice (ZTDSR), (ii) drum-seeded rice (DSDSR), (iii) mechanically transplanted rice under puddled condition (PMTR), and (iv) conventionally puddled transplanted rice (PTR); and five sub-main plots of wheat CEM: (i) sowing with zero-till drill (ZTW), (ii) sowing with Turbo Happy Seeder under rice residue (THSW + R), (iii) sowing with bed planter (BPW), (iv) sowing with rotary till drill (RTW), and (v) sowing after CT using seed-cum-fertilizer drill (CTW), respectively. Each experimental plot had dimensions of 48 × 5 m. Information on the treatments and management practices is provided in Table 1 and described below.

2.3 Rice crop

The medium-duration (135 days) rice variety “Saket-4” was sown during the rainy season throughout the study period, irrespective of the treatments. Each year, in the second or third week of June, rice was directly seeded under ZTDSR using a zero-till drill at a seed rate of 40 kg ha⁻¹, row spacing of 220 mm, and planting depth of 40 ± 10 mm, which was measured from soil surface to seed midpoint. In ZTDSR, the rice seeds were sown after the onset of pre-monsoon when there was sufficient soil moisture for sprouting. Five to eight supplementary irrigations were applied using an electrically operated submersible pump with wetting and drying methods after dry spells lasting more than 1 week, in the presence of hairline soil fissures, and based on the quantity and distribution of rainfall each year. In DSDSR, PMTR, and PTR treatments, plots were tilled with a harrow followed by a cultivator and rotavator in dry conditions. Thereafter, the puddling operation was performed in a ponding depth (100 ± 50 mm) of water with two passes of a rotavator. Under DSDSR, the 24-h soaked sprouted rice seeds were sown using a drum seeder at a seed rate of 30 kg ha⁻¹ in rows at a distance of 220 mm. The seeding for nursery preparation under PMTR and PTR was carried out on the same day as ZTDSR, following the recommended package of practices outlined by Singh et al. (2020) and Mishra et al. (2021). For PTR, nurseries were grown at a seed rate of 30 kg ha⁻¹, and the

25-day-old seedlings were transplanted manually under a puddled field at 200 × 150 mm spacing with 2–3 seedlings hill⁻¹. The mat-type rice seedlings were grown at a seed rate of 25 kg ha⁻¹ for the PMTR treatment. A polyethylene sheet with a thickness of 15–20 microns was used to grow seedlings. Because of the polyethylene covering, the roots of rice seedlings form a dense mat, making it easier to dislodge them for mechanical transplanting (Singh et al., 2020). The sprouted rice seeds were spread evenly over a uniformly distributed mixture of filtered soil and farmyard manure (FYM) in a 4:1 ratio, followed by covering the sprouted rice seeds with a thin layer of soil. The soil moisture was initially preserved by consistent water spraying and later maintained by irrigating the nursery two times a day. Thereafter, the 20-day-old, 2–3 seedlings per hill were transplanted with an eight-row self-riding type paddy transplanter (VST Pvt. Ltd., Bengaluru, Karnataka, India) at a spacing of 220 × 120 mm in a hill in 30 ± 20 mm of stagnant water and kept submerged for proper crop establishment during the initial 7–10 days as described by Chaudhary et al. (2017).

In the rice crop, inorganic fertilizers such as 120 kg N, 60 kg P₂O₅, 60 kg K₂O, 25 kg ZnSO₄, and 20 kg FeSO₄ per hectare were applied (Jat et al., 2014). In case of ZRDSR, 50% dose of N and complete basal dose of P₂O₅, K₂O, ZnSO₄, and FeSO₄ were applied at the time of sowing, whereas the remaining 50% dose of N was top-dressed in two splits, at tillering and panicle initiation stages of the crop. In PMTR and PTR, the basal dose of fertilizers was applied at the time of puddling, whereas in DSDSR, it was broadcast before drum seeding. In ZTDSR, the glyphosate was sprayed 1 week before the sowing at a rate of 1.0 kg a.i. ha⁻¹ to eradicate the prevailing weeds, whereas pendimethalin was also sprayed in ZTDSR and DSDSR at 1.0 a.i. kg ha⁻¹ as pre-emergence within 2 days after sowing (DAS). The pretilachlor 37% EW @ 1.0 kg ha⁻¹ was applied after 2–3 days transplanting (DAT) and bispyribac sodium at 25 g a.i. ha⁻¹ was applied after 20–25 DAS irrespective of the treatments. A manual weeding for leftover weeds was performed at 45–50 DAS, when the crop is in the late tillering to early panicle initiation stage. The rice was harvested from the second fortnight of October to the first fortnight of November after attaining maturity. Rice was harvested 7–10 days earlier under ZTDSR than under PMTR and PTR. For treatments of wheat sowing as ZTW, BPW, and CTW, the rice crop was harvested at ground level; however, for the treatment of THSW + R and RTW, it was harvested at ~30 and ~10 cm, respectively above ground level by hand with a sickle. Paddy was threshed manually with a tractor-operated multi-crop thresher after suitable sun drying. The grain and straw yields were recorded from a 1 × 1 m area, with grain adjusted to 14% moisture content.

2.4 Wheat crop

The brown rust-resistant wheat cultivar “PBW-343” was grown in the winter season according to the recommended package of practices throughout the study period after rice harvest. In ZTW, wheat was sown in a no-till field using a zero-till drill without loose paddy residues, whereas in THSW + R, wheat was drilled under no-till conditions using the Turbo Happy Seeder, with rice residues of approximately 6 t ha⁻¹. Both anchored and loose rice straw above the ground surface were collected, oven-dried, and measured at 6 t ha⁻¹. In BPW, during the first year of experiment, the plots were tilled with one pass of harrow followed by one pass of cultivator; one

TABLE 1 Agronomic practices adopted under the rice–wheat cropping system in different treatments during the 2006–07 to 2020–21 field experiment.

Treatments/ agronomic practices	Rice				Wheat				
	ZTDSR	DSDSR	PMTR	PTR	ZTW	THSW + R	BPW*	RTW	CTW
Tillage operation	–	One harrowing + one cultivating + thrice rototilling (twice rototilling for puddling)			–	–	Reshaping of bed	Shallow rotary tilling	Twice harrowing + twice tiller + once rotovator
Transplanting/Sowing	Direct seeding with zero-till drill in no-tilled field	Sprouted seed sowing by drum seeder (8-row) in puddled field	Transplanting of 20-day-old paddy seedlings with a self-propelled rice transplanter (8-row) in a puddled field	Manually transplanting 25-day seedlings in a puddled field	Seeding with zero-till drill under rice residue (6 t ha ⁻¹)	Seeding with Turbo Happy Seeder	Seeding with raised bed planter	Seeding with a rotary till drill	Seed-cum-fertilizer drill
Seed rate	40 kg ha ⁻¹ with line spacing of 220 mm		25 kg ha ⁻¹ seed used for mat-type nursery preparation and transplanting with row spacing of 220 mm and hill spacing of 100 mm		80 kg ha ⁻¹ with line spacing of 220 mm; however, in BPW, seeding was done with three rows at 150 cm apart on the top width of two raised beds of 370 mm				
Fertilizer application	Recommended dose of fertilizer, kg ha ⁻¹ (i.e., N:P:K::120:60:40). Basal dose of 50% N and full dose of P and K; and 25 kg ha ⁻¹ zinc sulfate and 20 kg ha ⁻¹ ferrous sulfate at the time of sowing. Top dressing: two split doses of 50% N at tillering and milking stage				Recommended dose of fertilizer, kg ha ⁻¹ (i.e., N:P:K::120:60:40). Basal dose applied: 50% N and full dose of P and K at the time of sowing; top dressing: in two split doses of 50% N at tillering and milking stage				
Intercultural and weeding	Non-selective herbicide: Glyphosate@ 61 ha ⁻¹ 360 g/L; Pre-emergence herbicide: Pendimethalin 30% EC at 4.5 kg ha ⁻¹ (1.50 kg a.i.ha ⁻¹)				Non-selective herbicides: Glyphosate at 6 l ha ⁻¹ (1.2 kg a.i. ha ⁻¹)		Nil		
	Post-emergence herbicide: Bispyribac sodium (nomaniglod) 300 ml ha ⁻¹ or 40 g ha ⁻¹ 10% a.i. followed by one manual spot weeding				Post-emergence herbicide: Sulfosulfuronat 25 ga.i. ha ⁻¹ + Metsulfuran methyl at 4.00 ga.i. ha ⁻¹ at 30 days after sowing (DAS), followed by one spot hand weeding on 40–45 DAS				
Irrigation	Wet and dry method	Wet and dry method	Flooding about 50-mm depth	Flooding about 50-mm depth	Irrigation depth: 5 ± 2 cm; no. of irrigation: 5	Irrigation depth: 5 ± 2 cm; no. of irrigation: 4	Irrigation depth: 5 ± 2 cm; no. of irrigation: 5	Irrigation depth: 5 ± 2 cm; no. of irrigation: 6	Irrigation depth: 5 ± 2 cm; no. of irrigation: 6
Pesticide application	Insecticides: Insecticide Furadan (carbofuran) 20 kg ha ⁻¹ content 19 mg kg ⁻¹ available Pesticides: Carbenzin–mancozeb 4 kg ha ⁻¹				Insecticides: Furadan (carbofuran) at 20 kg ha ⁻¹ @ content 19 mg kg ⁻¹ ; Fungicides: mancozeb (2.50 kg/ha a.i.) + propyconazole (at 2.0 kg/ha)				
Harvesting	Manually harvesting				Manually harvesting				
Threshing and winnowing	Threshing by tractor-operated power thresher				Threshing by tractor-operated power thresher				

*First year—tillage operation (twice harrowing + once tiller + once rotavator) and reshaped bed.

ZTDSR, zero-tilled direct-seeded rice; DSDSR, drum-seeded rice; PMTR, mechanically transplanted rice under puddled condition; PTR, conventionally puddled transplanted rice; ZTW, wheat sowing with zero-till drill; THSW + R, wheat sowing with Turbo Happy Seeder under rice residue; BPW, wheat sowing with bed planter; RTW, wheat sowing with rotary till drill; CTW, wheat sowing after conventional tillage using seed-cum-fertilizer drill.

pass of rotavator, and bed formation and sowing using a raised bed planter. The two beds, each 370 mm wide at the top, were drilled with three rows spaced 150 mm apart. In successive years, the beds were reshaped and planted using raised bed planters without additional tillage. In RTW, wheat was sown with one pass of a rotary till drill. In contrast, in CTW, the bed was prepared using two passes of harrowing followed by two passes of cultivator, two passes of rotavator, and sowing with seed-cum-fertilizer drill. The seed rate and row spacing were 80 kg ha⁻¹ and 220 mm, respectively, for all treatments except BPW, whereas the seeding depth was maintained at 40 ± 10 mm for all treatments. Farm machinery used for other operations, such as spraying, water pumping, and threshing, was the same across treatments. The recommended fertilizer dose of N:P:K (120:60:40 kg ha⁻¹) was applied for wheat as a basal treatment with 100% of phosphorus and potassium each and 50% of the N administered at sowing. The remaining 50% of nitrogen was applied in two separate top dressings. In the ZTW and THSW+R plots, the non-selective post-emergence herbicide glyphosate was applied at a rate of 1.2 kg a.i. ha⁻¹ before seeding, whereas in all treatments, 25 g a.i. ha⁻¹ of sulfosulfuron and 4.0 g a.i. ha⁻¹ of metsulfuron methyl were applied post-emergence at 25–30 DAS, followed by one spot hand weeding at 40–45 DAS in all the plots. Pre-sowing irrigation was applied in the ZTW and THSW + R plots to ensure proper seed germination. In addition, the zero-tillage (ZT) plots received five irrigations, while the THSW + R plots received four. Meanwhile, the BPW plots also received five irrigations, and the RTW and CTW plots were irrigated six times using the check basin method with an electric submersible pump. In irrigation, 40 ± 20 mm of water was applied based on soil conditions under each treatment. The irrigation schedule aligned with the critical growth stages of wheat, including CRI (Crown Root Initiation), tillering, flowering, milking, and grain filling. After reaching maturity, the wheat crop was manually harvested and threshed using a tractor-operated multi-crop thresher in April. Grain yield and biomass were recorded at 12% moisture content.

2.5 Energy budgeting

2.5.1 Input energy

The agricultural inputs for RWCS, such as seed, agrochemicals, fuel, water, and human labor, and outputs, such as grain and biomass, have been recorded under selected treatments. The various energy indices, such as total input energy (TIE), total output energy (TOE), net energy (NE), energy use efficiency (EUE), and specific energy (SE) were calculated based on the equations (Equations 1, 3–10), respectively given by Chaudhary et al. (2021) and Sawant et al. (2023). The energy components used in these equations were calculated by multiplying each input by its respective energy-equivalent factor, as indicated by Fagodiya et al. (2023) as per Equation 1.

$$TIE = \left[(E_m + E_f + E_{irr} + E_{Mach} + E_i)_{Rice} + (E_m + E_f + E_{irr} + E_{Mach} + E_i)_{wheat} \right] \quad (1)$$

where TIE is total input energy (MJ ha⁻¹); E_m is the manual energy (MJ ha⁻¹); E_f is the fuel energy (MJ ha⁻¹); E_{irr} is the irrigation

energy (MJ ha⁻¹); E_{Mach} is the farm machinery energy (MJ ha⁻¹); and E_i is the energy derived from all inputs (MJ ha⁻¹), including seed, fertilizer, agrochemicals, and crop residues.

The irrigation energy is an indirect source that encompasses the energy used for manufacturing pumps and energy from water. Electricity is the direct energy source consumed during pumping. The manufacturing, repairing, and transporting of farm machinery are also indirect input energy sources, determined by considering the actual field capacity of the machine as per Equation 2 (Chaudhary et al., 2021). The personified energy in farm machinery was expressed as MJ ha⁻¹.

$$E_{Mech} = (M_{TR} \times W) / (L \times AF_C) \quad (2)$$

where E_{Mech} is the farm machinery input energy (MJ ha⁻¹); M_{TR} is the manufacturing, transportation, and repairing energy (MJ ha⁻¹); W is the mass of the machinery (kg); L is the life span of the machinery (h); and AF_C is the actual field capacity of farm machinery (ha h⁻¹).

2.5.2 Output and net energy

Total output energy, i.e., the energy produced from grain and straw of rice and wheat, is calculated using Equations 3, 4.

$$TOE_g = (Y_g \times E_g)_{Rice} + (Y_g \times E_g)_{wheat} \quad (3)$$

$$TOE_t = [(Y_g \times E_g) + (Y_s \times E_s)]_{Rice} + [(Y_g \times E_g) + (Y_s \times E_s)]_{wheat} \quad (4)$$

where TOE_g is the total output energy from grain (MJ ha⁻¹); TOE_t is the total output energy from grain and straw (MJ ha⁻¹); Y_g is the crop grain yield (kg ha⁻¹); Y_s is the crop straw yield (kg ha⁻¹); E_g is the specific conversion factor for grain; and E_s is the specific conversion factor for straw.

The net energy of the RWCS estimated for grain and total is expressed in NE_g and NE_t , respectively, as given in Equations 5, 6.

$$NE_g = TOE_g - TIE \quad (5)$$

$$NE_t = TOE_t - TIE \quad (6)$$

where NE_g is the net energy from grain (MJ ha⁻¹); NE_t is the net energy from grain and straw (MJ ha⁻¹); TOE_g is the total output energy from grain (MJ ha⁻¹); and TOE_t is the total output energy from grain and straw (MJ ha⁻¹).

2.5.3 Energy use efficiency and specific energy

The EUE is represented in a dimensionless form and is calculated as the ratio of energy output to total energy input, as given in Equations 7, 8.

$$EUE_g = TOE_g / TIE \quad (7)$$

$$EUE_t = TOE_t / TIE \quad (8)$$

where EUE_g is the energy use efficiency of grain; TOE_g is the total output energy from grain (MJ kg⁻¹); EUE_t is the energy use efficiency of grain and straw; TOE_t is the total output energy

from grain and straw (MJ kg^{-1}); and TIE is the total input energy (MJ kg^{-1}).

The system-specific energy is the amount of energy used to produce 1 kg of grain. The system-specific energy for both grain (SSE_g) and total (SSE_t) in MJ kg^{-1} is estimated using Equations 9, 10.

$$\text{SSE}_g = \text{TIE} / [(Y_g)_{\text{Rice}} + (Y_g)_{\text{Wheat}}] \quad (9)$$

$$\text{SSE}_t = \text{TIE} / [(Y_g + Y_s)_{\text{Rice}} + (Y_g + Y_s)_{\text{Wheat}}] \quad (10)$$

where TIE is the total input energy (MJ kg^{-1}); Y_g is the grain yield (kg ha^{-1}); and Y_s is the straw yield (kg ha^{-1}).

2.6 Total greenhouse gas emission and carbon indices

2.6.1 Global warming potential

The total GHG emissions, both direct and indirect, were evaluated using default emission factors in accordance with the Tier 1 methodology provided by the Intergovernmental Panel on Climate Change (IPCC) (Fagodiya et al., 2020). This assessment was conducted across selected tillage methods within RWCS per unit area, expressed as CO_2 equivalents in $\text{kg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$. The conversion to CO_2 equivalents was performed by considering the GWP of CO_2 , CH_4 , and N_2O as 1, 34, and 298, respectively (Eggleston et al., 2006).

The GWP was estimated as follows, given by Babu et al. (2020) in Equation 11.

$$\text{GWP (kg CO}_2 \text{ Equation ha}^{-1}) = \{(N_2O (\text{direct} + \text{indirect}) \times 298) + (CH_4 \times 34) + CO_2\} \quad (11)$$

2.6.2 Greenhouse gas emissions

The GHG emissions from agricultural inputs, such as seeds, fertilizers, herbicides, and fuel consumption, were calculated by multiplying their application rates with the respective emission factors provided by Lal (2004). GHG emissions from farm machinery and electricity were determined by multiplying the energy used by the machinery (MJ ha^{-1}) and electricity consumed (kWh ha^{-1}) during rice and wheat crop cycles with the corresponding emission factors outlined by Pishgar-Komleh et al. (2013).

The GHG from various agronomic inputs and farm operations utilized in RWCS were calculated and expressed in CO_2 Equation ($\text{kg CO}_2 \text{ eq. ha}^{-1}$) as outlined in Equation 12.

$$\text{CO}_2 \text{ eq.} = \left[\text{diesel (l. ha}^{-1}) \times C_{EC} + \left(\text{farm machinery, MJ (kg.h)}^{-1} \times C_{EC} \right) + \left\{ \left(\text{fertilizers (N, P, K)} \times C_{EC} \right) + \left(\text{herbicides} \times C_{EC} \right) \right\} (\text{kg ha}^{-1}) + (\text{electricity (kWh ha}^{-1}) \times C_{EC}) \right] \times 12/44 \quad (12)$$

where C_{EC} is the carbon emission coefficient for each category of inputs multiplied by the respective quantity of inputs applied.

2.6.3 Nitrous oxide emissions

The N_2O emission is associated with the N sequence in the soil, originating from the applied chemical fertilizers and N present in crop residues, including roots (Bhatia et al., 2004; Khakbazan et al., 2009). The N_2O emissions are classified into two types: (1) direct emission of N from nitrification and denitrification of inorganic fertilizers, crop biomass, and roots, and (2) indirect emission of N from volatilization and leaching of inorganic fertilizers (Gregorich et al., 2005). To estimate the root biomass of the preceding rice crop, shoot-to-root proportions were utilized (Tabatabaie et al., 2012) and then multiplied by their respective N content to calculate N addition by crop residues. The N_2O was determined as per equations (Equations 13, 14) provided by Chaudhary et al. (2024).

$$N_2O_{\text{direct}} = (N_{\text{SNF}} + N_{\text{CR}} + N_{\text{root}}) \times EF \times \frac{44}{28} \times 298 \quad (13)$$

$$N_{\text{CR}} = CR_{\text{st}} \times \text{Frac}_{\text{NCRST}} \quad (14)$$

where $\text{N}_2\text{O}_{\text{direct}}$: direct N_2O emission; N_{SNF} : fertilizer quantity (N_2) applied to the crop per unit area; N_{CR} : nitrogen content in crop residue left on the soil surface; N_{root} : nitrogen content in crop roots left inside soil surface; EF: emission factor for N_2O -N released from nitrogen add-ons to the soil; CR_{st} = amount of crop residue left on the soil surface; $\text{Frac}_{\text{NCRST}}$ = nitrogen content of crop residues.

2.6.4 Methane and nitrous oxide emissions

Methane (CH_4) emission was measured from submerged rice fields (PMTR and PTR) only, as its emission under wet and dry methods of irrigated DSR (ZTDSR and DSDSR) treatments and wheat crop remains insignificant (Sapkota et al., 2015). Similarly, N_2O emission was considered negligible in submerged rice fields, and its emission occurs only when the soil becomes dry and aerobic conditions prevail (Pathak et al., 2003). Therefore, in PMTR and PTR, CH_4 emission was estimated based on a daily emission factor considering soil type, irrigation practice, cultivated crop, and environmental factors. The emissions of CH_4 and N_2O from the farmers' practice of rice cultivation under submerged fields with partial tillage were taken as 162 kg and 0.75 kg, respectively. The CH_4 and N_2O emission factors from intermittent wetting and drying methods and DSR were taken as 0.6 and 0.07, and 1.13, and 1.19, respectively, for simulating GHG emissions (Gupta et al., 2015). The CH_4 emission factors for puddled transplanted rice and wheat were 12.8 and 0 kg $\text{ha}^{-1} \text{ season}^{-1}$, respectively (Tirol-Padre et al., 2016). In Indian conditions, field experiment measurements by Jain et al. (2016) reported an emission factor for N_2O of 0.53 in wheat, whereas CH_4 emissions were absent. This is because wheat was cultivated under upland, well-aerated soil conditions where oxygen suppressed methanogenic activity responsible for CH_4 production in flooded anaerobic soils as in rice; hence, CH_4 emission from wheat fields was negligible, and GHG emissions were instead dominated by N_2O due to nitrogen fertilizer application.

2.6.5 Carbon indices

GHG emissions are considered a source of global warming by multiplying their accompanying GWP ($\text{CO}_2 \text{ eq. ha}^{-1}$)

(Basavalingaiah et al., 2020). Carbon indices (kg CO₂ Equivalent kg⁻¹ of grain) such as total carbon input (C_{input}), carbon output (C_{output}), carbon sustainability index (CSI), carbon efficiency ratio (CER), and GHG intensity were assessed using Equations 15–19, respectively, as cited by Chaudhary et al. (2021).

$$C_{input} = GWP \times 12/44 \quad (15)$$

$$C_{output} = Av. (Y_{sg} + Y_{Straw}) \times 0.4 \quad (16)$$

$$CSI = (C_{output} - C_{input})/C_{input} \quad (17)$$

$$CER = (C_{output}/C_{input}) \quad (18)$$

$$GHG \text{ intensity (kg CO}_2 \text{ e kg}^{-1} \text{ grain)} = GWP/Y_{sg} \quad (19)$$

2.7 Statistical analysis

The experiment was conducted using a split-split plot design with three replications. Data pertaining to yield, energy dynamics, and carbon indices were subjected to Analysis of Variance (ANOVA) following the methodology outlined by Gomez and Gomez (1984). SAS 9.4 (SAS Institute, Cary, North Carolina, USA) was used for the analysis, and *post hoc* mean separation was performed using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$.

3 Results

3.1 Yield attributes

An insightful comparison of total grain yield and total straw yield within an RWCS was conducted across four distinct rice tillage methods in the main plots, *viz.*, ZTDSR, DSDSR, PMTR, and PTR. These methods were further integrated into five sub-main plots for wheat, *viz.*, ZTW, THSW + R, BPW, RTW, and CTW (Figure 1). Total straw yield consistently exceeded total grain yield across all treatments and systems, with straw yields ranging from 10,573 to 12,021 kg ha⁻¹ and grain yields from 10,382 to 11,456 kg ha⁻¹. Among the rice management systems, PMTR achieved the highest yields for both grain and straw, demonstrating its superior productivity, followed by PTR. In contrast, direct-seeding methods like ZTDSR and DSDSR produced lower yields, indicating limitations in maximizing yield potential within the RWCS. In the case of the sub-main plot, THSW + R and ZTW consistently delivered the highest grain and straw yields across all management systems, underscoring their effectiveness. Meanwhile, BPW, RTW, and CTW exhibited lower productivity, reflecting their limited capacity for yield improvement. Under PMTR, the THSW + R reported the highest grain yield (11,456 kg ha⁻¹) and straw yield (12,021 kg ha⁻¹), which emerged as the most productive system for optimizing grain and straw yields. However, the interaction of main and sub-main treatments of grain and straw yield under RWCS had no significant effect.

3.2 Energy consumption

The source-wise energy input is figured for RWCS, which was minimum in ZTDSR-THSW + R (47,110 MJ ha⁻¹) and maximum in 65,830 MJ ha⁻¹ in PTR-CTW (Table 2). For RWCS, TIE was in the order of PTR-CTW > PMTR-CTW > PTR-RTW > PMTR-RTW > PTR-BPW > PTR-ZTW > PMTR-BPW > PTR-THSW + R > PMTR-ZTW > DSDSR-CTW > PMTR-THSW + R > ZTDSR-CTW > DSDSR-RTW > DSDSR-BPW > DSDSR-ZTW > DSDSR-THSW + R > ZTDSR-RTW > ZTDSR-BPW > ZTDSR-ZTW > ZTDSR-THSW + R. Among inputs, fertilizer shared the greatest portion of TIE (27–37%), followed by electricity (22–28.5%), irrigation water (21–25%), and diesel (5–11.2%). The pattern of energy usage based on different operations revealed that irrigation application has the primary share (45–53%), followed by fertilizers (27–37%), land preparations (8–13%), and sowing (5.5–6.5%) in RWCS (Table 2). Non-renewable (direct and indirect) energy sources accounted for 93–94% of TIE, whereas renewable energy sources constituted only 5–7% of TIE used to cultivate RWCS (Figure 2). The direct and indirect energy sources consumed 34–40% and 60–66% of TIE, respectively, irrespective of the treatments (Figure 3). The ZTDSR-ZTW and ZTDSR-THSW + R, as well as DSDSR-ZTW and DSDSR-THSW + R, recorded lower direct energy consumption than PTR-CTW (farmers' practice).

The main plot treatments of rice had significant effects on TIE. In the main plot, ZTDSR (49,563 MJ ha⁻¹) consumed significantly lower TIE, followed by DSDSR (52,944 MJ ha⁻¹), PMTR (59,942 MJ ha⁻¹), and PTR (60,825 MJ ha⁻¹). However, the TIE of PTR was on par with that of PMTR. In the case of sub-main plot treatments for wheat crop, THSW + R consumed significantly lower energy, followed by ZTW, BPW, RTW, and CTW. The TIE of BPW was statistically at par with RTW and CTW, as the differences were non-significant ($p > 0.05$). About 13–16%, 12–14%, 11–14%, and 7–9% higher TIE was observed under CTW than under THSW + R, ZTW, BPW, and RTW, respectively. In RWCS, the interaction effects of the selected treatments were not significant on TIE. However, under DSR and CTW, the TIE in ZTDSR-CTW (54,567 MJ ha⁻¹) and DSDSR-CTW (57,949 MJ ha⁻¹) was 14–21% lower than in PMTR-CTW (64,947 MJ ha⁻¹) and PTR-CTW (65,830 MJ ha⁻¹).

3.3 Output and net return energy

A significantly higher TOE_g was observed in the main plot of PMTR with 1.4%, 7%, and 7% against PTR, ZTDSR, and DSDSR, respectively (Table 3). Similarly, 2.8%, 7.0%, and 8.1% higher TOE_t were observed under the main plot for PMTR than under PMR, ZTDSR, and DSDSR, respectively. In sub-main plots, the significantly higher TOE_g was perceived for wheat under THSW + R (162,352 MJ ha⁻¹), followed by ZTW (161,934 MJ ha⁻¹), BPW (160,782 MJ ha⁻¹), RTW (160,364 MJ ha⁻¹), and CTW (160,521 MJ ha⁻¹). In contrast, TOE_t was observed to be significantly higher under THSW + R (311,921 MJ ha⁻¹) than under ZTW (311,002 MJ ha⁻¹), under CTW (305,714 MJ ha⁻¹), and under BPW (305,522 MJ ha⁻¹), whereas RTW and CTW were comparable to each other.

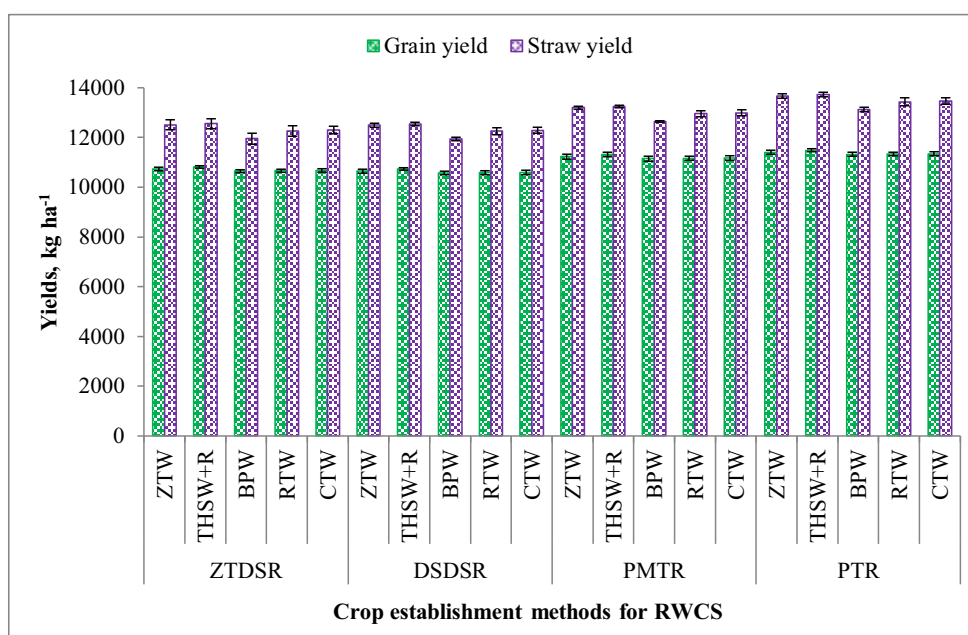


FIGURE 1

Total grain and straw yield in rice–wheat cropping system. ZTDSR, zero-tilled direct-seeded rice; DSDSR, drum-seeded rice; PMTR, mechanically transplanted rice under puddled condition; PTR, conventionally puddled transplanted rice; ZTW, wheat sowing with zero-till drill; THSW + R, wheat sowing with Turbo Happy Seeder under rice residue; BPW, wheat sowing with bed planter; RTW, wheat sowing with rotary till drill; CTW, wheat sowing after conventional tillage using seed-cum-fertilizer drill; RWCS, rice–wheat cropping system.

The NE_g under main and sub-main plots was observed in order of ZTDSR > PMTR > PTR > DSDSR and THSW + R > BPW > ZTW > RTW > CTW, respectively, whereas in the case of NE_t , the main and sub-main plots were observed in order of PMTR > PTR > ZTDSR > DSDSR for rice and THSW + R > ZTW > RTW ≥ BPW > CTW for wheat, respectively. The interaction effect of crop establishment methods for RWCS did not significantly affect TIE, TOE_g , TOE_t , and NE_t at 5% level of significance. However, higher net grain (NE_g) and total (grain + biomass) energy (NE_t) were observed in ZTDSR-ZT (12% and 4%) and ZTDSR-THSW + R (13% and 5%) than in conventionally puddled rice and wheat (PTR-CTW).

3.4 Energy use efficiencies

The significantly higher EUE_g and EUE_t were observed under main plots of ZTDSR (6.57 and 12.54), followed by DSDSR (6.27 and 11.91), PMTR (6.17 and 11.83), and PTR (6.06 and 11.51), respectively. Among the sub-main plot treatments, EUE_g and EUE_t were higher under THSW + R (6.77 and 13.03), followed by ZTW (6.59 and 12.67), BPW (6.50 and 12.20), RTW (6.04 and 11.49), and CTW (5.43 and 10.34), respectively. The interaction effect of main and sub-main plot treatments revealed that crop establishment methods had no significant effect on EUE_g and EUE_t . However, higher EUE_g and EUE_t values were observed under ZTDSR-THSW + R (7.08) and ZTDSR-ZTW (13.63), while lower values were observed in PTR-CTW (5.22 and 9.90), respectively.

3.5 System-specific energy

In RWCS, under the main plot, the SSE_g and SSE_t were observed significantly higher under PTR (11.45 and 5.59 MJ kg⁻¹) followed by PMTR (11.07 and 5.29 MJ kg⁻¹), DSDSR (10.09 and 5.23 MJ kg⁻¹), and ZTDSR (9.93 and 4.77 MJ kg⁻¹), whereas in the sub-main plot, it was significantly higher in CTW (11.41 and 5.66 MJ kg⁻¹), followed by RTW (10.65 and 5.30 MJ kg⁻¹), BPW (10.60 and 5.14 MJ kg⁻¹), THSW + R (10.18 and 4.97 MJ kg⁻¹), and ZTW (10.35 and 5.04 MJ kg⁻¹), respectively. The CA-based production system required less input energy and produced higher or at-par output energy, making it a more energy-efficient system. The interaction of main and sub-main plot treatments did not significantly affect SSE_g and SSE_t at the 5% level. However, ZTDSR-ZTW and ZTDSR-THSW + R became the most energy-efficient practices with the maximum EUE_g (12.3 and 13.6) and lowest SSE_g (9.5 MJ kg⁻¹) over the conventionally tilled practice (PTR-CTW) through reduced tillage practices (Table 3).

3.6 Global warming potential

The GWP and carbon indices of long-term experiments of RWCS were computed and presented in Table 4. The annual GWP among various treatments varied from 5,354 kg CO₂ eq. ha⁻¹ (ZTDSR-ZTW) to 11,688 kg CO₂ eq. ha⁻¹ (PTR-CTW). In the main plot treatment, significantly lower GWP was recorded under treatments ZTDSR (5,487 kg CO₂ eq. ha⁻¹ year⁻¹) and DSDSR

TABLE 2 Various source-wise input energy used (MJ ha⁻¹) as influenced by crop establishment and conservation tillage on various rice–wheat cropping systems (on average of long-term experiments during 2006–07 to 2020–21).

Treatment	Diesel	Labor	Electricity	Machinery	Fertilizers	Pesticides	Herbicides	Seed	Irrigation water	Total input energy (TIE)
Main plot treatment—crop establishment methods for rice										
ZTDSR	3,372	1,442	11,992	1,081	17,457	647	1,238	2,054	10,282	49,565
DSDSR	4,338	1,897	12,799	1,216	17,457	647	1,238	2,054	11,363	53,007
PMTR	5,862	1,488	15,786	1,433	17,457	647	542	1,686	15,007	59,909
PTR	5,795	1,941	15,934	1,469	17,457	647	542	1,760	15,280	60,824
Sub-main plot treatment—crop establishment methods for rice–wheat										
ZTW	4,059	1,697	13,370	1,248	17,457	647	1,108	1,826	12,682	54,094
THW + R	4,115	1,666	12,836	1,233	17,457	647	1,108	1,826	12,529	53,417
BPW	5,260	1,625	12,569	1,386	17,457	647	1,108	1,826	12,401	54,278
RTW	4,510	1,697	15,240	1,214	17,457	647	563	1,826	13,396	56,549
CTW	6,264	1,775	16,624	1,416	17,457	647	563	2,140	13,906	60,792
Crop establishment method for RWCS										
ZTDSR-ZTW	2,590	1,446	11,244	1,011	17,457	647	1,456	1,991	9,996	47,838
ZTDSR-THSW + R	2,646	1,415	10,710	996	17,457	647	1,456	1,991	9,792	47,110
ZTDSR-BPW	3,790	1,378	10,443	1,148	17,457	647	1,456	1,991	9,690	48,001
ZTDSR-RTW	3,040	1,446	13,114	990	17,457	647	911	1,991	10,710	50,306
ZTDSR-CTW	4,795	1,525	14,449	1,259	17,457	647	911	2,305	11,220	54,567
DSDSR-ZTW	3,556	1,901	12,051	1,146	17,457	647	1,456	1,991	11,016	51,220
DSDSR-THSW + R	3,612	1,870	11,517	1,131	17,457	647	1,456	1,991	11,016	50,696
DSDSR-BPW	4,756	1,833	11,249	1,283	17,457	647	1,456	1,991	10,812	51,484
DSDSR-RTW	4,006	1,901	13,920	1,124	17,457	647	911	1,991	11,730	53,688
DSDSR-CTW	5,760	1,980	15,256	1,394	17,457	647	911	2,305	12,240	57,949
PMTR-ZTW	5,080	1,492	15,000	1,438	17,457	647	760	1,624	14,722	58,218
PMTR-THSW + R	5,136	1,461	14,466	1,423	17,457	647	760	1,624	14,518	57,490
PMTR-BPW	6,280	1,424	14,198	1,575	17,457	647	760	1,624	14,416	58,380
PMTR-RTW	5,530	1,492	16,869	1,366	17,457	647	215	1,624	15,436	60,635
PMTR-CTW	7,285	1,571	18,398	1,366	17,457	647	215	1,938	15,946	64,821
PTR-ZTW	5,012	1,948	15,186	1,399	17,457	647	760	1,697	14,994	59,101
PTR-THSW + R	5,068	1,917	14,652	1,384	17,457	647	760	1,697	14,790	58,373
PTR-BPW	6,212	1,864	14,385	1,536	17,457	647	760	1,697	14,688	59,247
PTR-RTW	5,463	1,948	17,056	1,378	17,457	647	215	1,697	15,708	61,569
PTR-CTW	7,217	2,027	18,391	1,647	17,457	647	215	2,011	16,218	65,830

ZTDSR, zero-tilled direct-seeded rice; DSDSR, drum-seeded rice; PMTR, mechanically transplanted rice under puddled condition; PTR, conventionally puddled transplanted rice; ZTW, wheat sowing with zero-till drill; THSW + R, wheat sowing with Turbo Happy Seeder under rice residue; BPW, wheat sowing with bed planter; RTW, wheat sowing with rotary till drill; CTW, wheat sowing after conventional tillage using seed-cum-fertilizer drill.

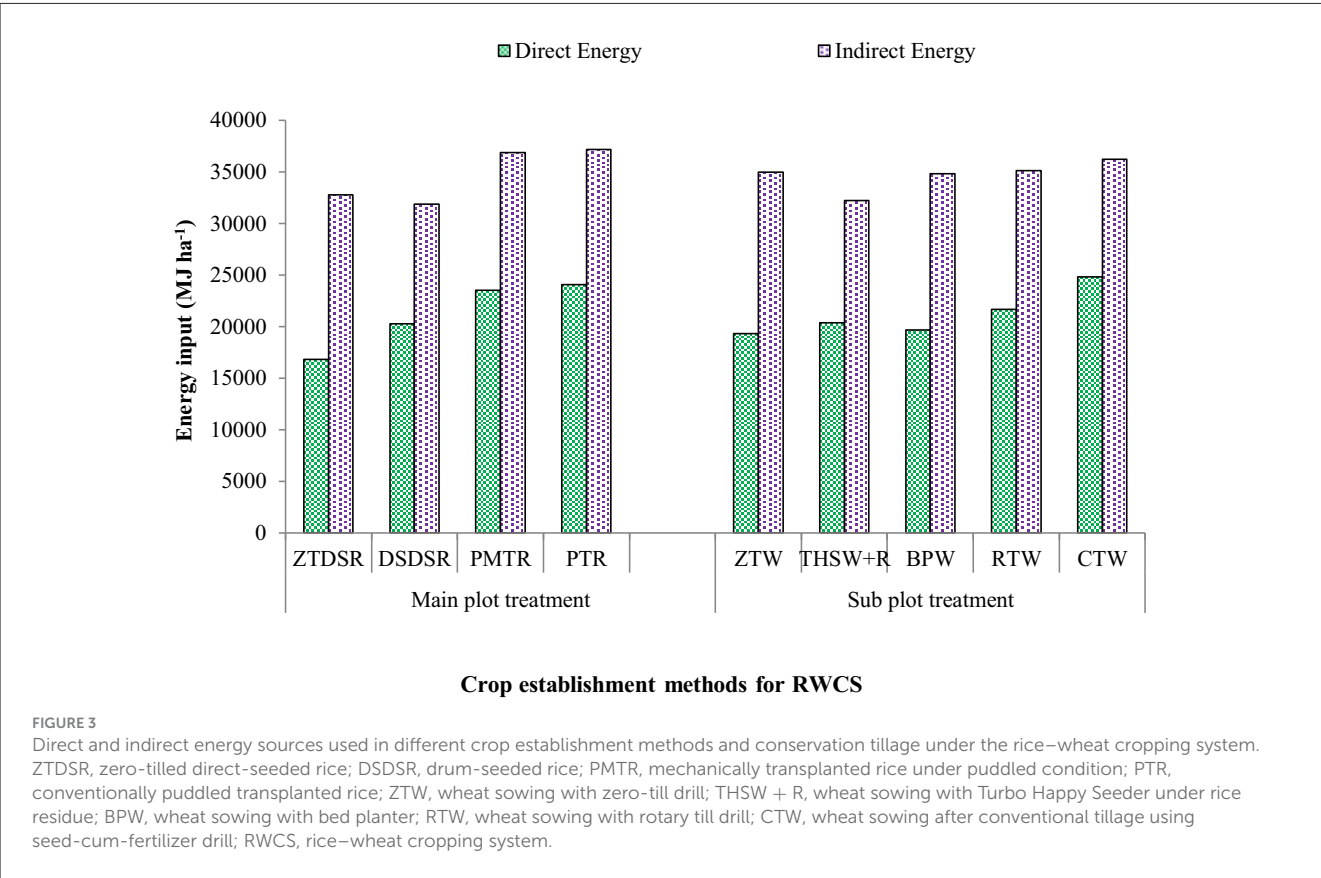
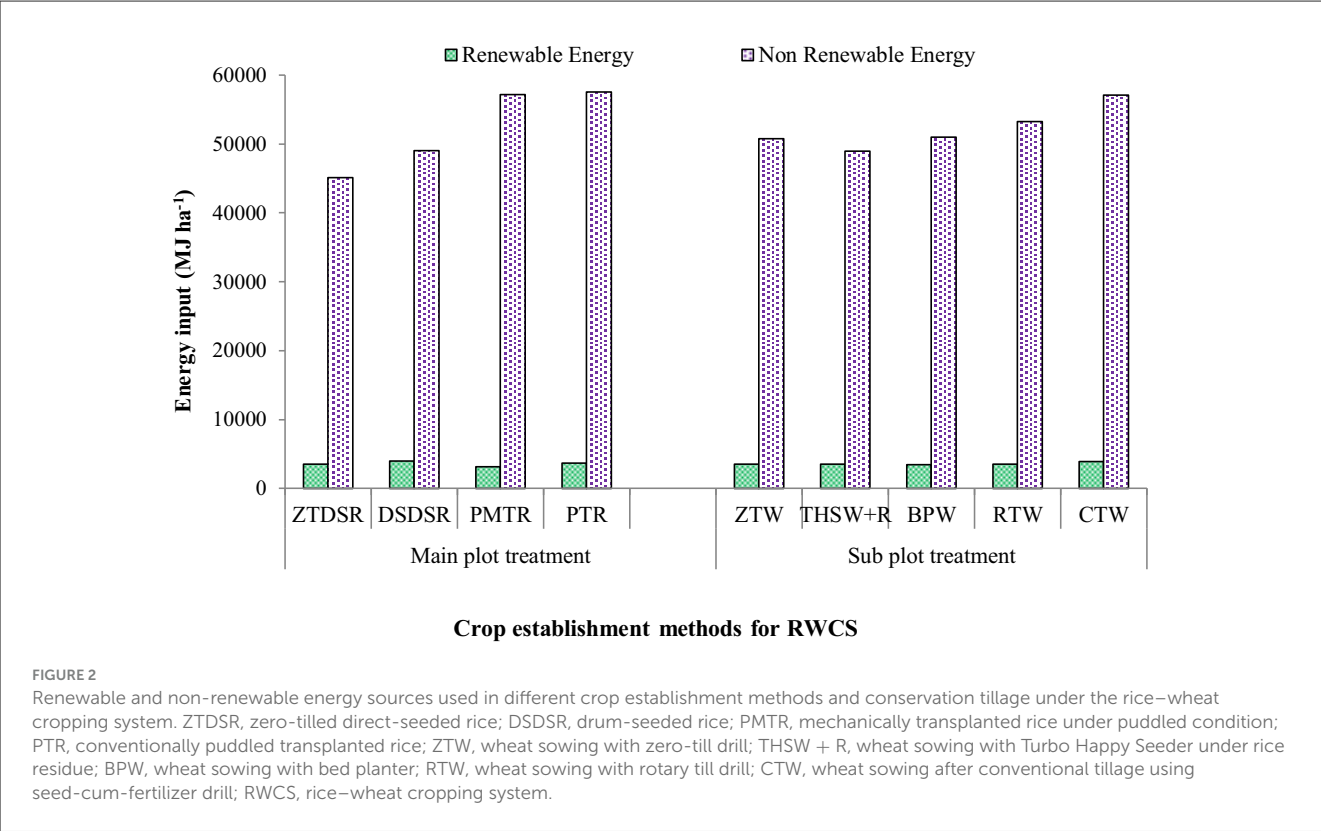


TABLE 3 Energy dynamics influenced by crop establishment methods under RWCS (average of long-term experiments during 2006–07 to 2020–21).

Treatments	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	TIE (kg ha ⁻¹)	TOE _g (kg ha ⁻¹)	TOE _t (kg ha ⁻¹)	NE _g (kg ha ⁻¹)	NE _t (kg ha ⁻¹)	EUE _g	EUE _t	SSE _g	SSE _t
Main plot treatment—crop establishment methods for rice											
ZTDSR	10,665 ^C	10,877 ^C	49,563 ^C	1,56,773 ^C	2,99,430 ^C	1,07,209 ^A	2,49,861 ^C	6.57 ^A	12.54 ^A	9.93 ^D	4.77 ^D
DSDSR	10,601 ^C	10,872 ^C	52,944 ^B	1,55,832 ^D	2,95,698 ^D	1,02,886 ^D	2,42,751 ^D	6.27 ^B	11.91 ^B	10.09 ^C	5.23 ^C
PMTR	11,377 ^A	11,777 ^A	59,942 ^A	1,67,240 ^A	3,21,845 ^A	1,05,833 ^B	2,61,900 ^A	6.17 ^C	11.83 ^C	11.07 ^B	5.29 ^B
PTR	11,219 ^B	11,483 ^B	60,825 ^A	1,64,917 ^B	3,12,769 ^B	1,04,911 ^C	2,51,941 ^B	6.06 ^D	11.51 ^D	11.45 ^A	5.59 ^A
Sub-main plot treatment—crop establishment methods for wheat											
ZTW	11,016 ^B	11,358 ^A	54,093 ^C	1,61,934 ^B	3,11,002 ^B	1,05,002 ^C	2,56,908 ^B	6.59 ^B	12.67 ^B	10.35 ^C	5.04 ^D
THSW + R	11,044 ^A	11,396 ^A	53,365 ^D	1,62,352 ^A	3,11,921 ^A	1,08,699 ^A	2,58,555 ^A	6.77 ^A	13.03 ^A	10.18 ^C	4.97 ^E
BPW	10,938 ^C	11,262 ^B	54,255 ^C	1,60,782 ^C	3,03,018 ^D	1,07,141 ^B	2,48,761 ^C	6.50 ^C	12.20 ^C	10.60 ^B	5.14 ^C
RTW	10,909 ^C	11,271 ^B	56,560 ^B	1,60,364 ^E	3,05,522 ^C	1,04,483 ^D	2,48,954 ^C	6.04 ^D	11.49 ^D	10.65 ^B	5.30 ^B
CTW	10,920 ^C	11,274 ^B	60,822 ^A	1,60,521 ^D	3,05,714 ^C	1,00,723 ^E	2,44,891 ^D	5.43 ^E	10.34 ^E	11.41 ^A	5.66 ^A
Crop establishment methods for RWCS											
ZTDSR-ZTW	10,715 ^a	11,083 ^a	47,838 ^a	1,57,517 ^a	3,02,994 ^a	1,09,678 ^a	2,55,156 ^a	6.89 ^a	13.26 ^a	9.48 ^a	4.59 ^a
ZTDSR-THSW + R	10,744 ^a	11,120 ^a	47,110 ^a	1,57,936 ^a	3,03,913 ^a	1,10,825 ^a	2,56,803 ^a	7.08 ^a	13.63 ^a	9.51 ^a	4.52 ^a
ZTDSR-BPW	10,587 ^a	10,637 ^a	48,001 ^a	1,56,366 ^a	2,95,009 ^a	1,08,365 ^a	2,47,009 ^a	6.80 ^a	12.80 ^a	9.94 ^b	4.69 ^a
ZTDSR-RTW	10,607 ^a	10,795 ^a	50,306 ^a	1,55,947 ^a	2,97,507 ^a	1,05,641 ^a	2,47,201 ^a	6.34 ^a	12.09 ^a	9.98 ^b	4.86 ^a
ZTDSR-CTW	10,619 ^a	10,798 ^a	54,567 ^a	1,56,104 ^a	2,97,706 ^a	1,01,536 ^a	2,43,139 ^a	5.74 ^a	10.94 ^a	10.74 ^c	5.22 ^a
DSDSR-ZTW	10,651 ^a	10,878 ^a	51,220 ^a	1,56,576 ^a	2,99,266 ^a	1,05,356 ^a	2,48,046 ^a	6.59 ^a	12.62 ^a	10.29 ^a	5.05 ^a
DSDSR-THSW + R	10,680 ^a	10,916 ^a	50,492 ^a	1,56,995 ^a	3,00,185 ^a	1,06,503 ^a	2,49,693 ^a	6.78 ^a	12.99 ^a	9.51 ^a	4.98 ^a
DSDSR-BPW	10,382 ^a	10,573 ^a	51,382 ^a	1,55,425 ^a	2,91,281 ^a	1,04,043 ^a	2,39,899 ^a	6.50 ^a	12.16 ^a	9.94 ^a	5.15 ^a
DSDSR-RTW	10,545 ^a	10,691 ^a	53,688 ^a	1,55,006 ^a	2,93,779 ^a	1,01,318 ^a	2,40,092 ^a	6.04 ^a	11.45 ^a	9.98 ^a	5.31 ^a
DSDSR-CTW	10,555 ^a	10,694 ^a	57,949 ^a	1,55,163 ^a	2,93,978 ^a	97,214 ^a	2,36,029 ^a	5.43 ^a	10.30 ^a	10.74 ^a	5.67 ^a
PMTR-ZTW	11,427 ^a	11,984 ^a	58,218 ^a	1,67,983 ^a	3,25,413 ^a	1,09,765 ^a	2,67,195 ^a	6.49 ^a	12.55 ^a	10.62 ^a	5.10 ^a
PMTR-THSW + R	11,456 ^a	12,021 ^a	57,490 ^a	1,68,402 ^a	3,26,332 ^a	1,10,912 ^a	2,68,842 ^a	6.68 ^a	12.92 ^a	10.65 ^a	5.03 ^a
PMTR-BPW	11,349 ^a	11,488 ^a	58,380 ^a	1,66,832 ^a	3,17,429 ^a	1,08,451 ^a	2,59,048 ^a	6.40 ^a	12.09 ^a	11.08 ^a	5.20 ^a
PMTR-RTW	11,321 ^a	11,696 ^a	60,686 ^a	1,66,413 ^a	3,19,927 ^a	1,05,727 ^a	2,59,241 ^a	5.94 ^a	11.38 ^a	11.12 ^a	5.37 ^a
PMTR-CTW	11,331 ^a	11,699 ^a	64,947 ^a	1,66,570 ^a	3,20,125 ^a	1,01,623 ^a	2,55,178 ^a	5.33 ^a	10.22 ^a	11.88 ^a	5.73 ^a
PTR-ZTW	11,269 ^a	11,489 ^a	59,101 ^a	1,65,661 ^a	3,16,337 ^a	1,06,560 ^a	2,57,236 ^a	6.38 ^a	12.23 ^a	11.00 ^a	5.41 ^a
PTR-THSW + R	11,298 ^a	11,526 ^a	58,373 ^a	1,66,079 ^a	3,17,256 ^c	1,07,707 ^a	2,58,883 ^a	6.57 ^a	12.59 ^a	11.03 ^a	5.34 ^a
PTR-BPW	10,993 ^a	11,191 ^a	59,263 ^a	1,64,509 ^a	3,08,352 ^a	1,05,246 ^a	2,49,089 ^a	6.29 ^a	11.76 ^a	11.4 ^a	5.51 ^a
PTR-RTW	11,163 ^a	11,201 ^a	61,569 ^a	1,64,091 ^a	3,10,850 ^a	1,02,522 ^a	2,49,282 ^a	5.83 ^a	11.05 ^a	11.50 ^a	5.67 ^a
PTR-CTW	11,083 ^a	11,173 ^a	65,830 ^a	1,64,248 ^a	3,11,049 ^a	98,418 ^a	2,45,219 ^a	5.22 ^a	9.90 ^a	12.26 ^a	6.03 ^a

ZTDSR, zero-tilled direct-seeded rice; DSDSR: drum-seeded rice; PMTR, mechanically transplanted rice under puddled condition; PTR, conventionally puddled transplanted rice; ZTW, wheat sowing with zero-till drill; THSW + R, wheat sowing with Turbo Happy Seeder under rice residue; BPW, wheat sowing with bed planter; RTW, wheat sowing with rotary till drill; CTW, wheat sowing after conventional tillage using seed-cum-fertilizer drill; TIE, total input energy; TOE_g, total output energy of grain; TOE_t, total output energy of grain and straw; NE_g, net energy of grain; NE_t, net energy of grain and straw; EUE_g, energy use efficiency of grain, EUE_t, energy use efficiency of grain and straw, SE_g, system-specific energy of grain; SE_t, system-specific energy of grain and straw. Means values under main and sub-main treatments followed by upper case superscript letters are not significantly different at $p < 0.05$ (LSD), while in interaction effects, mean values followed by lower case superscript letters are not significantly different at $p < 0.05$ (LSD).

TABLE 4 Global warming potential (GWP) and carbon indices in RWCS (average of long-term experiments during 2006-07 to 2020-21).

Treatments	GWP (kg CO ₂ eq. ha ⁻¹ year ⁻¹)	C _{Input} (kg C ha ⁻¹)	C _{Output} (kg C ha ⁻¹)	CSI	CER	kg CO ₂ eq. kg ⁻¹ grain
Main plot—crop establishment method of rice						
ZTDSR	5,487 ^B	1,497 ^B	8,543 ^C	11.68 ^A	13.68 ^A	1.11 ^B
DSDSR	5,773 ^B	1,575 ^B	8,434 ^D	11.32 ^B	13.32 ^B	1.18 ^B
PMTR	11,420 ^A	3,115 ^A	8,919 ^B	9.54 ^C	11.54 ^C	2.15 ^A
PTR	11,387 ^A	3,106 ^A	9,184 ^A	9.64 ^C	11.64 ^C	2.09 ^A
Sub-main plot—conservation tillage of wheat						
ZTW	8,384 ^E	2,287 ^E	8,879 ^B	11.52 ^A	13.52 ^A	1.61 ^D
THSW + R	8,407 ^D	2,293 ^D	8,907 ^A	11.43 ^A	13.43 ^A	1.61 ^D
BPW	8,439 ^C	2,301 ^C	8,631 ^D	10.63 ^B	12.63 ^B	1.62 ^C
RTW	8,571 ^B	2,338 ^B	8,717 ^C	10.06 ^C	12.06 ^C	1.65 ^B
CTW	8,785 ^A	2,396 ^A	8,719 ^C	9.08 ^D	11.08 ^D	1.68 ^A
Crop establishment method on rice × Conservation tillage on wheat						
ZTDSR-ZTW	5,354 ^a	1,460 ^a	8,652 ^a	12.66 ^a	14.66 ^a	1.08 ^a
ZTDSR-THSW + R	5,377 ^a	1,467 ^a	8,679 ^a	12.57 ^a	14.57 ^a	1.09 ^a
ZTDSR-BPW	5,408 ^a	1,475 ^a	8,404 ^a	11.77 ^a	13.77 ^a	1.12 ^a
ZTDSR-RTW	5,542 ^a	1,511 ^a	8,487 ^a	11.20 ^a	13.20 ^a	1.16 ^a
ZTDSR-CTW	5,755 ^a	1,570 ^a	8,492 ^a	10.22 ^a	12.22 ^a	1.15 ^a
DSDSR-ZTW	5,641 ^a	1,538 ^a	8,543 ^a	12.29 ^a	14.29 ^a	1.16 ^a
DSDSR-THSW + R	5,664 ^a	1,545 ^a	8,570 ^a	12.20 ^a	14.20 ^a	1.17 ^a
DSDSR-BPW	5,694 ^a	1,553 ^a	8,295 ^a	11.40 ^a	13.40 ^a	1.19 ^a
DSDSR-RTW	5,828 ^a	1,590 ^a	8,378 ^a	10.83 ^a	12.83 ^a	1.23 ^a
DSDSR-CTW	6,041 ^a	1,648 ^a	8,383 ^a	9.85 ^a	11.85 ^a	2.07 ^a
PMTR-ZTW	11,254 ^a	3,069 ^a	9,294 ^a	10.62 ^a	12.62 ^a	2.07 ^a
PMTR-THSW + R	11,277 ^a	3,076 ^a	9,320 ^a	10.53 ^a	12.53 ^a	2.08 ^a
PMTR-BPW	11,308 ^a	3,084 ^a	9,046 ^a	9.73 ^a	11.73 ^a	2.11 ^a
PMTR-RTW	11,442 ^a	3,120 ^a	9,128 ^a	9.16 ^a	11.16 ^a	2.14 ^a
PMTR-CTW	11,655 ^a	3,179 ^a	9,134 ^a	8.18 ^a	10.18 ^a	2.13 ^a
PTR-ZTW	11,287 ^a	3,078 ^a	9,029 ^a	10.51 ^a	12.51 ^a	2.13 ^a
PTR-THSW + R	11,310 ^a	3,085 ^a	9,055 ^a	10.42 ^a	12.42 ^a	2.13 ^a
PTR-BPW	11,341 ^a	3,093 ^a	8,781 ^a	9.63 ^a	11.63 ^a	2.14 ^a
PTR-RTW	11,474 ^a	3,129 ^a	8,863 ^a	9.06 ^a	11.06 ^a	2.17 ^a
PTR-CTW	11,688 ^a	3,188 ^a	8,869 ^a	8.07 ^a	10.07 ^a	2.20 ^a

ZTDSR, zero-tilled direct-seeded rice; DSDSR, drum-seeded rice; PMTR, mechanically transplanted rice under puddled condition; PTR, conventionally puddled transplanted rice; ZTW, wheat sowing with zero-till drill; THSW + R, wheat sowing with Turbo Happy Seeder under rice residue; BPW, wheat sowing with bed planter; RTW, wheat sowing with rotary till drill; CTW, wheat sowing after conventional tillage using seed-cum-fertilizer drill; GWP, global warming potential; C_{Input}, carbon input; C_{Output}, carbon output; CSI, carbon sustainability index; CER, carbon efficiency ratio.

Mean values under main and sub-main treatments followed by upper case superscript letters are not significantly different at $p < 0.05$ (LSD), while in interaction effects, mean values followed by lower case superscript letters are not significantly different at $p < 0.05$ (LSD).

(5,773 kg CO₂ eq. ha⁻¹ year⁻¹) than under PMTR (11,387 kg CO₂ eq. ha⁻¹ year⁻¹) and PTR (11,420 kg CO₂ eq. ha⁻¹ year⁻¹). ZTDSR and DSDSR were at par with each other. In the case of sub-main plots, significantly higher GWP was observed in CTW, followed by RTW, BPW, THSW + R, and ZTW. The carbon input pattern was similar to GWP. For C_{input} under main

plots, statistically higher C_{input} was observed under PMTR and PTR than that of ZTDSR and DSDSR. The significantly higher mean C_{output} was observed under different main plots of PMTR (9,184 kg C ha⁻¹), followed by PTR (8,919 kg C ha⁻¹), ZTDSR (8,543 kg C ha⁻¹), and DSDSR (8,434 kg C ha⁻¹). In sub-main plots, the C_{output} was significantly greater in ZTW and THSW +

R than in BPW, RTW, and CTW, which were at par with main plot treatments.

3.7 Carbon indices

Among main plots, CSI and CER were significantly higher under ZTDSR (11.7, 13.68), followed by DSDSR (11.3, 13.3), PMTR (9.6, 11.6), and PTR (9.54, 11.5). However, the CSI and CER were significantly greater under sub-main plots of ZTW than under THSW + R, followed by BPW, RTW, and CTW. In the main plots, the highest kg CO₂ Eq. kg⁻¹ grain was observed under PTR (2.15), followed by PMTR (2.09), DSDSR (1.18), and ZTDSR (1.11), whereas in the sub-main plots, kg CO₂ eq. kg⁻¹ grain was 4.35% lower under ZTW and THSW + R. The kg CO₂ eq. kg⁻¹ grain was 48–51% higher under PTR and CTW than under ZTDSR-ZTW and ZTDSR-THSW + R, as well as DSDSR-ZTW and DSDSR-THSW + R. The kg CO₂ eq. kg⁻¹ grain was significantly lower under ZTDSR-ZTW (1.08) and ZTDSR-THSW + R (1.09) than under ZTDSR-BPW (1.12), ZTDSR-CTW (1.15), and ZTDSR-RTW (1.16). It was also observed that PTR-CTW reported the highest kg CO₂ eq. kg⁻¹ grain (2.20), followed by PTR-RTW (2.17), PTR-BPW (2.14), PTR-THSW + R (2.13), and PTR-ZTW (2.13).

3.8 Uncertainty in assessment

CH₄ is a major constituent of emissions in PTR, whereas N₂O is in DSR and ZTW. CH₄ emissions are characteristic of paddy cultivation under submerged conditions in puddled and DSR rice, using wet and dry methods, which were assessed by the emission factor defined for Indian conditions by Jain et al. (2016) and Wassmann et al. (2009). The natural variability in the experiment, lack of coverage of measurements, and spatial aggregation may be major uncertainties of EF (Garg et al., 2006). In RWCS, the major emission of N₂O was from the consumption of inorganic fertilizers and extensive tillage operations. This emission is influenced by factors such as the amount of fertilizer utilized per crop and specific environmental characteristics of a location, including temperature and soil type. The main variations in emission are driven by factors such as soil moisture, precipitation, and temperature (Sharma et al., 2023). The IPCC (Tier 1 methodology) uses a default EF of 1.25% for direct emissions from soils based on N input. However, this approach does not account for variations in soil pH, temperature, climatic conditions, etc. The Indian-specific emission factor is 44% lower than the IPCC default emission factor (Dobbie and Smith, 2003; Lal, 2004). Jain et al. (2016) suggested an EF of 0.53 in Indian conditions, which varies from 0.14% to 12.8%. Consequently, this methodology lacks the ability to account for the potential effects of future climate and land use changes. Additionally, N₂O emissions from field operations may also introduce uncertainties. The emissions from the consumption of inorganic fertilizers and pesticides were considered, as reported by Shang et al. (2011), as no specific EFs are available for Indian conditions. In the current investigation, GWP measured through the total emission of CO₂, N₂O, and CH₄ was assessed under various tillage practices,

encompassing the emissions of GHGs from lands and all field agronomic activities in irrigated conditions of RWCS under a subtropical climate. The innovative management practices, such as ZT with crop residue, were observed to enhance soil carbon sequestration and mitigate GHG emissions (Mosier et al., 2006; Kumar and Sharma, 2016; Sahoo et al., 2021). Furthermore, energy and carbon indices were quantified in various rice crop growing systems and zero tillage in wheat crops. The DSR and ZTW, both with and without crop residues (i.e., ZTDSR-ZTW and ZTDSR-THSW + R; DSDSR-ZTW and DSDSR-THSW + R), demonstrated comparable yields, lower energy input, and reduced GHG emission per kg gain yield in the system compared to the conventionally tilled farmers' practice (PTR-CTW).

4 Discussion

Conventional intensive tillage and crop residue burning in the field lead to land degradation and air pollution, depletion of soil organic carbon, reduced carbon sequestration, increased energy consumption, higher GHG emissions, and reduced carbon indices (Francaviglia et al., 2023). Since RWCS in an IGP of India is a major cropping system, its CT cultivation is an energy-intensive practice (Singh et al., 2020). Therefore, a 15-year-long study using a split-split-plot design was conducted to assess the effects of different crop establishment methods, including ZT and CT, on yield, energetics, carbon indices, and GHG emissions of RWCS. The energy inputs from various sources under cultivation practices for RWCS revealed significant differences across all treatments, primarily due to variation in electricity use, irrigation water, diesel, labor, and agrochemicals. The rice grown under puddled conditions and wheat grown under CT exhibited the highest energy input due to intensive tillage practices. Conversely, ZTDSR for rice and THSW + R had the lowest TIE, emphasizing that direct-seeded rice and conservation tillage-based wheat offer considerable energy savings, making them more sustainable. When assessing the combined RWCS treatments, PTR-CTW and PMTR-CTW required the highest TIE, whereas ZTDSR-THSW + R was the most energy-efficient system. This could be because conservation tillage reduces primary and secondary tillage practices, which helps save diesel consumption and reduces the need for irrigation (Jat H. S. et al., 2019; Singh et al., 2022). Similar findings were reported by Chaudhary et al. (2024), which revealed that the elimination of tillage operations reduces water quantity during irrigation in sowing under no-tillage and by a happy seeder, which accounted for 21% and 23% lower energy inputs, respectively, over CT. The total energy used in THSW + R was 1.20% higher than in no residue treatments. It might be that surface residue mulching conserved soil moisture, which reduced the amount of irrigation water needed and consequently decreased the total input energy required (Mishra et al., 2021; Singh et al., 2022). Other researchers have highlighted that the reduction in tillage completely affected input energy (Tabatabaefar et al., 2009). Minimized tillage levels for numerous crops allow a significant decrease in energy input compared to CT, which requires 29–59% more diesel than reduced tillage (Elsoragaby et al., 2024).

The comparison of yield attributes under the RWCS across four CEM for rice (ZTDSR, DSDSR, PMTR, and PTR) and five CEM for wheat (ZTW, THSW + R, BPW, RTW, and CTW) reveals significant variation in productivity. PMTR emerged as the most productive rice tillage method, achieving the highest combined grain and straw yields, followed closely by PTR. In contrast, ZTDSR and DSDSR consistently yielded 10–15% less, highlighting their yield limitations in rice, a gap consistent with literature reporting 5–8% yield reduction in DSR than in PTR (Bhatt et al., 2023). In the case of wheat, ZTW and THSW + R performed better than BPW, RTW, and CTW, mainly due to improved soil structure, better moisture retention, and reduced evaporation under residue mulch (Jat S. L. et al., 2019; Kaur et al., 2022). Furthermore, these systems have been found to enhance resilience under heat stress, especially when wheat follows non-puddled rice or direct-seeded rice. The combination of PMTR-THSW + R and ZTDSR-THSW + R systems yielded the highest grain and straw yields. The multi-location trials in India confirm that CA-based practices like ZTW with or without residue retention not only sustain or enhance yield but also offer substantial economic and environmental benefits over conventional practices (Korav et al., 2024).

Energy budgeting across RWCS demonstrates energy-saving advantage in CA-based CEMs. Notably, the ZTDSR-THSW + R treatment exhibited the lowest TIE at 47,110 MJ ha⁻¹, while the traditional PTR-CTW treatment consumed the most at 65,830 MJ ha⁻¹ (Table 2). This gradient reflects the notable decrease in energy consumption by eliminating puddling during rice establishment and retaining rice residues in wheat, followed by sowing with the Turbo Happy Seeder. Fertilizer, electricity, irrigation water, and diesel comprised 27–37%, 22–28.5%, 21–25%, and 5–11.2% of TIE, respectively, with irrigation application accounting for 45–53% of operational energy use. The other major components are land preparation (8–13%) and sowing (5.5–6.5%) (Table 2). These findings are consistent with Nandan et al. (2021) and Walia et al. (2022), who reported that CA treatments in the IGP of India reduced energy use for land preparation by 69–100% and irrigation by 23–27% compared to conventional systems. Kumar et al. (2013) reported that out of total energy inputs, about 30% of energy spent on diesel for tillage operations could be saved in zero tillage without compromising yield. Additionally, non-renewable sources contributed over 90% of TIE, with indirect energy representing 60–66% and direct energy 34–40%, emphasizing the external energy footprint of modern farming inputs (Figures 2, 3). These results align with previous findings that modern agriculture relies heavily on fossil fuel-derived energy, particularly through synthetic fertilizers, irrigation, and mechanization inputs (Kiehadrouinezhad et al., 2025). Similarly, Sawant et al. (2023) have also reported that the increased quantity of irrigation water, higher electricity usage, and more fossil fuel consumption during land preparation and puddling operations in transplanted rice contributed to elevated utilization of direct energy and non-renewable sources in RWCS. Among rice establishment methods, ZTDSR (49,563 MJ ha⁻¹) required significantly less energy than DSDSR, PMTR, or PTR, while THSW + R was the most efficient wheat establishment method, followed by

ZTW, BPW, RTW, and CTW; CTW exceeded other methods by 7–16% in TIE. Furthermore, combining DSR-based methods with CA-based wheat resulted in 14–21% lower energy use than CTW systems. These results underscore the substantial energy conservation potential of integrated CA practices, especially those pairing ZT rice with residue-retaining wheat, thus validating CA's role in promoting resource-efficient and sustainable RWCS.

In main plots, the TOE_g and TOE_t highlighted the superior performance of PMTR, surpassing PTR, ZTDSR, and DSDSR by up to 8.1%, highlighting the efficiency of mechanization in energy returns. These outcomes align with findings from Jat et al. (2020), who reported that mechanized transplanting under leveled fields improves productivity and system energy returns in rice-based cropping systems. Meanwhile, the highest TOE_g and TOE_t were observed in the sub-main plots under THSW + R. This could be attributed to favorable soil physical conditions, enhanced nutrient recycling through residue retention, and improved root growth and tillering (Kumar et al., 2021).

The NE_g and NE_t of rice varied significantly with CEM, where ZTDSR recorded the highest NE_g, followed by PMTR, PTR, and DSDSR. Similarly, among wheat establishment methods, THSW + R exhibited superior NE_g and NE_t, indicating that CA-based practices enhance energy profitability by reducing input costs of labor, diesel, and irrigation water while maintaining high output energy (Mitra et al., 2018; Babu et al., 2020). Notably, although the interaction effects of main and sub-main treatments were not statistically significant at the 5% level, the integrated CA system, ZTDSR-THSW + R, outperformed conventional practices (PTR-CTW), showing 13% higher NE_g and 5% higher NE_t.

This study explored the higher energy input associated with increased tillage and irrigation practices in PTR-CTW, which resulted in the comparative benefit of achieving higher yields but exhibited significantly lower EUE than ZTDSR-ZTW, DSDSR-ZTW, and DSDSR-THSW + R. The CA-based crop cultivation practices (ZTDSR-ZTW and ZTDSR-THSW + R) had lower input energy and provided at-par output energy than conventional practice, which enhanced their EUE_t (Pratibha et al., 2019; Jat S. L. et al., 2019).

The significantly higher SSE_g and SSE_t were recorded under PTR and CTW in the main and sub-main plots, respectively, indicating greater energy input requirements. In contrast, CA-based practices (ZTDSR and ZTW) consistently showed lower SSE values, highlighting their energy-saving potential. Notably, ZTDSR-ZTW and ZTDSR-THSW + R combinations demonstrated the highest energy use efficiency (EUE_g of 12.3 and 13.6) with the lowest SSE_g (9.5 MJ kg⁻¹), reinforcing the advantage of reduced tillage systems. Though the interaction effect was statistically non-significant, these combinations emerged as promising CA-based strategies for energy-efficient RWCS, aligning with findings of Jat et al. (2020) and Singh et al. (2022) on energy optimization through minimal soil disturbance.

More than 52% higher GWP was recorded under PMTR and PTR than under DSR (ZTDSR and DSDSR), which could be due to greater amounts of fossil fuels used in tillage operations and electricity for irrigation under conventional methods of rice

cultivation than under zero-tillage methods (Samal et al., 2017; Mishra et al., 2021). A significantly greater value of GWP in the CTW treatment was reported because of greater energy use and GHG emissions, with higher GWP in irrigation practices, as more irrigation water was needed in flood irrigation than in no-tilled plots (Kakraliya et al., 2018). Similarly, 44–47% (Sapkota et al., 2015; Gupta et al., 2016) and 26–40% (Kakraliya et al., 2021) lower GWP was reported in CA-based RWCS than in CT, without any yield penalty. This is because, in the case of RWCS, adoption of CT led to higher GWP for puddled transplanted rice, owing to methane emission in stagnant water and fossil fuel burning in wheat tillage (Gupta et al., 2016). The no-tillage system reduced soil disturbance, crop biomass incorporation, and microbial activity, thereby reducing CO₂ emissions compared with farmer practices (Drury et al., 2006).

The adoption of DSR in both dry and wet beds, along with ZT wheat sown under crop biomass mulching, contributed to the reduction in GHG emissions, particularly methane, from puddled rice (Metay et al., 2007) and CO₂ due to lower fossil fuel consumption in no-till fields (Reeves et al., 2001), as well as irrigation water savings (Chaudhary et al., 2021), aligning with findings reported by Jat M. L. et al. (2019) and Singh et al. (2022). The CSI and CER of ZTDSR-ZTW and ZTDSR-THSW + R, as well as of DSDSR-ZTW and DSDSR-THSW + R, were recorded as higher than PMTR/PTR-CTW. It was due to greater C_{output} than C_{input} under ZT, owing to low fossil fuel burning and reduced electricity consumption in RWCS (Mondal et al., 2020). This study evidently showed that changing from conventional farmers' practices (PTR and CTW) to no-tillage (ZTDSR and ZTW/THSW + R) with residue management benefited in decreasing total GHG emissions to a greater extent by eliminating land preparation and CH₄ emissions from submerged rice fields (Gupta et al., 2015, 2016). The C_{input} was also observed to be higher in the treatment, where tillage intensity was greater, particularly when tillage practices were adopted in both *kharif* and *rabi* seasons, as in PMTR and PTR. In the case of sub-main plots, C_{input} in CTW was significantly higher, followed by RTW, BPW, THSW + R, and ZTW. Adoption of zero-tillage plant establishment methods in RWCS (ZTDSR-ZTW and ZTDSR-THSW + R; and DSDSR-ZTW and DSDSR-THSW + R) led to a 53–54% reduction in GWP compared to PTR-CTW and PMTR-CTW. In terms of interaction effects, higher C_{output} was observed in PMTR-THSW + R (9,320 kg C ha⁻¹) and MTR-ZTW (9,294 kg C ha⁻¹), which could be attributed to the higher system grain production (12.6 t ha⁻¹) under PMTR and ZTW (Chaudhary et al., 2021). Comparable outcomes were also reported by Chaudhary et al. (2017). These outcomes affirm that CA modules, especially those involving zero-tillage and residue retention, are instrumental in improving energy efficiency and sustainability in RWCS of the Indo-Gangetic Plains (Singh et al., 2021; Mondal et al., 2020).

5 Conclusion

Limited experiments have been conducted on energy conservation methods, GWP, and carbon indices for various

zero-tillage practices under RWCS in the IGP of India, and none exceeded 10 years. Therefore, a long-term experiment was conducted to study the effects of various crop establishment methods, such as ZTDSR, DSDSR, PMTR, and PTR for rice (main effect) and ZTW, THSW + R, BPW, RTW, and CTW for wheat (sub-main effect), on energy indices, GHG emissions, and carbon indices. The 15-year field study on RWCS in the IGP demonstrated that CA-based practices significantly enhanced crop yields, energy efficiency, and carbon indices and reduced GHG emissions compared to CT systems. Conventional methods, such as PTR and CTW, were associated with the highest TIE, greater reliance on fossil fuels, and higher GWP. In contrast, ZTDSR combined with THSW + R or ZTW significantly lowered TIE, irrigation water demand, and energy from non-renewable sources, while maintaining comparable system yields. The ZTDSR-THSW + R system was the most energy-efficient, recording the highest EUE, lowest SSE, and a 53–54% lower GWP than CT systems. Moreover, CA practices improved net energy output and carbon use metrics, with higher C_{output} and CSI, due to reduced soil disturbance, better residue retention, and efficient input use. Although some CA systems showed slightly lower rice yields (ZTDSR), the overall system productivity and sustainability benefits outweighed the tradeoffs. Thus, the integration of DSR and zero-till wheat with residue management offers a viable pathway for energy-smart, climate-resilient, and environmentally sustainable intensification of RWCS in the IGP of India. By integrating agronomic, energetic, and environmental metrics, this study provides a comprehensive assessment that can inform both farmers and policymakers in making informed decisions toward more sustainable cropping systems. The strength of the research lies in its long-term field experimentation, which not only enhances the reliability of the findings but also addresses a critical knowledge gap in region-specific evaluations of conservation agriculture.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

VC: Writing – original draft, Writing – review & editing. CS: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. AG: Formal analysis, Methodology, Writing – review & editing. RG: Data curation, Writing – review & editing. AK: Data curation, Formal analysis, Validation, Writing – review & editing. AM: Data curation, Formal analysis, Methodology, Writing – review & editing. GW: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. VK: Data curation, Formal analysis, Validation, Visualization, Writing – review & editing. RC: Investigation, Methodology, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The authors acknowledge the financial, technical, and research facilities provided by ICAR-Indian Institute of Farming Systems Research, Modipuram; ICAR-Central Institute of Agricultural Engineering, Bhopal; and National Innovations in Climate Resilient Agriculture (NICRA), ICAR, New Delhi, India, which made the successful completion of the research study possible.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Acosta-Silva, Y. D. J., Torres-Pacheco, I., Matsumoto, Y., Toledano-Ayala, M., Soto-Zarazúa, G. M., Zelaya-Ángel, O., et al. (2019). Applications of solar and wind renewable energy in agriculture: a review. *Sci. Prog.* 102, 127–140. doi: 10.1177/0036850419832696
- Babu, S., Mohapatra, K. P., Das, A., Yadav, G. S., Tahasildar, M., Singh, R., et al. (2020). Designing energy-efficient, economically sustainable and environmentally safe cropping system for the rainfed maize–fallow land of the Eastern Himalayas. *Sci. Total Environ.* 722:137874. doi: 10.1016/j.scitotenv.2020.137874
- Basavalingaiah, K., Ramesha, Y. M., Paramesh, V., Rajanna, G. A., Jat, S. L., Dhar Misra, S., et al. (2020). Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: a case study from puddled transplanted rice and direct-seeded rice system of Karnataka, India. *Sustainability* 12:6439. doi: 10.3390/su12166439
- Bhatia, A., Pathak, H., and Aggarwal, P. K. (2004). Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. *Curr. Sci.* 87, 317–324. <https://www.jstor.org/stable/24108935>.
- Bhatt, R., Kukal, S. S., Busari, M. A., Arora, S., and Yadav, M. (2016). Sustainability issues on rice–wheat cropping system. *Int. Soil Water Conserv. Res.* 4, 64–74. doi: 10.1016/j.iswcr.2015.12.001
- Bhatt, R., Oliveira, M. W., Kumar Garg, A., Sharma, S., de Freitas Santos, D., Gathala, M. K., et al. (2023). Mechanical transplanting of rice for reducing water, energy, and labor footprints with improved rice yields in the tropics. *AMA*, 54, 13253–13288.
- Brar, S. K., Dhaliwal, S. S., Sharma, V., Sharma, S., and Kaur, M. (2023). Replacement of rice–wheat cropping system with alternative diversified systems concerning crop productivity and their impact on soil carbon and nutrient status in soil profile of north-west India. *Cogent Food Agricult.* 9:2167483. doi: 10.1080/23311932.2023.2167483
- Chaudhary, V. P., Chandra, R., Chaudhary, R., and Bhattacharyya, R. (2021). Global warming potential and energy dynamics of conservation tillage practices for different rabi crops in the Indo-Gangetic Plains. *J. Environ. Manage.* 296:113182. doi: 10.1016/j.jenvman.2021.113182
- Chaudhary, V. P., Pandey, D. K., Gangwar, K. S., and Sharma, S. K. (2012). Energy auditing of different weed management practices for wheat in India. *Trop. Agricult.* 89:229. <https://journals.sta.uwi.edu/ojs/index.php/ta/article/view/996>.
- Chaudhary, V. P., Sawant, C. P., Chaudhary, R., Gautam, R., and Wakchaure, G. C. (2024). 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. *Int. J. Plant Prod.* 18, 531–549. doi: 10.1007/s42106-024-00308-0
- Chaudhary, V. P., Singh, K. K., Pratibha, G., Bhattacharyya, R., Shamim, M., Srinivas, I., et al. (2017). Energy conservation and greenhouse gas mitigation

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

under different production systems in rice cultivation. *Energy*. 130, 307–317. doi: 10.1016/j.energy.2017.04.131

Derpsch, R., Kassam, A., Reicosky, D., Friedrich, T., Calegari, A., Basch, G., et al. (2024). Nature's laws of declining soil productivity and Conservation Agriculture. *Soil Secur.* 14:100127. doi: 10.1016/j.soisec.2024.100127

Dhanda, S., Yadav, A., Yadav, D. B., and Chauhan, B. S. (2022). Emerging issues and potential opportunities in the rice–wheat cropping system of North-Western India. *Front. Plant Sci.* 13:832683. doi: 10.3389/fpls.2022.832683

Dobbie, K. E., and Smith, K. A. (2003). Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Glob. Chang. Biol.* 9, 204–218. doi: 10.1046/j.1365-2486.2003.00563.x

Drury, C. F., Reynolds, W. D., Tan, C. S., Welacky, T. W., Calder, W., McLaughlin, N. B., et al. (2006). Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. *Soil Sci. Soc. Am. J.* 70, 570–581. doi: 10.2136/sssaj2005.0042

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Available online at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm> (Accessed September 3, 2025).

Elsooragaby, S., Kheiralla, A. F., Tola, E., Yahya, A., Mairghany, M., Ahmed, M., et al. (2024). Energy Utilization and Greenhouse Gas (GHG) emissions of tillage operation in wetland rice cultivation. *Land* 13:587. doi: 10.3390/land13050587

Fagodiya, R. K., Pathak, H., Bhatia, A., Jain, N., and Gupta, D. K. (2020). Global warming potential and its cost of mitigation from maize (Zea mays)-wheat (Triticum aestivum) cropping system. *Indian J. Agric. Sci.* 90, 69–74. doi: 10.56093/ijas.v90i1.98535

Fagodiya, R. K., Singh, A., Singh, R., Rani, S., Kumar, S., Rai, A. K., et al. (2023). The food–energy–water–carbon nexus of the rice–wheat production system in the western Indo-Gangetic Plain of India: an impact of irrigation system, conservation tillage and residue management. *Sci. Total Environ.* 860:160428. doi: 10.1016/j.scitotenv.2022.160428

Francaviglia, R., Almagro, M., and Vicente-Vicente, J. L. (2023). Conservation agriculture and soil organic carbon: principles, processes, practices and policy options. *Soil Syst* 7:17. doi: 10.3390/soilsystems7010017

Garg, A., Shukla, P. A., and Kapshe, M. (2006). The sectoral trends of multigas emissions inventory of India. *Atmos. Environ.* 40, 4608–4620. doi: 10.1016/j.atmosenv.2006.03.045

Gathala, M. K., Timsina, J., Islam, M. S., Rahman, M. M., Hossain, M. I., Harun-Ar-Rashid, M., et al. (2015). Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: evidence from Bangladesh. *Field Crops Res.* 172, 85–98. doi: 10.1016/j.fcr.2014.12.003

- Gomez, K. A., and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*. Hoboken, NJ: John Wiley and Sons.
- Gregorich, E. G., Rochette, P., VandenBygaart, A. J., and Angers, D. A. (2005). Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil Tillage Res.* 83, 53–72. doi: 10.1016/j.still.2005.02.009
- Gupta, D. K., Bhatia, A., Kumar, A., Chakrabarti, B., Jain, N., Pathak, H., et al. (2015). Global warming potential of rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system of the Indo-Gangetic Plains. *Indian J. Agric. Sci.* 85, 807–816. doi: 10.56093/ijas.v85i6.49243
- Gupta, D. K., Bhatia, A., Kumar, A., Das, T. K., Jain, N., Tomer, R., et al. (2016). Mitigation of greenhouse gas emission from rice–wheat system of the Indo-Gangetic plains: Through tillage, irrigation and fertilizer management. *Agric. Ecosyst. Environ.* 230, 1–9. doi: 10.1016/j.agee.2016.05.023
- Hobbs, P. R., Sayre, K., and Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philos. Transac. Royal Soc. B Biol. Sci.* 363, 543–555. doi: 10.1098/rstb.2007.2169
- Jain, N., Arora, P., Tomer, R., Mishra, S. V., Bhatia, A., Pathak, H., et al. (2016). Greenhouse gases emission from soils under major crops in Northwest India. *Sci. Total Environ.* 542, 551–561. doi: 10.1016/j.scitotenv.2015.10.073
- Jain, N., Bhatia, A., and Pathak, H. (2014). Emission of air pollutants from crop residue burning in India. *Aerosol Air Q. Res.* 14, 422–430. doi: 10.4209/aaqr.2013.01.0031
- Jat, H. S., Datta, A., Choudhary, M., Sharma, P. C., Yadav, A. K., Choudhary, V., et al. (2019). Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. *Catena*, 181, 104059. doi: 10.1016/j.catena.2019.05.005
- Jat, H. S., Kumar, V., Datta, A., Choudhary, M., Kakraliya, S. K., Poonia, T., et al. (2020). Designing profitable, resource use efficient and environmentally sound cereal based systems for the Western Indo-Gangetic plains. *Sci. Rep.* 10:19267. doi: 10.1038/s41598-020-76035-z
- Jat, M. L., Gathala, M., Saharawat, Y. S., Ladha, J. K., and Singh, Y. (2019). Conservation agriculture in intensive rice-wheat rotation of western Indo-Gangetic plains: effect on crop physiology, yield, water productivity and economic profitability. *Int. J. Environ. Sci. Nat. Resour.* 18, 88–102. doi: 10.19080/IJESNR.2019.18.55988
- Jat, R. K., Sapkota, T. B., Singh, R. G., Jat, M. L., Kumar, M., Gupta, R. K., et al. (2014). Seven years of conservation agriculture in a rice–wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. *Field Crops Res.* 164, 199–210. doi: 10.1016/j.fcr.2014.04.015
- Jat, S. L., Parihar, C. M., Singh, A. K., Kumar, B., Choudhary, M., Nayak, H. S., et al. (2019). Energy auditing and carbon footprint under long-term conservation agriculture-based intensive maize systems with diverse inorganic nitrogen management options. *Sci. Total Environ.* 664, 659–668. doi: 10.1016/j.scitotenv.2019.01.425
- Kakraliya, S. K., Jat, H. S., Sapkota, T. B., Singh, I., Kakraliya, M., Gora, M. K., et al. (2021). Effect of climate-smart agriculture practices on climate change adaptation, greenhouse gas mitigation and economic efficiency of rice-wheat system in India. *Agriculture* 11:1269. doi: 10.3390/agriculture11121269
- Kakraliya, S. K., Jat, H. S., Singh, I., Sapkota, T. B., Singh, L. K., Sutaliya, J. M., et al. (2018). Performance of portfolios of climate smart agriculture practices in a rice-wheat system of western Indo-Gangetic plains. *Agricult. Water Manag.* 202, 122–133. doi: 10.1016/j.agwat.2018.02.020
- Kaur, M., Malik, D. P., Malhi, G. S., Sardana, V., Bolan, N. S., Lal, R., et al. (2022). Rice residue management in the Indo-Gangetic Plains for climate and food security. A review. *Agron. Sustain. Dev.* 42:92. doi: 10.1007/s13593-022-00817-0
- Khakbazan, M., Mohr, R. M., Derksen, D. A., Monreal, M. A., Grant, C. A., Zentner, R. P., et al. (2009). Effects of alternative management practices on the economics, energy and GHG emissions of a wheat–pea cropping system in the Canadian prairies. *Soil Tillage Res.* 104, 30–38. doi: 10.1016/j.still.2008.11.005
- Kiehadrouinezhad, M., Hosseinzadeh-Bandbafha, H., Tajuddin, S. A. F. S. A., Tabatabaei, M., and Aghbashlo, M. (2025). A critical review of life cycle assessment of renewable agricultural systems. *Sustain. Energy Technol. Assess.* 73:104100. doi: 10.1016/j.seta.2024.104100
- Korav, S., Yadav, D. B., Yadav, A., Rajanna, G. A., Parshad, J., Tallapragada, S., et al. (2024). Rice residue management alternatives in rice–wheat cropping system: impact on wheat productivity, soil organic carbon, water and microbial dynamics. *Sci. Rep.* 14:1822. doi: 10.1038/s41598-024-52319-6
- Kumar, A., and Sharma, M. P. (2016). A modeling approach to assess the greenhouse gas risk in Koteswar hydropower reservoir, India. *Human Ecol. Risk Assess. Int. J.* 22, 1651–1664. doi: 10.1080/10807039.2016.1209077
- Kumar, A., Sharma, M. P., and Yang, T. (2018). Estimation of carbon stock for greenhouse gas emissions from hydropower reservoirs. *Stoch. Environ. Res. Risk Assess.* 32, 3183–3193. doi: 10.1007/s00477-018-1608-z
- Kumar, N., Chhokar, R. S., Meena, R. P., Kharub, A. S., Gill, S. C., Tripathi, S. C., et al. (2021). Challenges and opportunities in productivity and sustainability of rice cultivation system: a critical review in Indian perspective. *Cereal Res. Commun.* 50, 573–601. doi: 10.1007/s42976-021-00214-5
- Kumar, R., Saurabh, K., Kumawat, N., Mishra, J. S., Hans, H., Krishna, B., et al. (2019). “Conservation Agriculture: perspectives on soil and environmental management in Indo-Gangetic plains of South Asia,” in *Sustainable Management of Soil and Environment* (Singapore: Springer), 123–168.
- Kumar, V., Jat, H. S., Sharma, P. C., Singh, B., Gathala, M. K., Malik, R. K., et al. (2018). Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agricult. Ecosyst. Environ.* 252, 132–47. doi: 10.1016/j.agee.2017.10.006
- Kumar, V., Saharawat, Y. S., Gathala, M. K., Jat, A. S., Singh, S. K., Chaudhary, N., et al. (2013). Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. *Field Crop Res.* 142, 1–8. doi: 10.1016/j.fcr.2012.11.013
- Lal, R. (2004). Carbon emission from farm operations. *Environ. Int.* 30, 981–990. doi: 10.1016/j.envint.2004.03.005
- Lohan, S. K., Jat, H. S., Yadav, A. K., Sidhu, H. S., Jat, M. L., Choudhary, M., et al. (2018). Burning issues of paddy residue management in north-west states of India. *Renew. Sustain. Energy Rev.* 81, 693–706. doi: 10.1016/j.rser.2017.08.057
- Metay, A., Oliver, R., Scopel, E., Douzet, J. M., Moreira, J. A. A., Maraux, F., et al. (2007). N₂O and CH₄ emissions from soils under conventional and no-till management practices in Goiânia (Cerrados, Brazil). *Geoderma* 141, 78–88. doi: 10.1016/j.geoderma.2007.05.010
- Mishra, J. S., Poonia, S. P., Kumar, R., Dubey, R., Kumar, V., Mondal, S., et al. (2021). An impact of agronomic practices of sustainable rice-wheat crop intensification on food security, economic adaptability, and environmental mitigation across eastern Indo-Gangetic Plains. *Field Crops Res.* 267:108164. doi: 10.1016/j.fcr.2021.108164
- Mitra, B., Patra, K., Bhattacharya, P. M., and Chowdhury, A. K. (2018). Unpuddled transplanting: a productive, profitable and energy efficient establishment technique in rice under Eastern sub-Himalayan plains. *ORYZA-Int. J. Rice* 55, 459–466. doi: 10.5958/2249-5266.2018.00055.3
- Mondal, S., Poonia, S. P., Mishra, J. S., Bhatt, B. P., Karnena, K. R., Saurabh, K., et al. (2020). Short-term (5 years) impact of conservation agriculture on soil physical properties and organic carbon in a rice–wheat rotation in the Indo-Gangetic plains of Bihar. *Eur. J. Soil Sci.* 71, 1076–1089. doi: 10.1111/ejss.12879
- Mosier, A. R., Halvorson, A. D., Reule, C. A., and Liu, X. J. (2006). Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. *J. Environ. Qual.* 35, 1584–1598. doi: 10.2134/jeq2005.0232
- Nandan, R., Poonia, S. P., Singh, S. S., Nath, C. P., Kumar, V., Malik, R. K., et al. (2021). Potential of conservation agriculture modules for energy conservation and sustainability of rice-based production systems of Indo-Gangetic Plain region. *Environ. Sci. Pollut. Res.* 28, 246–261. doi: 10.1007/s11356-020-10395-x
- Omotoso, A. B., and Omotayo, A. O. (2024). The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa. *Reg. Environ. Change* 24:1. doi: 10.1007/s10113-023-02159-3
- Pata, U. K., and Kumar, A. (2021). The influence of hydropower and coal consumption on greenhouse gas emissions: a comparison between China and India. *Water* 13:1387. doi: 10.3390/w13101387
- Pathak, H., Ladha, J. K., Aggarwal, P. K., Peng, S., Das, S., Singh, Y., et al. (2003). Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Res.* 80, 223–234. doi: 10.1016/S0378-4290(02)00194-6
- Pishgar-Komleh, S. H., Omid, M., and Heidari, M. D. (2013). On the study of energy use and GHG (greenhouse gas) emissions in greenhouse cucumber production in Yazd province. *Energy*, 59, 63–71. doi: 10.1016/j.energy.2013.07.037
- Pratibha, G., Srinivas, I., Rao, K. A., Raju, B. M. K., Thyagaraj, C. R., Korwar, G. R., et al. (2015). Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea–castor systems. *Eur. J. Agron.* 66, 30–40. doi: 10.1016/j.eja.2015.02.001
- Pratibha, G., Srinivas, I., Rao, K. V., Raju, B. M. K., Shanker, A. K., Jha, A., et al. (2019). Identification of environment friendly tillage implement as a strategy for energy efficiency and mitigation of climate change in semiarid rainfed agro ecosystems. *J. Clean. Prod.* 214, 524–535. doi: 10.1016/j.jclepro.2018.12.251
- Reeves, T. G., Pingali, P. L., Rajaram, S., and Cassaday, K. (2001). “Crop and natural resource management strategies to foster sustainable wheat production in developing countries,” in *Wheat in a Global Environment: Proceedings of the 6th International Wheat Conference, 5–9 June 2000, Budapest, Hungary* (Springer Netherlands), 23–36.
- Sahoo, U. K., Tripathi, O. P., Nath, A. J., Deb, S., Das, D. J., Gupta, A., et al. (2021). Quantifying tree diversity, carbon stocks, and sequestration potential for diverse land uses in Northeast India. *Front. Environ. Sci.* 9:724950. doi: 10.3389/fenvs.2021.724950
- Samal, S. K., Rao, K. K., Poonia, S. P., Kumar, R., Mishra, J. S., and McDonald, A. (2017). Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: carbon dynamics and productivity. *Eur. J. Agron.* 90, 198–208. doi: 10.1016/j.eja.2017.08.006
- Sapkota, T. B., Jat, M. L., Shankar, V., Singh, L. K., Rai, M., Grewal, M. S., et al. (2015). Tillage, residue and nitrogen management effects on methane

and nitrous oxide emission from rice–wheat system of Indian Northwest Indo-Gangetic Plains. *J. Integr. Environ. Sci.* 12, 31–46. doi: 10.1080/1943815X.2015.1110181

Sawant, C. K. P., Kumar, A., Mani, I., Singh, J. K., Yadav, R., Sahoo, R. N., et al. (2019). Performance evaluation of IARI wheat seed-cum-fertilizer plot drill for pearl millet-wheat cropping system on permanent raised bed system. *J. Agricult. Eng.* 55, 1–12. doi: 10.52151/jae2018554.1664

Sawant, C. P., Singh, K. P., Singh, R. S., Lakaria, B. L., Nandeha, N., Patel, A., et al. (2023). Irrigation and conservation agricultural practices improve crop yield, water productivity and energetics of chickpea (*Cicer arietinum* L.) in Vertisols of central India. *Irrig. Drain.* 72, 664–681. doi: 10.1002/ird.2817

Shang, Q., Yang, X., Gao, C., Wu, P., Liu, J., Xu, Y., et al. (2011). Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. *Global Change Biol.* 17, 2196–2210. doi: 10.1111/j.1365-2486.2010.02374.x

Sharma, T., Das, T. K., Maity, P. P., Biswas, S., Sudhishri, S., Govindasamy, P., et al. (2023). Long-term conservation agriculture influences weed diversity, water productivity, grain yield, and energy budgeting of wheat in north-western Indo-Gangetic plains. *Sustainability* 15:7290. doi: 10.3390/su15097290

Shyamsundar, P., Springer, N. P., Tallis, H., Polasky, S., Jat, M. L., Sidhu, H. S., et al. (2019). Fields on fire: alternatives to crop residue burning in India. *Science* 365, 536–538. doi: 10.1126/science.aaw4085

Singh, M., Kumar, P., Kumar, V., Solanki, I. S., McDonald, A. J., Kumar, A., et al. (2020). Intercomparison of crop establishment methods for improving yield and profitability in the rice-wheat system of Eastern India. *Field Crops Res.* 250:107776. doi: 10.1016/j.fcr.2020.107776

Singh, P., Singh, G., and Sodhi, G. P. S. (2021). Energy and carbon footprints of wheat establishment following different rice residue management strategies vis-à-vis

conventional tillage coupled with rice residue burning in north-western India. *Energy* 200:117554. doi: 10.1016/j.energy.2020.117554

Singh, R., Sharma, A. R., Dhyani, S. K., and Dube, R. K. (2011). Tillage and mulching effects on performance of maize (*Zea mays*)-wheat (*Triticum aestivum*) cropping system under varying land slopes. *Indian J. Agricult. Sci.* 81, 330.

Singh, R., Singh, A., Sheoran, P., Fagodiya, R. K., Rai, A. K., Chandra, P., et al. (2022). Energy efficiency and carbon footprints of rice-wheat system under long-term tillage and residue management practices in western Indo-Gangetic Plains in India. *Energy* 244:122655. doi: 10.1016/j.energy.2021.122655

Tabatabaefar, A., Emamzadeh, H., Varnamkhasti, M. G., Rahimizadeh, R., and Karimi, M. (2009). Comparison of energy of tillage systems in wheat production. *Energy* 34, 41–45. doi: 10.1016/j.energy.2008.09.023

Tabatabaie, S. M. H., Rafiee, S., and Keyhani, A. (2012). Energy consumption flow and econometric models of two plum cultivars productions in Tehran province of Iran. *Energy* 44, 211–216. doi: 10.1016/j.energy.2012.06.036

Tirol-Padre, A., Rai, M., Kumar, V., Gathala, M., Sharma, P. C., Sharma, S., et al. (2016). Quantifying changes to the global warming potential of rice wheat systems with the adoption of conservation agriculture in northwestern India. *Agricult. Ecosyst. Environ.* 219, 125–137. doi: 10.1016/j.agee.2015.12.020

Walia, S. S., Babu, S., Gill, R. S., Kaur, T., Kohima, N., Panwar, A. S., et al. (2022). Designing resource-efficient and environmentally safe cropping systems for sustainable energy use and economic returns in Indo-Gangetic Plains, India. *Sustainability* 14:14636. doi: 10.3390/su142114636

Wassmann, R., Jagadish, S. V. K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., et al. (2009). Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Adv. Agron.* 102, 91–133. doi: 10.1016/S0065-2113(09)01003-7