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Energy and Carbon Footprint in Maize and Wheat Production: Impact of Tillage, Residue and Nitrogen Management in Indo-Gangetic Plains

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ABSTRACT

Background: Continuous adoption of the rice-wheat system in the Indo-Gangetic plains has led to soil health depletion, escalating production costs and rising carbon footprints. In this regard, a field experiment was conducted in the research farms of ICAR-IARI.

Methods: The experiment was conducted in a split-plot design and had three crop establishment practices (Zero tillage with residue retention (ZT + R), Zero tillage (ZT) and conventional tillage (CT) and four nitrogen placement methods, *viz*. control, recommended dose of nitrogen (RDN), improved RDN and improved 80% RDN with varying application timings and doses. The study optimised nitrogen use and crop yields under different tillage and nitrogen management practices.

Result: For both maize and wheat, the ZT had lower energy inputs than CT. Total output energy was higher in the ZT + R by 8.46% and ZT by 4.98% compared to CT for maize, while in wheat it was 9.48% and 2.06% compared to CT. energy use efficiency (EUE) was higher in ZT than CT by 26.28% for maize while in wheat, the ZT + R had higher energy use efficiency than CT by 22.6%. Carbon inputs were lower in ZT, with higher carbon efficiency and carbon sustainability index (CSI) in the ZT and ZT + R. Control plots had higher EUE and energy productivity. Improved RDN among NPMs had significantly higher total output energy, energy use efficiency than the RDN due to higher yield obtained in the improved RDN. The research highlights the benefits of ZT and the ZT + R in maize and wheat, reducing energy inputs, increasing efficiency and productivity and lowering carbon emissions. Along with it, the improved nitrogen application techniques like the subsurface placement of nitrogen improves carbon and energy parameters of maize and wheat in maize-wheat system.

Key words: Carbon auditing, Conservation agriculture, Energy auditing, Residue, Subsurface banding.

INTRODUCTION

The rice-wheat cropping system (RWCS) currently occupies approximately 14 million hectares across the indo-gangetic plains (IGP) and is responsible for roughly 75% of the total food grain output in India (Alam *et al*., 2016). Nevertheless, the prolonged utilization of this sequence has precipitated multiple challenges, including the depletion of groundwater resources, mounting operational costs, a shortage of farm labour, the widespread burning of crop residues and an escalation in greenhouse gas (GHG) emissions (Jat *et al*., 2018; Mondal *et al*., 2020). Consequently, the maize-wheat cropping system has surfaced as a viable substitute, presenting benefits such as better soil preservation, decreased water requirements and increased economic returns for farmers (Jat *et al*., 2018). To accurately evaluate the long-term viability of shifting to this new system, the implementation of comprehensive carbon and energy auditing frameworks is essential.

Evaluating system efficiency through energy auditing involves comparing the total invested inputs-such as seeds, irrigation, fertilizers and mechanical operations-against the final energy value of the crop output. In parallel, calculating the carbon footprint involves tracking GHG emissions, primarily N_2O and CO_2, that originate from both field activities and the manufacturing of agricultural inputs (Chakraborty *et al*., 2023; Bhattacharyya *et al*., 2025). Previous energy assessments within the IGP have successfully highlighted substantial efficiency gaps between conventional farming and conservation agriculture (CA) frameworks (Jat *et al*., 2019; Saad *et al*., 2016; Meena *et al*., 2024). Likewise, carbon footprinting of cereal rotations dependent on nitrogen fertilization indicates that fertilizer management contributes disproportionately to the overall GHG emissions of the system, underscoring the necessity of optimizing nitrogen rates and placement to mitigate the carbon footprint (Bhatia *et al*., 2023; Bhattacharyya *et al*., 2025).

Even with the expanding uptake of conservation agriculture in the IGP, exhaustive energy and carbon

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evaluations targeting the maize-wheat system are still scarce. This data deficit complicates the task of precisely measuring the environmental compromises associated with adopting this alternative cropping system (Bhatia *et al.*, 2023; Parihar *et al.*, 2018). Consequently, this investigation was initiated to address the following primary goals: (i) to assess and contrast the energy inputs, output energy and energy use efficiency (EUE) of both maize and wheat when subjected to zero tillage with residue retention (ZT+R), zero tillage (ZT) and conventional tillage (CT); (ii) to evaluate how different nitrogen placement methods-specifically the RDN, Improved RDN and improved 80% RDN-influence the carbon footprint and carbon sustainability index (CSI) of the cultivated crops and (iii) to determine the optimal integration of nitrogen management and tillage that delivers the highest energy efficiency and carbon sustainability for the maize-wheat system in the indo-gangetic plains.

MATERIALS AND METHODS

Study area and experimental design

The current field research took place at the ICAR-Indian Agricultural Research Institute (ICAR-IARI) located in New Delhi across two consecutive growing cycles: 2022-23 and 2023-24. This specific geographical location features a subtropical semi-arid climate. Over the two respective years, the site recorded average rainfall amounts of 780 mm and 580 mm. The soil profile of the testing ground was classified as sandy clay loam. Researchers utilized a split-plot structural design, applying treatments to permanent conservation agriculture plots that had been initially established and maintained since 2012.

The main plots were dedicated to three distinct crop establishment practices (CEP): Zero tillage with residue retention (ZT+R), Zero tillage (ZT) and conventional tillage (CT). The secondary sub-plots incorporated four separate nitrogen placement methods (NPMs)(NPMs): (i) Control: Fertilised with only phosphorus (P) and potassium (K) at sowing time; (ii) Recommended dose of nitrogen (RDN): 1/3rd N applied as basal, followed by two 1/3rd N applications as surface placement at the V_6 stage and tasselling stage in maize and at the 1st and 3rd irrigations in wheat; (iii) Improved RDN: 1/3rd N applied as basal, followed by 1/3rd N as subsurface placement at V_6/1st irrigation and 1/3rd N as surface placement at the tasselling/3rd irrigation in maize and wheat, respectively; and (iv) Improved 80% RDN: 30% N applied as basal, followed by 30% N as subsurface placement at V_6/1st irrigation and 20% N surface broadcast at the tasselling/3rd irrigation in maize and wheat, respectively. The mung bean crop was also planted and harvested after wheat harvest and before maize sowing in both years, as legume inclusion in cereal-based cropping systems has been demonstrated to enhance soil organic carbon inputs and improve subsequent maize productivity through residue-mediated nitrogen enrichment (Shukla *et al.*, 2025).

Energy and carbon auditing calculations

To evaluate energy dynamics, the straw and grain outputs from the wheat and maize harvests, alongside their equivalent yields, were transformed into terms of energy (MJ/ha) utilizing specific coefficients established by Mittal and Dhawan (1988). The precise energy equivalent coefficients implemented for these conversions are detailed in Table S1.

Field emissions of N_2O and CO_2 were harmonized into a standardized CO_2 (carbon dioxide equivalent) metric by multiplying them by their respective global warming potentials (GWP)-which are 298 for N_2O and 1 for CO_2 in accordance with the IPCC Fourth Assessment Report (IPCC, 2007). To estimate direct soil emissions, the Tier 1 protocol from the IPCC (2006) was utilized, which applies an emission factor of 0.01 kg N_2O-N per kg of N applied. This emission factor (0.01) was multiplied by the total N introduced into the system *via* crop residue and synthetic fertilizer to compute the emitted kg N_2O-N per kg N input. Standardized emission coefficients were further utilized to translate the scope of field operations and applied inputs into their corresponding equivalent emissions.

$$N_2O \text{ emissions} = \text{Quantity of external N applied (kg/ha)} \times 0.01 \times 1.571 \text{ (kg } N_2O\text{/year)}$$

Table S1: Energy equivalent of various inputs used in study for energy dynamics (Mittal and Dhawan, 1988).

Particulars	Units	Equivalent energy (MJ)
A. Inputs		
Human labour		
(a) Adult man	Man-hour	1.96
(b) Woman	Woman-hour	1.57
Animals	Bullock-pair/day	64.56
Diesel	Litre	56.3
Machinery		
(a) Electric motor	kg	64.8
(b) Farm machinery	kg	62.7
Electricity	kWh	11.93
Chemical fertilizers		
(a) Nitrogen	kg	60.6
(b) Phosphorus	kg	11.1
(c) Potash	kg	6.7
FYM	kg	0.3
Chemicals	kg	120
Seed	-	As per the output of system
B. Output		
Main product		
(a) Maize	kg	14.7
(b) Wheat	kg	14.7
By product		
(a) Stover/stalk/straw	kg	12.5

Factor 1.571 was the conversion of N to N_2O (44/28). GWP of emitted CO_2 was computed as follows:

$$GWP = (\text{Emitted } N_2O \times 298) + \text{Emitted } CO_2$$

The carbon indices *i.e.*, C-output, c-efficiency (CE) and C-sustainability index (CSI) were calculated according to Jat *et al*. (2019); Choudhary *et al*. (2017) and Lal (2004). Carbon efficiency (CE) measures the ratio of carbon assimilated in crop biomass to the carbon emitted through all inputs, indicating the carbon return per unit of carbon cost.

$$CE = \frac{\text{C-output}}{\text{C-input}}$$

The carbon sustainability index (CSI), proposed by Lal (2004), represents the net carbon gain relative to inputs; a positive CSI indicates carbon accumulation in the system.

$$CSI = \frac{\text{C output - C-input}}{\text{C-input}}$$

RESULTS AND DISCUSSION

Energy auditing

Maize

The implementation of conservation tillage substantially minimized the required energy inputs while concurrently boosting the total output energy, thereby demonstrating a distinct efficiency advantage over CT. ZT reduced total energy inputs by 13.50% relative to CT, yet the ZT and ZT + R achieved 4.98% and 8.46% higher output energy, respectively (Table 1; Fig 1). When evaluating the NPMs, the Improved RDN strategy consumed the highest amount of energy input-remaining statistically comparable to both the Improved 80% RDN and RDN-yet it generated the greatest output energy, exceeding RDN by 3.28%. EUE followed a consistent tillage hierarchy: ZT exceeded CT by 26.28%, while ZT+R, despite superior output energy, registered lower EUE owing to its elevated input burden from residue incorporation. A significant CEP × NPM interaction regarding EUE confirmed that conservation tillage significantly amplifies the benefit of optimized nitrogen management.

Wheat

In wheat, the energy efficiency advantage shifted from ZT (as observed in maize) to ZT+R, which recorded the highest EUE-exceeding ZT and CT by 7.17% and 22.68%, respectively. Output energy ranked ZT+R > ZT > CT, with margins of 9.48% and 2.06% over CT, while Improved RDN consistently outperformed RDN and Improved 80% RDN in output energy by 7.57% and 6.71%, respectively. No significant CEP × NPM interaction was detected for total output energy (Table 1; Fig 1). Energy productivity under ZT+R and ZT exceeded CT by 22.58% and 13.97%, respectively.

Carbon auditing

Maize

The CT registered the maximum carbon input (608.05 kg ha^{-1}), although it significantly lagged behind ZT+R and ZT in terms of carbon output by 9.04% and 4.52%, respectively. Evaluating the NPMs, the Improved 80% RDN strategy established the most advantageous balance between carbon inputs and outputs, recording significantly lower carbon inputs than Improved RDN and RDN due to its 20% cutback in applied nitrogen. Across the crop establishment practices, both CE and CSI maintained a consistent ranking order of ZT > ZT+R > CT (Table 2; Fig 2).

Wheat

Wheat carbon trends closely paralleled those observed in maize. ZT+R and ZT surpassed CT in carbon output by 9.61% and 2.11%, respectively and exceeded CT in CE by 13.38% and 9.83% and in CSI by 14.95% and 10.98% (Table 2; Fig 2). Among NPMs, Improved RDN delivered the highest carbon output, exceeding RDN and Improved 80% RDN by 7.46% and 6.72%.

Energy efficiency under conservation tillage: Mechanisms beyond input reduction

The notable dominance of ZT compared to CT regarding energy use efficiency across both crops highlights an underlying mechanistic reality that goes far beyond merely subtracting the arithmetic cost of reduced tillage passes. Following a decade of conservation protocols on the experimental plots (established, 2012), the minimized soil disruption under ZT fosters the formation of stable macroaggregates and continuous biopores, which enhance deep root proliferation, nutrient interception efficiency and water infiltration. This directly translates into an improved ratio of yield-per-unit-input-the fundamental agronomic basis for elevated EUE-which functions independently of and additively to, the immediate energy conserved by skipping tillage operations (Parihar *et al.*, 2018; Jat *et al.*, 2019).

Our investigation provides novel insights regarding how this efficiency advantage differs crop-specifically within a continuous maize-wheat cycle, demonstrating that the leadership in EUE shifts from ZT during the maize phase to ZT+R during the wheat phase-a pattern that has not been previously documented for this rotation in the region. Mechanistically, this transition is attributable to the carry-over benefits of maize residues left on the soil surface throughout the *rabi* season. Notably, maize residue retained on the soil surface under ZT+R has a high C:N ratio and decomposes slowly, enabling a gradual and sustained release of carbon and nitrogen that supports long-term soil organic carbon accrual (Kumar *et al.*, 2024).

The significant interaction between CEP and NPM regarding EUE, which was uniquely observed in maize, highlights a functional synergy uniting precision nitrogen

Table 1: Effect of conservation tillage and nitrogen placement methods on the energy auditing of maize and wheat in maize-wheat system (pooled mean over two years).

Treatments	Total input energy ($\times 10^3$ MJ/ha) ×		Total output energy ($\times 10^3$ MJ/ha)		Energy use efficiency		Energy productivity (kg/Mj input)	
	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
Year (Y)								
2022-23	22.22	17.42	184.80	172.31	11.48	13.80	0.93	1.03
2023-24	22.23	17.51	187.97	177.46	11.72	14.13	0.93	1.06
SEm±	0.003	0.003	1.10	1.15	0.08	0.11	0.004	0.006
LSD (p=0.05)	NS	NS	NS	3.78	NS	NS	‘	0.02
Crop establishment practices (CEP)								
ZT + R	40.43	23.88	193.5^{a}	184.37^{a}	4.76^{c}	15.25^{a}	0.38^{c}	1.14^{a}
ZT	12.17	13.34	187.3^{b}	171.87^{b}	16.77^{a}	14.21^{b}	1.30^{a}	1.06^{b}
CT	14.07	15.24	178.4^{c}	168.39^{c}	13.28^{b}	12.43^{c}	1.10^{b}	0.93^{c}
SEm±	-	-	1.39	142	0.10	0.13	0.01	0.01
LSD (p=0.05)	-	-	4.43	4.63	0.34	0.43	0.02	0.03
Nitrogen placement methods (NPM)								
Control	14.93	9.75	134.4^{c}	123.93^{c}	15.21^{a}	18.40^{a}	1.19^{a}	1.38^{a}
RDN	25.35	20.60	200.8^{b}	186.65^{b}	9.88^{c}	11.66^{d}	0.79^{d}	0.87^{d}
Improved RDN	25.35	20.70	207.4^{a}	200.79^{a}	10.20^{c}	12.53^{c}	0.82^{c}	0.93^{c}
Improved 80% RDN	23.26	18.90	203.0^{b}	188.16^{b}	11.11^{b}	13.27^{b}	0.89^{b}	0.99^{b}
SEm±	-	-	1.39	1.38	0.11	0.12	0.01	0.01
LSD (p=0.05)	-	-	3.99	3.96	0.32	0.34	0.02	0.03
CEP×NPM	-	-	6.92	NS	0.56	0.59	0.03	0.04
Y×CEP	-	-	NS	NS	NS	NS	0.03	NS
Y×NPM	-	-	NS	NS	NS	NS	NS	NS
Y×CEP×NPM	-	-	NS	NS	NS	NS	NS	NS

(Superscript small letters mean within a column followed by the same lowercase letter are not significantly different at $p = 0.05$. NS= Not significant. ZT+R= Zero tillage with residue retention; ZT= Zero tillage; CT= Conventional tillage; RDN= Recommended dose of nitrogen; EUE= Energy use efficiency. Overall trend: ZT-based practices reduced total energy inputs and improved EUE and energy productivity relative to CT across both crops; Improved RDN consistently delivered the highest total output energy).

Table 2: Effect of crop establishment practices and nitrogen placement methods on the carbon auditing of the maize and wheat crop in maize-wheat system (pooled mean over two years).

Treatments	Total carbon input (kg/ha)		Total carbon output ($\times 10^3$ kg/ha)		Carbon efficiency		Carbon sustainability index	
	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
Year (Y)								
2022-23	597.79	623.17	6.43	5.32	13.36	10.20	12.36	9.20
2023-24	597.85	623.22	6.47	5.48	13.48	10.40	12.48	9.40
SEm±	-	0.003	0.11	0.03	0.07	0.09	0.07	0.09
LSD (p=0.05)	-	NS	NS	0.11	NS	NS	NS	NS
Crop establishment practices (CEP)								
ZT + R	604.53	628.29	6.75^{a}	5.70^{a}	13.82^{b}	10.84^{a}	12.82^{b}	9.84^{a}
ZT	580.89	607.50	6.47^{b}	5.31^{b}	14.12^{a}	10.50^{a}	13.12^{a}	9.50^{a}
CT	608.05	633.81	6.19^{c}	5.20^{c}	12.33^{c}	9.56^{b}	11.33^{c}	8.56^{b}
SEm±	-	-	0.03	0.04	0.09	0.12	0.09	0.12
LSD(p=0.05)	-	-	0.09	0.14	0.30	0.38	0.30	0.38
Nitrogen placement methods (NPM)								
Control	195.95^{c}	219.04	4.83^{c}	3.85^{c}	24.78^{a}	17.65^{a}	23.78^{a}	16.65^{a}
RDN	769.67^{a}	795.81	6.93^{b}	5.76^{b}	9.01^{c}	7.24^{c}	8.01^{c}	6.24^{d}
Improved RDN	770.22^{a}	796.11	7.13^{a}	6.19^{a}	9.27^{c}	7.78^{c}	8.27^{c}	6.78^{c}
Improved 80% RDN	655.44^{b}	681.85	6.97^{b}	5.80^{b}	10.64^{b}	8.52^{b}	9.64^{b}	7.52^{b}
SEm±	-	-	0.04	0.03	0.09	0.10	0.09	0.10
LSD(p=0.05)	-	-	0.11	0.11	0.27	0.27	0.27	0.27
CEP×NPM	-	-	0.19	0.19	0.47	NS	0.47	NS
Y×CEP	-	-	NS	NS	NS	NS	NS	NS
Y×NPM	-	-	0.16	0.17	NS	NS	NS	NS
Y×CEP×NPM	-	-	0.27	0.30	NS	NS	NS	NS

(Means within a column followed by the same lowercase letter are not significantly different at p = 0.05. NS= Not significant. CE= Carbon efficiency; CSI= Carbon sustainability Index. Overall trend: CT recorded the highest carbon inputs yet the lowest carbon outputs; ZT+R achieved the most favourable carbon balance, while Improved 80% RDN recorded the lowest carbon input due to reduced N_2O-associated emissions).

placement with conservation tillage. Within a ZT framework, the structural integrity of the soil profile is maintained, preserving the spatial geometry of subsurface-banded nitrogen strictly within the active zone of root absorption. Conversely, the repeated soil inversion inherent in CT destabilizes this carefully arranged placement, largely dissipating the spatial benefits provided by the Improved RDN strategy.

Carbon footprint dynamics: Dual-pathway advantage of conservation agriculture

The sustained superiority of the ZT+R and ZT paradigms over CT in relation to the carbon efficiency (CE) and carbon sustainability index (CSI) is driven by two independent, compounding mechanisms. The initial pathway is emission suppression: by completely eliminating tillage procedures and thereby slashing diesel consumption, the heightened direct CO_2 emissions characteristic of CT are successfully avoided. The secondary pathway involves biomass carbon accumulation: The robust biological activity, superior moisture retention and upgraded soil architecture fostered under long-term ZT+R stimulate greater crop biomass generation, subsequently elevating carbon output. The resulting CSI measurements confirm that the ZT+R system sustains a net positive carbon balance, which serves as a fundamental prerequisite for the long-term accrual of soil organic carbon (SOC).

The near-parity in carbon input between CT and ZT+R observed specifically in wheat (0.87% difference), in contrast to the substantial divergence recorded in maize, reflects the lower tillage intensity of conventional wheat establishment relative to post-*kharif* maize land preparation. This crop-specific asymmetry demonstrates that system-level carbon footprint assessments cannot be extrapolated from single-crop data.

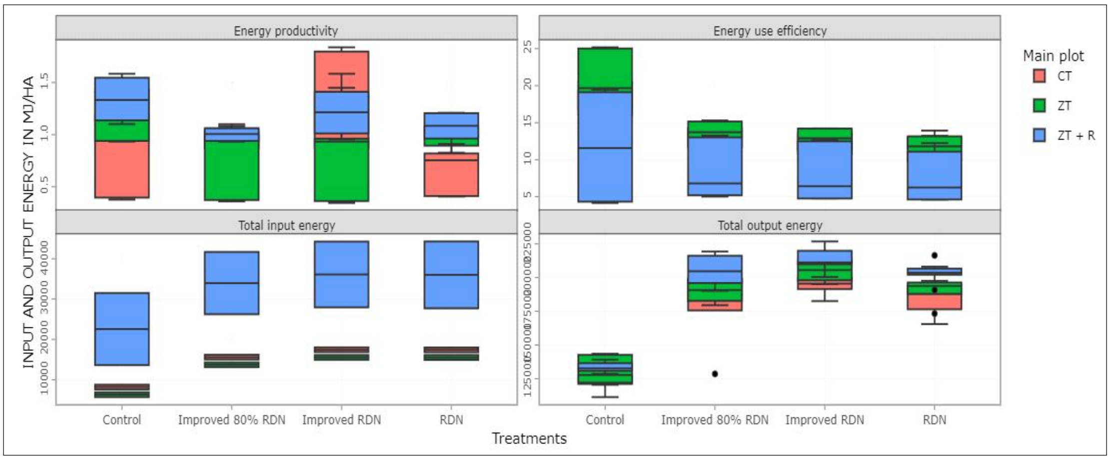

Fig 1: Effect of crop establishment practices and nitrogen placement methods on the energy auditing of maize-wheat system (pooled mean over 2 years).

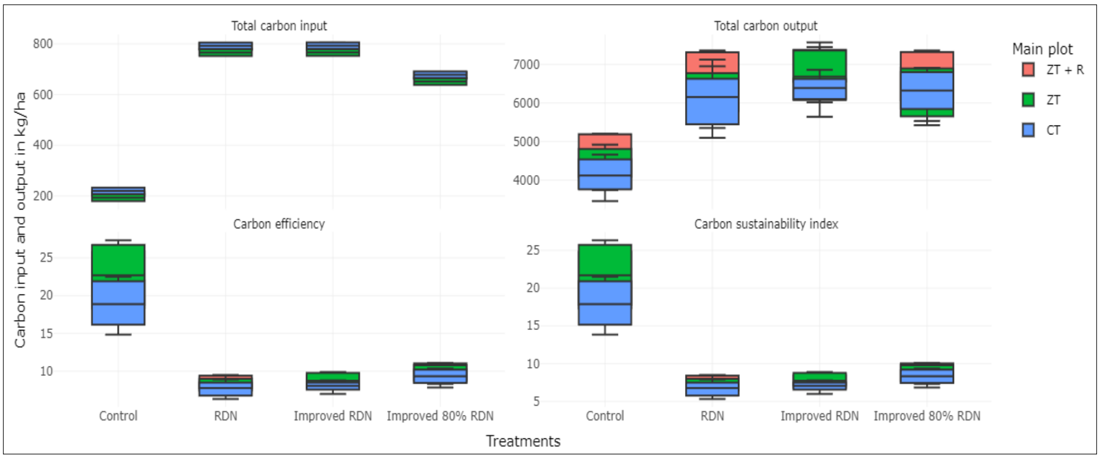

Fig 2: Effect of crop establishment practices and nitrogen placement methods on the carbon auditing of maize-wheat system (pooled mean over two years).

Nitrogen management and carbon footprint: The non-linear emission pathway

The markedly reduced carbon inputs observed in the Improved 80% RDN configuration relative to the full-rate NPMs-and its consequent dominance in CSI-is dictated by the highly non-linear relationship linking applied synthetic nitrogen with N_2O emissions. Whenever the concentration of mineral nitrogen in the soil surpasses the immediate demand of the crop, the processes of nitrification and denitrification accelerate disproportionately, generating N_2O flux rates that climb much more rapidly than the linear addition of fertilizer. Consequently, decreasing the nitrogen load by 20% under the Improved 80% RDN protocol yields an amplified, greater-than-proportional drop in the overall carbon loading driven by N_2O.

System-level synthesis: Toward sustainable intensification in the IGP

Across all energy and carbon parameters, the ZT+R × Improved RDN combination consistently emerged as the most resource-efficient and environmentally sustainable management strategy. To the best of our knowledge, this is the first study to simultaneously quantify the full energy audit and carbon footprint profile across both crops of a maize-wheat rotation under long-term CA plots integrated with subsurface nitrogen banding in the IGP.

The policy implications of these results are directly actionable. The Government of India's stringent enforcement against crop residue burning creates an urgent demand for alternatives. ZT+R directly addresses this by incorporating residue into a productive system. Simultaneously, the carbon footprint benefits of Improved RDN and Improved 80% RDN align with the objectives of India's Soil Health Card scheme and the PM-PRANAM programme.

Limitations and future scope

Although this investigation supplies a rigorous, full-rotation assessment spanning two years and two crops, it remains constrained by certain factors. Primarily, the trial was exclusively executed on the sandy clay loam soils of ICAR-IARI, New Delhi; consequently, the outcomes might differ if replicated across diverse pedological profiles. Therefore, multi-location validation is highly recommended. Second, the specific energy equivalent coefficients applied were derived from Mittal and Dhawan (1988), which may not perfectly capture the energy demands of contemporary agricultural operations. Subsequent investigations should update these multipliers using the latest life cycle inventory data. Finally, this current research did not directly record belowground biomass carbon, methane (CH_4) flux, or definitive changes in soil organic carbon (SOC) stocks. Future scholarly work should prioritize complete LCA-driven carbon footprinting that includes these crucial dynamics, alongside comprehensive economic analysis to gauge the practical adoption feasibility for smallholder farmers.

CONCLUSION

The present study demonstrates that the adoption of zero tillage-based crop establishment practices-particularly ZT+R-in conjunction with precision nitrogen placement through Improved RDN, constitutes the most energy-efficient and carbon-sustainable management combination for the maize-wheat cropping system in the indo-gangetic plains. ZT consistently reduced total energy inputs relative to CT while simultaneously delivering higher output energy, energy use efficiency and energy productivity. The carbon auditing data reinforced this conclusion, with ZT+R achieving superior carbon efficiency and CSI values. Among nitrogen placement methods, Improved RDN delivered the highest output energy, while Improved 80% RDN achieved the most favourable carbon input profile through its non-linear suppression of N_2O emissions. Collectively, these findings provide robust, rotation-level quantitative evidence that the integration of conservation tillage with subsurface nitrogen banding represents an agronomically superior and environmentally sound alternative to conventional management.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

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