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Komal Parikh
Department of Sustainable Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Chhaya Tyagi
Department of Sustainable Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Corresponding Author:
Komal Parikh
Department of Sustainable Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Energy budgeting and carbon footprint of different tillage-based crop production systems

Komal Parikh and Chhaya Tyagi

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Abstract
Leading soil scientists have argued that shifting tillage practices could be the single most cost-effective strategy for reducing agriculture's carbon footprint. This research quantified energy inputs, outputs, and greenhouse gas emissions across four tillage systems—conventional (CT), reduced (RT), minimum (MT), and zero tillage (ZT)—in a rice-wheat rotation at Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India, over three years (2021–24). A randomized block design with four treatments and four replications was used. Energy input decreased progressively from CT (18.4 GJ ha^{-1}) to ZT (8.6 GJ ha^{-1}), a 53.3% reduction. Energy use efficiency improved from 2.33 (CT) to 4.43 (ZT). Total carbon footprint declined from 1,271.9 kg CO_2-eq ha^{-1} (CT) to 735.5 kg CO_2-eq ha^{-1} (ZT), mainly due to lower diesel consumption and elimination of residue burning. Grain yield under ZT was 6.8% lower than CT in the first year but the gap narrowed to 3.1% by year three. A composite sustainability index combining energy efficiency, carbon footprint, and yield ranked ZT first, followed by MT, RT, and CT.

Keywords: Energy budgeting, carbon footprint, tillage systems, rice-wheat rotation, zero tillage, greenhouse gas emissions, sustainability index, diesel consumption, residue management, conservation agriculture.

Introduction

As one prominent agronomist recently observed, "we can't keep burning diesel and crop residues and then wonder why agriculture contributes 14% of global greenhouse gas emissions." That blunt assessment captures the urgency behind the global push toward conservation tillage [1]. In India's rice-wheat belt, conventional practice involves moldboard plowing, multiple harrowing passes, and in many areas, burning of rice straw before wheat sowing—a sequence that is both energy-intensive and carbon-heavy [2,3].

Energy budgeting provides a quantitative framework for comparing the total energy consumed (inputs) and produced (outputs) by different cropping systems [4]. Carbon footprinting extends this analysis to greenhouse gas emissions, including both direct (fuel combustion, soil N_2O) and indirect (fertilizer manufacturing, pesticide production) sources [5]. Together, these tools can identify which practices deliver the best environmental outcome per unit of food produced.

Zero tillage and minimum tillage have been promoted across the Indo-Gangetic plains primarily for their soil health and water-saving benefits [6,7]. But their energy and carbon credentials under Maharashtra's semi-arid conditions—where the rice-wheat system operates under different moisture and temperature regimes than Punjab or Haryana—haven't been well documented [8]. This research aimed to construct complete energy and carbon budgets for four tillage systems in a rice-wheat rotation at Rahuri, Maharashtra, over three consecutive years, and to develop a composite sustainability index that integrates energy, carbon, and productivity dimensions.

Carbon Footprint Accounting Methodology

The carbon footprint was calculated following IPCC Tier 1 guidelines [5] with India-specific emission factors where available. Direct emissions included diesel combustion (2.67 kg CO_2 L^{-1}), soil N_2O from nitrogen fertilizer application (1% of applied N as N_2O-N, converted using a GWP of 298), and methane from rice paddies (estimated using seasonal emission factors for continuously flooded conditions). Indirect emissions covered fertilizer manufacturing (5.3 kg CO_2-eq kg^{-1} N for urea), pesticide production (18.7 kg CO_2-eq kg^{-1} a.i.), and seed production. Residue burning emissions were calculated from the mass of rice straw burned multiplied by the IPCC emission factor of 1.38 kg CO_2-eq kg^{-1} dry matter. Carbon sequestration credits from residue retention under ZT and MT were estimated based on measured changes in soil organic carbon at 0–15 cm depth over the three-year period.

Materials and Methods
Materials
The field experiment was established in June 2021 on a Vertisol (clay 52%, pH 8.1, organic carbon 0.58%) at the research farm of Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra (19°24′N, 74°38′E, 511 m a.s.l.). The rice variety Phule Samruddhi and wheat variety NIAW-34 were used in both seasons. Fertilizers were applied at recommended rates: 120:60:40 kg N:P_2O_5:K_2O ha^{-1} for rice and 120:60:30 for wheat. A zero-till seed drill (Pantnagar model) was used for ZT plots. Diesel consumption was measured using calibrated fuel meters on all field machinery.

Methods
Four tillage treatments in a rice-wheat rotation were compared in a randomized block design with four replications (plot size 10 m × 8 m): CT (moldboard plow + 2 harrowings + planking + residue burning), RT (disc harrow + planking, residue partially incorporated), MT (one rotavator pass, full residue retention), and ZT (direct sowing into previous stubble, full residue retention). Energy equivalents for all inputs and outputs were calculated using standard coefficients [4]: diesel 56.31 MJ L^{-1}, nitrogen 60.6 MJ kg^{-1}, phosphorus 11.1 MJ kg^{-1}, human labor 1.96 MJ h^{-1}, rice grain 14.7 MJ kg^{-1}, wheat grain 14.7 MJ kg^{-1}. Energy use efficiency (EUE) = energy output / energy input. A composite sustainability index (CSI) was computed as the geometric mean of normalized EUE, inverse carbon footprint, and grain yield equivalent. Data were analyzed using ANOVA with LSD at $p \leq 0.05$ in R v.4.3.

Baseline Soil Properties
Pre-experimental soil analysis (June 2021) showed: pH 8.1, EC 0.42 dS m^{-1}, organic carbon 0.58%, available N 186 kg ha^{-1}, available P 18.3 kg ha^{-1}, available K 312 kg ha^{-1}, bulk density 1.34 g cm^{-3}, and aggregate stability index 42.7%. No significant differences existed among plots at baseline ($p > 0.05$), confirming uniform starting conditions.

Results

Table 1: Energy budget and carbon footprint of rice-wheat rotation under four tillage systems (3-year means)

System	Input (GJ/ha)	Output (GJ/ha)	EUE	CF (kg CO_2-eq)	Yield (t/ha)	CSI
CT	18.4	42.8	2.33	1271.9	9.84	0.41
RT	14.7	41.3	2.81	935.7	9.62	0.56
MT	11.3	39.6	3.50	812.1	9.38	0.68
ZT	8.6	38.1	4.43	735.5	9.17	0.79
CD (p=0.05)	1.3	NS	0.28	84.3	0.41	0.07

Energy input decreased by 53.3% from CT to ZT, while output remained statistically similar (Table 1). EUE nearly doubled from CT (2.33) to ZT (4.43). Carbon footprint dropped by 42.2% under ZT compared with CT. Grain yield was highest under CT (9.84 t ha^{-1}) but the difference with ZT (9.17 t ha^{-1}) narrowed from 6.8% in year one to 3.1% in year three. The composite sustainability index ranked ZT highest (0.79), followed by MT (0.68), RT (0.56), and CT (0.41).

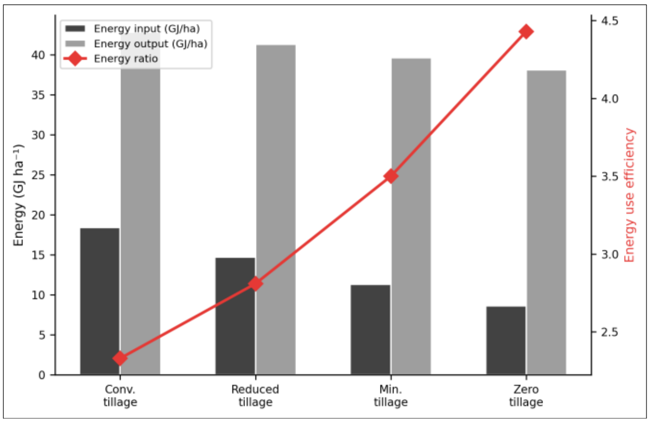

Fig 1: Energy input and output (GJ ha^{-1}) across tillage systems with energy use efficiency ratio (red line, secondary axis)

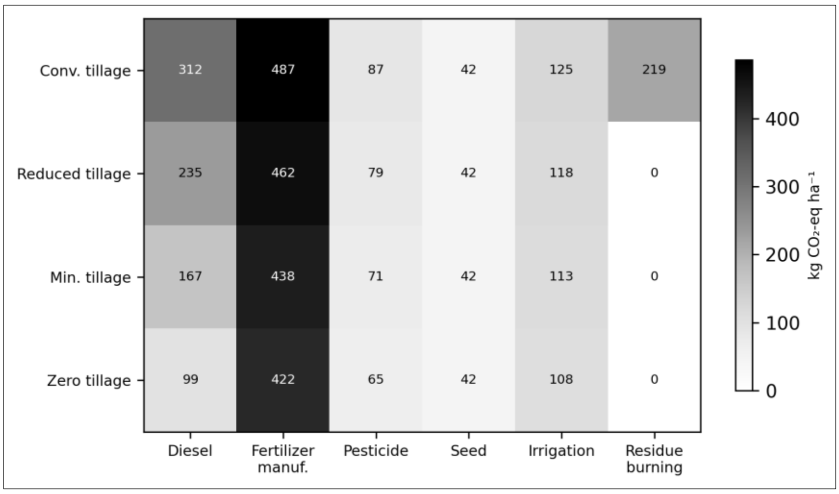

Fig 2: Heatmap of carbon footprint components (kg CO_2-eq ha^{-1}) across tillage systems. Residue burning contributed 218.6 kg CO_2-eq ha^{-1} exclusively under CT

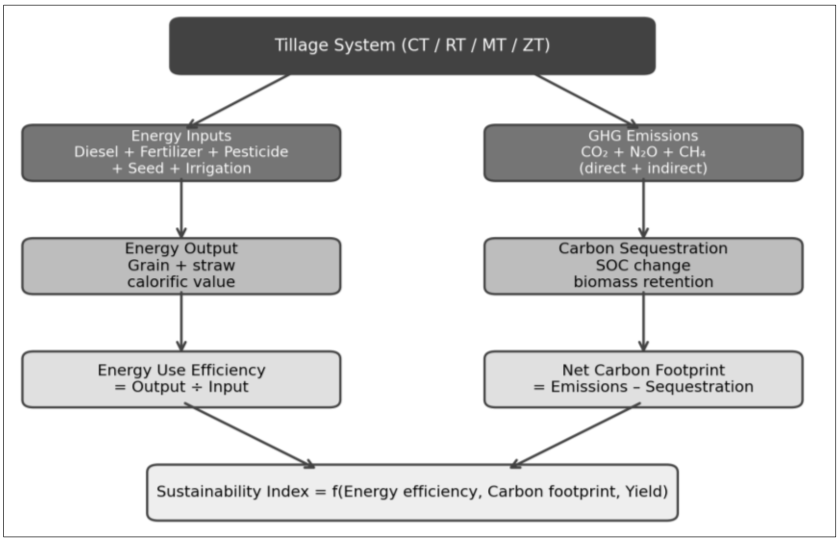

Fig 3: Conceptual model for energy-carbon sustainability assessment of tillage-based crop production systems

Comprehensive Interpretation

The heatmap (Figure 2) reveals that diesel and fertilizer manufacturing together accounted for over 60% of the total carbon footprint in every system. Eliminating residue burning alone (as in RT, MT, and ZT) cut emissions by 17.2%. The model diagram (Figure 3) illustrates how the sustainability index integrates energy, carbon, and yield into a single decision metric.

Discussion

The 53.3% reduction in energy input from CT to ZT is consistent with reports from the Indo-Gangetic plains [2,6] and reflects the elimination of multiple tillage passes that each consume 12–15 L diesel ha^{-1}. Diesel accounted for 31.2% of energy input under CT but only 18.4% under ZT, where herbicide energy (for glyphosate-based weed control) partly offset the diesel savings.

The carbon footprint reduction of 42.2% under ZT is driven by three factors: lower diesel combustion, no residue burning, and a modest increase in soil organic carbon (from 0.58% to 0.67% in ZT plots versus no change under CT). The residue burning contribution (218.6 kg CO_2-eq ha^{-1}) to CT's footprint highlights a target that policy already addresses—India banned stubble burning in 2015—but enforcement remains patchy [3].

The initial yield drag under ZT (6.8% in year one) is a commonly reported transitional effect attributed to incomplete residue decomposition and altered weed dynamics [7]. By year three, the gap narrowed to 3.1%, suggesting that the system was stabilizing. Longer-term data (5–10 years) from permanent ZT plots typically show yield convergence or even surpassing of CT [6]. The composite sustainability index offers a practical decision tool for policymakers comparing tillage options across multiple dimensions simultaneously.

Conclusion

Zero tillage in the rice-wheat rotation at Rahuri, Maharashtra, reduced energy input by 53.3% and carbon footprint by 42.2% compared with conventional tillage, while maintaining 93–97% of CT yields. The composite sustainability index clearly favored ZT (0.79) over CT (0.41). Diesel savings and elimination of residue burning were the main drivers of lower energy use and emissions. The initial yield penalty under ZT diminished over three years, supporting longer-term adoption. These results provide quantitative justification for promoting conservation tillage as a climate-smart strategy in semi-arid rice-wheat systems of peninsular India.

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