Indian Journal of Agricultural Sciences **96** (5): 577–584, May 2026/Article
https://doi.org/10.56093/ijas.v96i5.163569

Residue retention and soil matric potential-based irrigation to improve productivity, energy efficiency and profitability of wheat (*Triticum aestivum*)

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Received: 12 January 2025; Accepted: 23 April 2026

ABSTRACT

High energy consumption and declining profitability in wheat (*Triticum aestivum* L.) production following rice (*Oryza sativa* L.) pose significant challenges to sustainable agriculture. Inefficient residue management practices, and traditional irrigation methods lead to excessive energy use, environmental degradation, and reduced economic returns. To address these issues, a field experiment was conducted during winter (*rabi*) season of 2021–22 and 2022–23 at Punjab Agricultural University, Ludhiana, Punjab to evaluate the productivity, energetics and profitability of wheat under residue management and soil matric potential-based irrigation. The experiment was laid out in randomised complete block design (RCBD) comprising nine treatments of crop residue management including conventional tillage (CT) with/without rice residue, zero tillage (ZT) with/without rice residue, ZT with rice residue and retention of wheat residue, ZT after partial burning of rice residue, with irrigation at 35±1 kPa in all crop residue management treatments. Higher grain yield, net energy, energy use efficiency and energy productivity were obtained in ZT (double crop residue) + irrigation at 35±1 kPa while, economic returns, viz. net returns, gross returns and benefit-cost ratio were maximum under ZT (single crop residue) + irrigation at 35±1 kPa. Principal component analysis further indicated strong positive relationships among grain yield, energy output, net energy and economic returns, with residue retention treatments showing close association with improved productivity and energy efficiency. Overall, the study suggests that ZT with rice residue retention combined with soil moisture potential-based irrigation scheduling (35±1 kPa) is an effective strategy for improving productivity, energy efficiency and profitability of wheat grown after rice.

Keywords: Economics, Energetics, Residue management, Soil moisture potential, Wheat

The rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system (RWCS) is one of the most important and intensive agricultural production systems in South Asia, covering nearly 24 mha across India, China, Pakistan, Nepal and Bangladesh (Kaur *et al.* 2021). This system plays a vital role in ensuring food security for millions of people in the Indo-Gangetic Plains. However, the sustainability of the RWCS is increasingly threatened by issues such as declining soil health, inefficient resource utilisation, rising production costs and environmental pollution associated with residue burning.

Crop residue management has emerged as a major challenge in the RWCS. In north-western India, large quantities of rice straw are left in the field after combine harvesting, which often leads farmers to burn the residues to facilitate timely sowing of wheat. Burning of crop residues releases significant quantities of pollutants such as CO_2, CH_4, N_2O, CO, NH_3, SO_2 and particulate matter into the atmosphere, thereby contributing to environmental pollution and climate change (Mittal *et al.* 2009, Zhang *et al.* 2011). Apart from environmental concerns, residue burning results in the loss of valuable plant nutrients and organic carbon that could otherwise improve soil fertility and productivity.

The presence of large amounts of loose and unevenly distributed rice straw in the field also creates operational difficulties for wheat establishment, making tillage and sowing operations more complex and resource-intensive (Sidhu *et al.* 2007). Conventional tillage (CT) practices generally involve multiple field operations to incorporate or remove residues before wheat sowing, which increases fuel consumption, labour use and overall production costs. Consequently, CT systems require higher energy inputs, which not only increase the cost of cultivation but also reduce the overall energy efficiency of crop production systems (Nandan *et al.* 2019, Singh *et al.* 2020).

Resource-conserving technologies such as zero tillage (ZT) and residue retention have been widely promoted as sustainable alternatives for wheat establishment after rice. These practices reduce the number of field operations, thereby lowering fuel consumption and energy inputs while maintaining crop productivity (Pratibha *et al.* 2016, Yadav *et al.* 2017). Retention of rice straw on the soil surface also acts

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as mulch, which improves soil physical conditions, reduces evaporation losses and enhances soil moisture conservation (Gupta *et al.* 2021b). Such improvements in soil moisture dynamics may reduce irrigation requirement and improve water use efficiency of wheat (Gupta *et al.* 2021a).

Efficient irrigation management is another important factor influencing productivity, energy consumption and profitability of wheat production. In many regions, irrigation scheduling is traditionally based on fixed crop growth stages, which may not accurately reflect the actual soil moisture status. Soil moisture-based irrigation scheduling using tensiometers allows irrigation to be applied when soil moisture reaches a critical threshold, thereby improving irrigation efficiency and reducing unnecessary water and energy use.

Energy use efficiency and economic profitability are important indicators for evaluating the sustainability of crop production systems. Conservation agriculture practices that reduce tillage operations and optimise irrigation management can significantly decrease energy inputs and cost of cultivation while improving net returns from wheat production (Kumar *et al.* 2013, Gupta *et al.* 2022). However, limited information is available on the combined effect of rice residue management and soil moisture-based irrigation scheduling on wheat productivity, energetics and profitability. Therefore, the present study was undertaken to evaluate the effect of residue management and soil matric potential-based irrigation on productivity, energetics and profitability of wheat grown after rice.

MATERIALS AND METHODS

A field experiment was conducted during winter (*rabi*) season of 2021–22 and 2022–23 at Punjab Agricultural University, Ludhiana (30°54´N, 75°40´E, 247 m amsl), Punjab. The soil of the experimental field was sandy loam in texture. The treatments were comprised of nine residue management practices, viz. Transplanted paddy (TP)-Conventional tillage (CT) wheat without paddy residue (T_1); TP-Zero tillage (ZT) wheat without paddy residue (T_2); TP-CT wheat after paddy residue incorporation (T_3); TP-ZT wheat with paddy residue retention (T_4); Direct seeded paddy (DSP)-ZT wheat with paddy residue retention (T_5); DSP-ZT wheat after removing paddy residue (T_6); TP-ZT wheat after partial burning of paddy residue (T_7); TP-wheat sowing by rotavator with paddy residue (T_8) and TP with wheat residue-ZT wheat with paddy residue (T_9) and irrigation scheduling at soil moisture potential of 35±1 kPa to all the treatments. In the T_9, wheat residue produced during the previous *rabi* season was retained after the harvest of crop and then incorporated at the time of puddling before transplanting of rice (approx. 5 t/ha). The experiment was laid out in a randomised complete block design (RCBD) having three replications. Experiment commenced with rice, grown as residue crop and wheat as main crop. Various operations involved in field preparation and sowing of wheat preceded by transplanted puddled rice or direct seeded rice were as follows: CT (T_1), 1 times disc harrow + 2 times cultivator + conventional seed cum fertiliser drill + planker. ZT without residue (T_2 and T_6): zero till drill. CT with residue (T_3): 2 times disc harrow + 2 times cultivator + conventional seed cum fertiliser drill + planker. ZT plots with paddy residue (T_4, T_5 and T_9): cutter-cum spreader + happy seeder. Burning treatment (T_7): partial burning + zero till drill. Rotavator sown treatments (T_8): broadcasting of seed + cutter-cum spreader + rotavator (1 time).

Rice residue was retained on the soil surface at approximately 7 t/ha, representing the average straw load remaining after combine harvesting. In treatments involving residue incorporation, the same quantity of residue was incorporated into the soil during tillage operations. In partial burning treatment, approximately 70% rice residue (5 t/ha of loose straw) was burned after combine harvesting. Wheat was sown on 29th and 26th October during 2021 and 2022 respectively, with a row spacing of 20 cm. Wheat variety PBW 824 was sown using seed rate of 100 kg/ha during both the years. Fertiliser application was done according to the recommended dose i.e. 125 kg N and 62.5 kg P_2O_5 per hectare. Diammonium phosphate (46% P_2O_5, 18% N) was drilled at sowing and urea (46% N) was applied in two splits before first and second irrigation in all the treatments during both the years. Potassium fertiliser was not applied because the experimental soil contained adequate levels of available potassium (>300 kg/ha), which falls under the sufficient category for wheat cultivation in Punjab soils according to Punjab Agricultural University fertiliser recommendations. For the control of grass and broadleaf weeds, Clodinafop 15 WP @60 g a.i./ha and Algrip 20 WP @25 g a.i./ha was applied 33–40 DAS after mixing in 375 L of water. Propiconazole 25 EC @125 g a.i./ha was sprayed at booting and heading stage to protect the wheat crop against yellow rust during both years and two sprays of Thiamethoxam 25 WG @12.5 g a.i./ha was done at heading stage and milking stage for the control of aphids during 2021–22 and one spray of Thiamethoxam 25 WG @12.5 g a.i./ha was done at heading stage for the control of aphids during 2022–23. Irrigation scheduling was done based on soil matric potential using tensiometers installed at 30 cm depth. Irrigation was applied when soil matric potential reached 35 ± 1 kPa, which represents moderate soil moisture stress for wheat and has been reported as an efficient threshold for optimising water use efficiency and grain yield under conservation agriculture systems in the Indo-Gangetic Plains (Gupta *et al.* 2016). This threshold ensures adequate soil moisture availability during critical growth stages while avoiding excessive irrigation. Each irrigation was applied at a depth of 75 mm, which corresponds to the average irrigation depth commonly recommended for wheat under flood irrigation in north-western India to ensure adequate wetting of the active root zone (0–60 cm). Harvesting of wheat was done on 12th and 15th April during 2022 and 2023, respectively.

The gross plot size for each treatment was 40 m^2 (16 m × 2.5 m), with a net harvest area of 15 m^2 used for yield observations. Grain yield of wheat was adjusted at

12% moisture content. In the present study, crop residues were not considered as external energy inputs in the energy budgeting analysis, as the residues were generated within the cropping system itself and were either incorporated/retained on the soil surface or removed depending on the treatment. Therefore, residue management was treated as a field management practice influencing soil microclimate, moisture conservation and crop performance, rather than an externally added energy input. Similar methodological approaches have been followed as in earlier studies evaluating energetics of conservation agriculture practices in cereal based systems. The energy input and output were computed by using the energy equivalents given by Panesar and Bhatnagar (1994) (Table 1). Net energy was determined by deducting the total energy input from the energy output. Energy use efficiency and productivity were computed following the methodology outlined by Demircan *et al.* (2006).

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad (1)$$

$$\text{Energy productivity (kg/MJ)} = \frac{\text{Grain yield (kg/ha)}}{\text{Energy input (MJ/ha)}} \quad (2)$$

Cost of cultivation was calculated as per treatments by using enterprise budget data for *rabi* crops of 2021–22 and 2022–23, provided by the Department of Economics and Sociology at PAU, Ludhiana, Punjab. Gross returns were worked out by multiplying the grain and straw yields with their prevailing market prices. The market prices of wheat grain were ₹2,015 in 2021–22 and ₹2,125/q in 2022–23 and that of wheat *bhusa* was taken as ₹425 in 2021–22 and ₹450/q in 2022–23. Net returns were computed by subtracting the total cultivation cost from the gross returns. The benefit-cost ratio was derived by dividing net returns by the cultivation cost under respective treatments.

The data was analysed by analysis of variance (ANOVA) for randomised complete block design (RCBD) (Cochran and Cox 1957) using CPCS1 (Cheema and Singh 1991) developed by the Department of Statistics, Punjab Agricultural University, Ludhiana, Punjab. The differences between the treatment means were evaluated by using the least significant difference (LSD) at $p \leq 0.05$.

RESULTS AND DISCUSSION

Yield: Grain yield of wheat was significantly influenced by different rice residue management practices (Table 2). Among the treatments, zero tillage (ZT) with retention of rice residue (T_4) and ZT with both rice and wheat residue (T_9) recorded higher grain yields compared with other treatments during both years of the study. The highest grain yield was obtained under T_9 (6246.7 and 6353.3 kg/ha) which was statistically at par with T_4 (6183.3 and 6303.3 kg/ha) and T_3 (6047.3 and 6176.7 kg/ha) during 2021–22 and 2022–23, respectively. In contrast, the lowest grain yield was observed under ZT without residue (T_2), which recorded 4725.3 and 4920.0 kg/ha during 2021–22 and 2022–23, respectively.

Table 1 Energy equivalents of different inputs and output of agronomic practices

Particulars	Unit	Equivalent energy (MJ)
Input		
Human labour	h	1.96
Machinery		
(a) Farm machinery	h	62.70
(b) Tractor	h	64.80
Diesel	L	56.31
Seed	kg	14.70
Fertilisers		
(a) N	kg	60.60
(b) P_2O_5	kg	11.10
Irrigation water	m^3	0.63
Plant protections		
(a) Herbicides	kg	238.00
(b) Fungicides	kg	92.00
(c) Insecticides	kg	199.00
Output		
Wheat grain	kg	14.70
Wheat residue	kg	12.50

Retention of rice residue under ZT improved grain yield by 29–32% over ZT without residue and by 7–8% over conventional tillage (CT) without residue. Similar trends were also observed in straw yield, where treatments involving residue retention produced higher straw yields compared with treatments without residue. The higher grain yield under residue retained treatments may be attributed to improved soil moisture conservation, enhanced nutrient availability and favourable soil micro-environment created by residue mulch. Rice straw mulch reduces soil evaporation losses and improves infiltration of irrigation water, thereby maintaining better soil moisture availability during critical growth stages of wheat (Dhaliwal *et al.* 2020, Gupta *et al.* 2021b). Improved soil moisture conditions under residue mulch are particularly beneficial under soil moisture potential-based irrigation scheduling, which ensures timely irrigation and reduces moisture stress.

Residue retention also improves soil physical properties such as soil structure and organic matter content, which in turn enhances root growth and nutrient uptake by the crop. These improvements collectively contribute to better crop growth and higher yield under residue retained treatments. Similar findings have been reported by Gupta *et al.* (2016) and Sidhu *et al.* (2019), who observed higher wheat yields under residue retention and conservation tillage practices in the rice–wheat system.

On the other hand, lower yields under ZT without residue may be due to relatively poor soil moisture conservation and lower nutrient availability compared with residue-retained treatments. Absence of residue mulch exposes the soil surface to higher evaporation losses and temperature fluctuations, which can adversely affect crop growth and yield. Similar observations were also reported by Kumar *et al.* (2013) and Singh *et al.* (2020), who reported improved wheat productivity under residue retention and conservation agriculture practices compared with conventional systems.

Overall, the results indicate that retention of rice residue under ZT provides a favourable environment for wheat growth, resulting in improved productivity compared with residue removal or burning practices.

Irrigation frequency and irrigation water applied: Crop residue management substantially influenced the irrigation requirement of wheat (Fig. 1). During 2021–22, three irrigations were required under ZT with single and double crop residue (T_4, T_5 and T_9), whereas four irrigations were required in treatments where residues were removed or incorporated (T_1, T_2, T_3, T_6 and T_8). Similarly, during 2022–23, residue retained treatments required four irrigations compared to five irrigations in treatments without residue retention. Consequently, the lowest irrigation water requirement (225 and 300 mm) was recorded under residue retention treatments, whereas higher irrigation water requirement (300 and 375 mm) were applied in treatments without residue retention and incorporation during 2021–22 and 2022–23, respectively. The reduced irrigation requirement under residue retained treatments might be attributed to the mulching effect of surface residues, which likely reduced soil evaporation, moderated soil temperature and improved soil moisture conservation. Residue cover may also enhance water infiltration and reduce runoff losses, thereby increasing soil water storage and its availability to the crop. In contrast, the absence of residue might have accelerated soil moisture depletion due to greater evaporative losses and exposure of the soil surface, resulting in higher irrigation frequency and irrigation water requirement in treatments where residues were removed or incorporated. Similar findings on improved soil moisture conservation and reduced irrigation requirement under residue retained conservation agriculture systems have been reported by Ram *et al.* (2013), Sidhu *et al.* (2019) and Prem *et al.* (2026).

Energy input and output: Energy input under different crop residue and irrigation management treatments in wheat was computed for two years (Fig. 2). Total energy input depicted in circular bar plot ranged from 13,270–18,850 MJ/ha in 2021–22 and 13,710–19,290 MJ/ha in 2022–23. Fertilisers contributed the major share of total energy input, followed by diesel, irrigation, seed, machinery, human labour and plant protection chemicals. Among treatments, CT with residue incorporation (T_3) recorded the highest energy input (18,850 and 19,290 MJ/ha), followed by CT without residue (T_1) (17,640 and 18,080 MJ/ha). In contrast, ZT with both paddy and wheat residues (T_9) required substantially lower energy input (14,140 and 14,580 MJ/ha), representing a reduction of 25.0 and 24.4% compared with T_3 and T_1 during 2021–22 and 2022–23, respectively. The lower energy requirement under ZT with residue retention may be attributed to the elimination of intensive tillage operations and reduced irrigation requirement due to improved soil moisture conservation under surface residue mulch. Residue retained treatments saved 75 mm of irrigation water, thereby reducing irrigation related energy inputs compared with treatments where residues were removed or incorporated. Similar reductions in energy input under ZT with residue

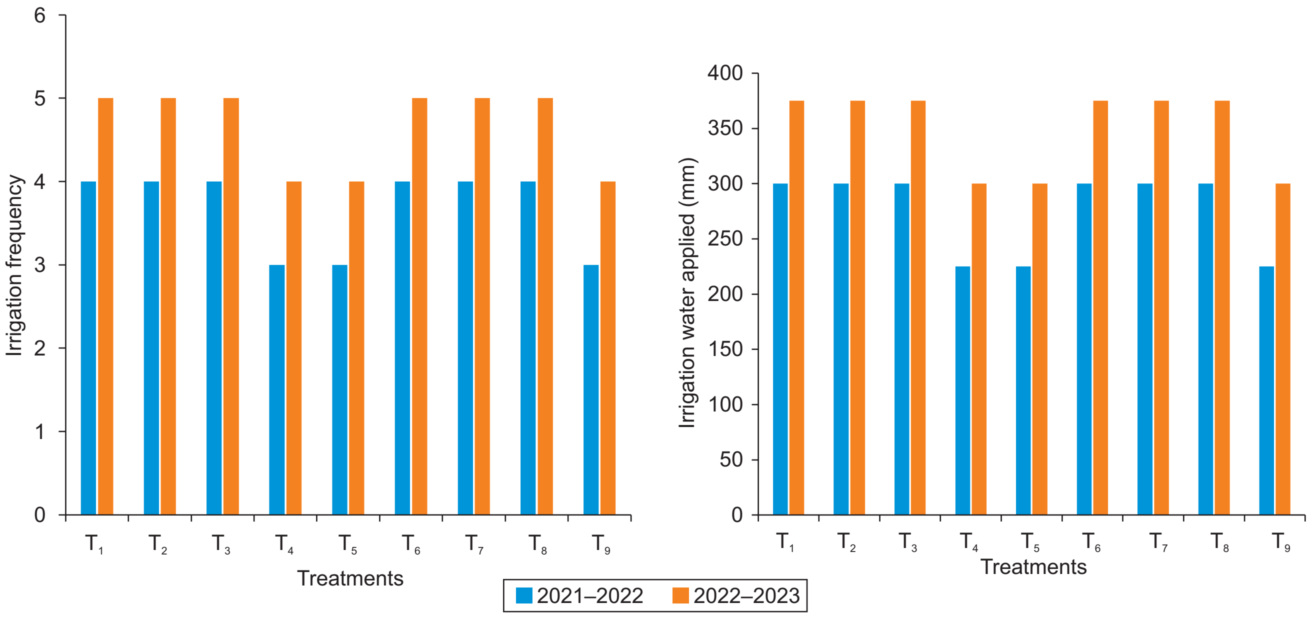

Fig. 1 Irrigation frequency and irrigation water applied during 2021–22 and 2022–23. Treatment details are given under Materials and Methods.

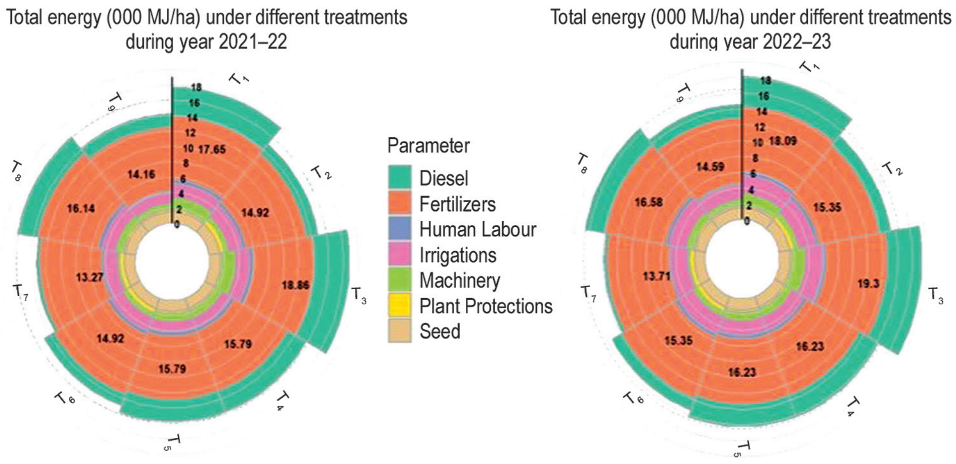

Fig. 2 Energy input under different treatments during *rabi* 2021–22 and 2022–23. Treatment details are given under Materials and Methods.

retention have also been reported by Singh *et al.* (2020).

On contrary, energy output (Table 2) was significantly higher under ZT with both paddy and wheat residues (T_9) (193,000 and 195,900 MJ/ha) than CT without residue (T_1) (182,700 and 186,000 MJ/ha) during 2021–22 and 2022–23, respectively. Consequently, net energy was also highest under T_9 (178,800 and 181,300 MJ/ha) compared with T_1 (165,000 and 167,900 MJ/ha), while the lowest net energy was observed under ZT without residue. Energy use efficiency (EUE) was significantly higher under ZT with both paddy and wheat residues (13.6 and 13.4) compared with CT without residue (10.4 and 10.3), representing an increase of 30.8 and 30.1% during 2021–22 and 2022–23, respectively. Similarly, Energy productivity of ZT retaining both paddy and wheat residue was 441.6 and 435.6 kg grain/MJ and was significantly higher over all other residue management treatments during both years.

The higher net energy, energy use efficiency and energy productivity observed under ZT with both paddy and wheat residues (T_9) may be attributed to higher energy output resulting from improved crop yield along with lower energy input consumption. Conservation tillage practices reduce energy use associated with tillage operations while maintaining higher productivity, thereby improving overall energy efficiency. Pramanick *et al.* (2024) also reported 14–18% and 15–20% higher gross and net energy output, respectively, under conservation tillage practices such as permanent beds and ZT compared with CT. Similar findings were reported by Kumar *et al.* (2024).

Table 2 Yield and energetics of wheat crop influenced by residue management and soil matric potential-based irrigation

Treatments	Grain yield (kg/ha)		Straw yield (kg/ha)		Energy output (000 MJ/ha)		Net energy (000 MJ/ha)		Energy use efficiency		Energy productivity (kg grain/MJ)	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
T_1	5800.0	5900.0	7794.4	7942.9	182.7	186.0	165.0	167.9	10.4	10.3	328.7	326.3
T_2	4725.3	4920.0	6913.4	6945.2	155.9	159.1	141.0	143.8	10.5	10.4	316.9	320.5
T_3	6047.3	6176.7	7904.0	8046.3	187.7	191.4	168.8	172.1	10.0	9.9	320.8	320.2
T_4	6183.3	6303.3	8026.7	8171.7	191.2	194.8	175.4	178.6	12.1	12.0	391.8	388.6
T_5	5726.7	5830.0	7668.9	7903.8	180.0	184.5	164.3	168.2	11.4	11.4	362.8	359.4
T_6	5050.0	5243.3	7126.7	7299.2	163.3	168.3	148.4	153.0	11.0	11.0	338.7	341.6
T_7	5480.0	5566.7	7585.0	7629.2	175.4	177.2	162.1	163.5	13.2	12.9	412.9	406.0
T_8	5995.3	6080.0	7822.0	7976.3	185.9	189.1	169.8	172.5	11.5	11.4	371.7	367.0
T_9	6246.7	6353.3	8092.0	8196.6	193.0	195.9	178.8	181.3	13.6	13.4	441.6	435.6
LSD (p=0.05)	417.5	444.4	481.8	784.3	6.5	9.0	6.5	9.0	0.5	0.6	29.4	27.4

Treatment details are given under Materials and Methods.

Table 3 Economics of wheat crop influenced by residue management and soil matric potential-based irrigation

Treatment	Cost of cultivation (₹000/ha)		Gross returns (₹000/ha)		Net returns (₹000/ha)		Benefit-cost ratio	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
T_1	45.8	45.2	150.0	161.1	104.2	116.0	2.27	2.57
T_2	39.3	38.7	124.6	135.8	85.3	97.1	2.17	2.51
T_3	43.5	42.9	155.4	167.5	111.9	124.6	2.57	2.91
T_4	35.2	34.6	158.7	170.7	123.5	136.2	3.51	3.94
T_5	35.2	34.6	148.0	159.5	112.8	124.9	3.20	3.61
T_6	39.3	38.7	132.0	144.3	92.7	105.6	2.36	2.73
T_7	28.2	27.6	110.4	118.3	82.2	90.7	2.91	3.28
T_8	37.2	36.5	154.0	165.1	116.9	128.6	3.14	3.52
T_9	29.0	28.3	125.9	135.0	96.9	106.7	3.34	3.77
LSD (p=0.05)	-	-	8.1	8.5	8.1	8.5	0.26	0.23

Treatment details are given under Materials and Methods.

Economics: The data pertaining to cost of cultivation revealed that cost of cultivation under ZT (with both paddy and wheat residue) (T_9) was ₹29,000 and 28,300/ha which was lower than under CT (without residue) (T_1) ₹45,800 and 45,200/ha during 2021–22 and 2022–23, respectively (Table 3). Lower cost of cultivation in ZT with residue retention with the help of Happy seeder was due to less number of operations and lower cost involved in sowing, residue management and other operations. These results are in agreement with the results of Kumar *et al.* (2013). Higher gross returns were obtained in ZT with residue retention (T_4) (₹158,700 and 170,700/ha) which was statistically at par with CT with residue incorporation (T_3) (₹155,400 and 167,500/ha), rotavator sown wheat (T_8) (₹154,000 and 165,100/ha) and significantly higher over CT without residue (T_1) (₹150,000 and 161,100/ha) during 2021–22 and 2022–23, respectively. Similarly, higher net returns were obtained under ZT with residue retention (T_4) (₹123,500 and 136,200/ha) over CT without residue (T_1) (₹104,200 and 116,000/ha) but at par with rotavator sown wheat (T_8) (₹116,900 and 128,600/ha) and lowest net returns were obtained in ZT after partial burning (T_7) (₹82,200 and 90,700/ha). The increase in net returns of ZT with residue retention (T_4) was 18.5 and 17.4% over CT (T_1) during 2021–22 and 2022–23, respectively. Higher yield of ZT with residue retention resulted in higher gross returns and net returns (Raghavendra *et al.* 2020). Significantly higher benefit-cost ratio was obtained in ZT with residue retention (T_4) (3.51 and 3.94) owing to higher net returns and lower cost of cultivation and at par with ZT wheat sown by happy seeder with both rice and wheat crop residue (T_9). Sandhu *et al.* (2016) and Gupta *et al.* (2022) also confirm the similar findings that ZT (happy seeder sowing) gave higher net returns and benefit-cost ratio over CT.

Principal Component Analysis (PCA) for productivity, energy efficiency and profitability: Principal component analysis was performed to understand the relationship between wheat productivity, energy parameters and economic returns under different residue management treatments (Fig. 3). The first two principal components explained 94.27% of the total variation, indicating that these two components adequately represent the variability among treatments. The PCA biplot clearly shows the association between treatments and different productivity, energy and economic parameters. Variables such as grain yield (GY), energy output, net energy and net returns are positively aligned along the positive direction of PC1, indicating a strong positive relationship among these parameters. Similarly, energy use efficiency and energy productivity also lie in the positive quadrant of the PCA plot, suggesting that treatments associated with higher productivity also tended to have improved energy efficiency. T_9 (ZT with residue of both rice and wheat) was positioned close to the vectors representing energy use efficiency and energy productivity, indicating that this treatment was strongly associated with improved energy efficiency and productivity. In contrast, treatments such as T_2 and T_6 (ZT without residue) were positioned on the negative side of PC1, showing weaker association with productivity and energy-related variables. This suggests comparatively lower yield, energy efficiency and profitability under residue removal conditions.

The results of the study demonstrated that residue management and soil moisture-based irrigation significantly influenced productivity, energetics and profitability of wheat. It can be concluded that ZT with residue of both crops (rice and wheat) + irrigation at 35±1 kPa soil matric potential helped to obtain higher grain yield, net energy, energy use efficiency and energy productivity. ZT with residue retention of paddy straw (single crop residue) + irrigation at 35±1 kPa resulted in maximum gross and net returns and benefit-cost ratio. Both, zero-tillage with double crop residue or single crop residue resulted higher benefit-cost ratio. The principal

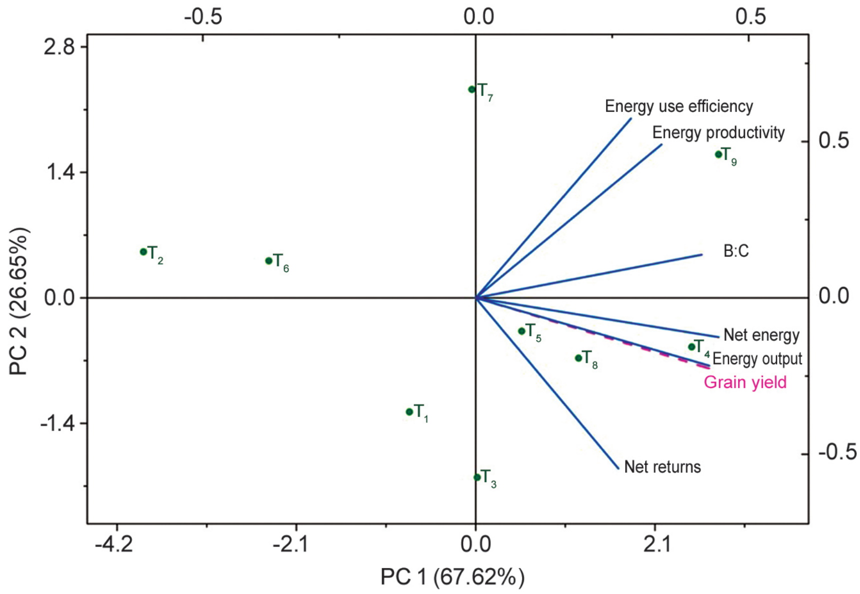

Fig. 3 Principal component analysis.
Treatment details are given under Materials and Methods.

component analysis (PCA) further supported these findings by clearly associating residue retention treatments with higher grain yield, energy efficiency and economic returns, while treatments without residue retention showed relatively weaker association with these performance indicators. The PCA biplot revealed strong positive relationships among grain yield, energy output, net energy and net returns, indicating that improvements in productivity were closely linked with better energy efficiency and profitability. Thus, under rice–wheat cropping system, ZT with either single crop residue or double crop residue with irrigation at 35±1 kPa is beneficial for obtaining higher yield and profitability but ZT with double crop residue + irrigation at 35±1 kPa is more energy efficient.

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