



RESEARCH ARTICLE

Energy dynamics of rice cultivation: Comparative analysis of establishment methods for sustainable production

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Abstract

Rice (*Oryza sativa* L.) is a staple crop critical for food and nutritional security in India, but its cultivation under traditional puddled transplanted rice is highly resource-intensive, demanding excess water, labour and energy. With growing concerns about groundwater depletion, energy scarcity and rising production costs, resource-efficient alternatives such as dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR), coupled with improved irrigation regimes, are gaining importance. The present field investigation was conducted during the kharif seasons of 2021 and 2022 at the Agricultural Research Station, Kammasagar, Telangana, to evaluate the energetics of rice under three establishment methods and three irrigation regimes [conventional submergence, saturation and alternate wetting and drying irrigation (AWDI)]. Results revealed significant differences among establishment methods for specific energy, energy productivity and energy efficiency ratio, whereas irrigation regimes showed non-significant effects. Among the establishment methods, WDSR recorded the lowest specific energy requirement (5.8 MJ kg⁻¹), the highest energy productivity (0.18 kg MJ⁻¹) and superior energy efficiency ratio (2.6), thereby outperforming transplanted rice (TPR) and DDSR. This advantage is particularly relevant under conditions of groundwater depletion and rising energy costs, as rice alone accounts for nearly 50–60 % of irrigation water withdrawals in India, while groundwater pumping contributes about 25 % of total farm energy costs. Across irrigation regimes, AWDI lowered specific energy by ~7–8 % compared to conventional submerged (CS) (5.9 vs. 6.4 MJ kg⁻¹) and improved energy productivity by ~6–12 % (0.17–0.18 vs. 0.16–0.17 kg MJ⁻¹), with efficiency ratio gains of ~4–9 % (2.4–2.6 vs. 2.3–2.4), although differences were statistically non-significant. Overall, WDSR combined with AWDI emerged as the most energy-efficient approach, ensuring sustainable resource utilization without compromising yield. Energetics evaluation thus highlights the potential of alternative establishment methods and water-saving irrigation practices to enhance energy-use efficiency, supporting eco-friendly and economically viable rice cultivation in semi-arid canal command regions.

Keywords: energy productivity; establishment methods; irrigation regimes; rice; sustainability

Introduction

Rice (*Oryza sativa* L.) is the most important staple crop, sustaining over half of the global population and in India it plays a pivotal role in ensuring food and nutritional security, particularly in semi-arid and canal command regions (1). The global importance of rice is underscored by its significant contribution to food security and agricultural livelihoods. In the 2024-25 period, China emerged as the top producer of paddy rice, yielding 145.3 million metric tonnes, closely followed by India with 145.00 million metric tonnes (2). Within India, rice cultivation spans approximately 50 million hectares, achieving an average productivity of 4.35 t ha⁻¹(3). Telangana, a key rice-producing state, demonstrated notable performance during the kharif (Vanakalam) season, with rice cultivation covering 26.3 lakh hectares. The state's paddy production reached 15.3 million metric tonnes, with an impressive productivity of 5.2 t ha⁻¹(4).

Traditionally, rice is cultivated through puddled transplanted rice (TPR), which, despite ensuring assured crop establishment and weed control, is highly resource-intensive, demanding large amounts of water, energy and labour. With increasing concerns of groundwater depletion, erratic canal supplies and rising labour costs, alternative crop establishment methods such as dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR) are being promoted as sustainable options. These methods have shown potential to reduce water demand, save energy and improve resource-use efficiency without compromising yield (5). However, some studies report a yield gap of 5–15 % under DDSR and WDSR compared to TPR, mainly due to uneven crop establishment, nutrient losses and higher weed pressure, highlighting the need for optimized management practices.

Alongside establishment methods, irrigation scheduling plays a pivotal role in enhancing water and energy productivity.

Conventional submergence (CS) consumes maximum water, while practices such as saturation and alternate wetting and drying irrigation (AWDI) are recognized for their water-saving and energy-efficient potential. Evaluating these irrigation regimes in combination with different establishment methods provides critical insights for identifying sustainable rice production practices (6). CS consumes the maximum water, while practices such as saturation and AWDI are recognized for their water-saving and energy-efficient potential. Evaluating these irrigation regimes in combination with different establishment methods provides critical insights for identifying sustainable rice production practices. However, despite the benefits of DDSR and WDSR, challenges such as higher weed pressure, uneven crop establishment and nutrient management constraints need to be addressed to fully realize their potential.

In present-day agriculture, where energy costs, water scarcity and climate variability increasingly threaten farm profitability, energetics calculations including specific energy requirement, energy productivity and energy efficiency ratio have become essential tools for farmers and policymakers. For instance, conventional TPR can consume 20–30 % more energy per hectare compared to direct-seeded methods due to intensive land preparation, transplanting and irrigation. Such assessments enable the identification of superior crop establishment-irrigation combinations that maximize output per unit of energy invested, thereby ensuring both economic viability and ecological sustainability. Hence, the present investigation was undertaken to quantitatively evaluate the energy inputs and efficiencies of different rice establishment methods under varying irrigation regimes, with the objective of recommending the most resource-efficient practices for semi-arid rice production.

Materials and Methods

Site description

The field experiment was conducted during the kharif seasons of 2021 and 2022 at the Agriculture Research Station, Kampasagar, Nalgonda district, Telangana state, India. The station is located at 16°51'9.559" N latitude and 79°28'26.581" E longitude, at an altitude of 126.93 m above mean sea level and falls under the southern Telangana agro-climatic zone (STZ).

Soil properties

The experimental field had sandy clay loam soil with a pH of 8.0 and electrical conductivity of 0.27 dS m⁻¹. The soil was low in organic carbon (0.41 %) and available nitrogen (237.7 kg ha⁻¹), high in available phosphorus (27.1 kg ha⁻¹) and moderate in available potassium (369.3 kg ha⁻¹).

Experimental design

The experiment was laid out in a split-plot design with three main

plot treatments (rice establishment methods) and three sub-plot treatments (irrigation regimes) (Table 1). Each plot was bounded by 0.2 m high earthen bunds lined with polythene sheets (extending 0.5 m below the soil surface) and separated by 1 m wide buffer zones to minimize lateral water movement and plot interference. Irrigation water was measured using a water meter.

Crop management

Rice variety KNM – 118 with around 120 days seed to seed duration was taken as a test crop. The field was ploughed twice using cultivator and rotavator to obtain fine tilth. In DDSR, rice seeds were sown using a tractor-drawn seed drill at a seed rate of 25 kg ha⁻¹ on well-moistened soil with a row-to-row spacing of 30 cm, whereas in WDSR and TPR, seeds were used at seed rates of 25 and 50 kg ha⁻¹ respectively, after soaking for 12 hr and incubating to induce sprouting. In WDSR, well-sprouted seeds were sown next day with a four-row drum seeder (30 cm row spacing). In TPR, sprouted seeds were broadcast in nursery beds and 25-day-old seedlings were transplanted at 2 seedlings per hill with 15 × 15 cm spacing.

Irrigation management

Irrigation was applied according to the respective treatments: CS, saturation and AWDI. Irrigation channels, buffer channels and bunds were provided to facilitate uniform water application (7).

Fertilizer schedule

Nutrient management followed the package of practices. For nursery beds, fertilizers were applied at 10–5–5 kg N:P₂O₅:K₂O per 1000 m². In the main field, the recommended dose of fertilizer (RDF) of 120–60–40 kg ha⁻¹ of N, P₂O₅ and K₂O was applied uniformly across all establishment methods. Phosphorus was applied as di-ammonium phosphate basally, potassium as muriate of potash in two equal splits (basal and panicle initiation) and nitrogen as urea in three equal splits. In DDSR, nitrogen was applied at basal, active tillering and panicle initiation stages, whereas in WDSR and TPR it was applied at 15–20 days after sowing, active tillering and panicle initiation stages.

Statistical analysis

The data on phenology, nutrient content and uptake studied during the investigation were statistically analysed as suggested in earlier studies (8). Wherever statistical significance was observed, critical difference (CD) at 0.05 level of probability was worked out for comparison. Non-significant comparison was indicated as 'NS'.

Energetics (input and output energy)

Energy budgeting was done by including the input energy consumed in various operations and farm input and output energy produced in terms of grain and straw yield. For calculating energy consumption or input energy, data on various agricultural inputs (fertilizers, seeds, plant protection chemicals, fuels, human labour and machinery power) and field operations were taken into account. Further in detail energy analysis was based on field

Table 1. Treatment details of establishment methods and irrigation regimes

Method / regime	Code	Treatment description
Dry direct-seeded rice	M ₁ : DDSR	Sowing with seed drill under dry soil conditions.
Wet direct-seeded rice	M ₂ : WDSR	Sowing with drum seeder under puddled conditions.
Manual transplanted rice	M ₃ : TPR	Manual transplanting of seedlings in puddled field.
Continuous submergence	I ₁ : CS	Ponded water depth of 5 ± 2 cm maintained continuously from transplanting until physiological maturity.
Saturation	I ₂ : Sat	Fields irrigated to maintain soil at or near saturation (no standing water); ponded water allowed to disappear, then irrigation applied to restore saturation; assessed visually.
Alternate wetting and drying	I ₃ : AWDI	Irrigation after ponded water disappears, soil dried until hairline surface cracks appear (3–5 days depending on weather), then water reapplied to 5 ± 2 cm depth.

operations (land preparation, sowing, interculture, harvesting and residue management) as well as on the direct (fuel and human labour) and indirect (machinery) energy sources involved in the crop production process.

The direct sources of energy are those that release the energy directly-like manpower, bullocks, stationary and mobile mechanical or electric power units, such as diesel engines, electric motor, power tiller and tractors. The indirect sources of energy are those which do not release energy directly but release it by conversion process. Some energy is invested in producing indirect sources of energy. Seeds, manures (farmyard and poultry), chemicals, fertilizers and machinery can be classified under indirect sources of energy.

For direct energy: (MJ ha⁻¹)

1. Direct energy of labour = number of labours × working hours × energy equivalent
2. Direct energy of fuel = fuel consumption × operational time × energy equivalent
3. Direct energy of electricity = units consumed × energy equivalent

(Unit consumed = pump power × 0.746 × pump efficiency × operational time)

For indirect energy: (MJ ha⁻¹)

1. Indirect energy = weight/ life × energy equivalent × operational time (tractor, machinery).
2. Indirect energy = Weight of seed × energy equivalent (seed).
3. Indirect energy = Amount used × energy equivalent (fertilizers, herbicides).

Inputs and outputs were converted from physical to energy unit measures through published conversion coefficients (Table 2). Energy equivalents for all inputs were summed to provide an estimate of total energy inputs. Energy output from the economic yield (grain) and by-product (straw) was calculated by multiplying the amount of production by its corresponding energy equivalent.

Various energy use indices were computed by using following formula (11).

$$\text{Energy use efficiency} = \frac{\text{Total output energy (MJ ha}^{-1}\text{)}}{\text{Total input energy (MJ ha}^{-1}\text{)}}$$

Energy use ratio =

$$\frac{\text{Total output energy in main product (MJ ha}^{-1}\text{)}}{\text{Total input energy (MJ ha}^{-1}\text{)}}$$

Energy productivity =

$$\frac{\text{Total main product yield (kg ha}^{-1}\text{)}}{\text{Total input energy (MJ ha}^{-1}\text{)}}$$

$$\text{Specific energy} = \frac{\text{Total input energy (MJ ha}^{-1}\text{)}}{\text{Total main product yield (MJ ha}^{-1}\text{)}}$$

Net energy gain =

$$\text{Total output energy (MJ ha}^{-1}\text{)} - \text{Total input energy (MJ ha}^{-1}\text{)}$$

Results and Discussion

Total energy input (MJ ha⁻¹)

In 2021, the highest total energy input was observed under TPR (41471 MJ ha⁻¹), followed by DDSR (37473 MJ ha⁻¹) and WDSR (37020 MJ ha⁻¹). Similarly, in 2022, TPR (40039 MJ ha⁻¹) recorded greater energy input compared to DDSR (36962 MJ ha⁻¹) and WDSR (37099 MJ ha⁻¹) (Table 3). The higher input under TPR can be attributed to greater nursery management, puddling and transplanting energy requirements. Conversely, DDSR and WDSR, being direct-seeded methods, demanded relatively lower inputs due to reduced tillage, transplanting and irrigation energy. Irrigation regimes did not exert significant influence on total energy input across both years, indicating that planting method predominantly governs energy consumption.

The variations in energy input can be attributed to differences in field preparation, sowing techniques and water management practices. These results are in line with previous findings that among different crop planting methods of rice, highest input energy were consumed in manually transplanted rice which was followed by mechanically transplanted rice and direct seeding of sprouted rice seed by drum seeder (14). The lowest energy was consumed under direct seeding of rice by zero till. TPR consumed ~9–10 % more total energy than DDSR and WDSR, primarily due to energy-intensive puddling and transplanting operations rather than irrigation pumping, which had no significant effect across treatments. Similar results were also reported (15). Significant variations in grain and straw yields brought out dissimilarity in gross input energy among the different irrigation regimes (7).

Table 2. Energy conversion factors adopted in the present study

S. No.	Energy source	Equivalent energy	Reference
1.	Adult man	1.96 MJ h ⁻¹	(9)
2.	Diesel	56.31 MJ lit ⁻¹	(9)
3.	Electricity	11.93 kWh ⁻¹	(10)
4.	Fungicide	196 MJ kg ⁻¹ a.i	(11)
5.	Herbicide	288 MJ kg ⁻¹ a.i.	(11)
6.	Insectide	237 MJ kg ⁻¹ a.i.	(11)
7.	K ₂ O	6.7 MJ kg ⁻¹	(10)
8.	Nitrogen	60.6 MJ kg ⁻¹	(10)
9.	P ₂ O ₅	11.1 MJ kg ⁻¹	(10)
10.	Paddy grain	14.70 MJ kg ⁻¹	(9)
11.	Petrol	48.23 MJ lit ⁻¹	(9)
12.	Sickle	0.03 MJ h ⁻¹	(9)
13.	Sprayer	0.5 MJ h ⁻¹	(12)
14.	Paddy straw	12.5 MJ kg ⁻¹	(9)
15.	Water	1.02 MJ m ⁻³	(11)
16.	Women	1.57 MJ h ⁻¹	(9)
17.	Tractor	68.5 MJ h ⁻¹	(13)
18.	Farm machinery (cultivator, drum seeder, rotavator)	62.7 MJ h ⁻¹	(13)

Table 3. Total energy input (MJ ha⁻¹), total energy output (MJ ha⁻¹), net energy gain (MJ ha⁻¹) and energy use efficiency of rice as influenced by different planting methods and irrigation scheduling during kharif 2021 and 2022

Treatments	Total energy input (MJ ha ⁻¹)			Total output energy (MJ ha ⁻¹)			Net energy gain (MJ ha ⁻¹)			Energy use efficiency		
	2021	2022	Mean	2021	2022	Mean	2021	2022	Mean	2021	2022	Mean
Main												
M ₁ : DDSR	37473.1	36961.7	37217.4	192736.7	199980.8	196358.7	155263.6	163019.1	159141.3	5.2	5.5	5.3
M ₂ : WDSR	37020.3	37098.9	37059.6	201159.1	209796.7	205477.9	164138.8	172697.8	168418.3	5.5	5.7	5.6
M ₃ : TPR	41471.0	40039.6	40755.3	194611.9	204946.5	199779.2	153140.8	164907.0	159023.9	4.7	5.2	4.9
SEm±	675.309	182.042	336.594	530.852	1015.105	696.993	873.693	1118.452	959.001	0.080	0.060	0.051
CD (p=0.05)	2650.766	714.563	1321.220	2083.735	3984.555	2735.880	3429.474	4390.218	3764.332	0.314	0.235	0.198
Sub												
I ₁ : CS	40564.0	40437.2	40500.6	198284.6	207150.2	202717.4	157720.5	166713.0	162216.8	5.0	5.1	5.1
I ₂ : Sat	38452.9	37434.3	37943.6	195582.8	203375.2	199479.0	157129.9	165940.9	161535.4	5.1	5.5	5.3
I ₃ : AWDI	36947.5	36228.8	36588.2	194640.3	204198.6	199419.4	157692.7	167969.8	162831.3	5.3	5.7	5.5
SEm±	1078.9	1409.6	1034.1	1952.2	1672.0	1367.8	2155.6	2229.8	1791.3	0.16	0.20	0.15
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction												
SEm±	1668.5	2001.8	1500.7	2811.5	2573.2	2056.1	3171.2	3346.0	2708.8	0.24	0.29	0.22
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction												
SEm±	1868.7	2441.5	1791.1	3381.4	2895.9	2369.1	3733.7	3862.2	3102.7	0.27	0.35	0.27
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

DDSR: dry direct seeding of rice with seed drill; CS: continuous submergence; WDSR: wet direct seeding of rice with drum-seeder; AWDI: alternate wetting and drying irrigation; TPR: manual transplanted puddled rice.

Total energy output (MJ ha⁻¹)

In 2021, WDSR recorded the maximum output energy (201159 MJ ha⁻¹), which was statistically superior to DDSR (192737 MJ ha⁻¹) and TPR (194612 MJ ha⁻¹). A similar trend was observed in 2022, where WDSR (209797 MJ ha⁻¹) outperformed both DDSR (199981 MJ ha⁻¹) and TPR (204947 MJ ha⁻¹) (Table 3). The superiority of WDSR in output energy indicates its higher productivity potential under semi-arid conditions, possibly due to better crop stand establishment and efficient utilization of resources. Irrigation schedules did not significantly alter output energy, although AWDI and saturation regimes recorded slightly higher values compared to continuous submergence, reflecting efficient water-energy conversion.

The superior effect of WDSR treatment in terms of energy output can be attributed to its higher grain and straw yields, which improved the overall energy returns. This trend was consistent across both years, reflecting the sustained efficiency of wet direct seeding over time (7). WDSR achieved the highest output energy and net energy gain (~6 % greater than TPR and DDSR), largely attributable to better root vigour, uniform plant stand and the absence of transplanting shock, which together supported higher biomass and grain yield. Irrigation schedules did not significantly alter energy indices, reflecting the relative yield stability of rice across continuous submergence, saturation and AWDI regimes under the experimental conditions. Higher gross output energy was attributed to higher grain and straw yields under alternate wetting and drying (16, 17).

Net energy gain (MJ ha⁻¹)

Net energy gain was markedly higher in WDSR during both 2021 (164139 MJ ha⁻¹) and 2022 (172698 MJ ha⁻¹), followed by DDSR (155264 and 163019 MJ ha⁻¹) and TPR (153141 and 164907 MJ ha⁻¹) (Table 3). This reinforces the energy advantage of WDSR due to reduced input costs coupled with higher grain yields. Among irrigation regimes, AWDI registered marginally greater net energy gain (157693 and 167970 MJ ha⁻¹ in 2021 and 2022 respectively), followed by saturation and continuous submergence. However, the differences were non-significant. These findings highlight that adopting WDSR along with judicious irrigation management enhances the net energy return to farmers. The results indicate

that WDSR effectively optimizes energy utilization, leading to better net energy returns. The findings align with previous research emphasizing the efficiency of direct-seeded rice in reducing energy input while maximizing energy output. Significantly higher gross energy output and net energy output were observed under puddled transplanted rice compared to direct seeded on sandy clay loam soil of New Delhi during the kharif seasons (18).

Energy use efficiency (EUE)

Energy use efficiency showed significant variation across establishment methods. In 2021, WDSR recorded the highest EUE (5.5), followed by DDSR (5.2) and TPR (4.7). A similar trend was consistent in 2022, where WDSR (5.7) surpassed DDSR (5.5) and TPR (5.2) (Table 3). The superior EUE in WDSR can be ascribed to higher yield gains relative to lower energy investments. In contrast, TPR, despite producing comparable output energy, consumed considerably higher inputs, resulting in reduced efficiency.

Irrigation regimes showed non-significant differences; however, AWDI maintained slightly higher efficiency (5.3 in 2021 and 5.7 in 2022), indicating its role in improving water and energy productivity. The improved energy efficiency in WDSR can be linked to reduced labour necessities, effective water use and improved physiological growth parameters that contributed to increased productivity. These results are in consonance with earlier findings on the advantages of direct seeding for energy efficiency (14). Similar trends were also reported under semi-arid conditions and confirmed in multi-location trials (19, 20). However, in terms of EUE, AWDI showed a competitive advantage, suggesting that controlled irrigation could optimize energy consumption without compromising productivity (7, 21).

The interaction amongst planting methods and irrigation scheduling exhibited a non-significant effect on EUE parameters. The conclusions strengthen that while discrete factors such as planting methods and irrigation schedules significantly impact energy dynamics, their collective influence remains statistically negligible. WDSR achieved the highest EUE (~14 % higher than TPR), not only because of better crop vigour and the absence of transplanting shock but also due to savings in labour and improved mechanization. The use of a drum seeder in WDSR reduced the need for nursery raising, manual uprooting and transplanting operations,

all of which are energy- and labour-intensive in TPR. By minimizing manual labour requirements and relying more on mechanized sowing, WDSR lowered specific energy input per unit area while maintaining higher output energy, thereby enhancing overall efficiency. Overall, the study highlights the potential of wet direct-seeding and strategic irrigation scheduling in enhancing energy efficiency in rice cultivation.

Specific energy (MJ kg⁻¹ ha⁻¹)

In 2021, TPR recorded the highest specific energy (6.7 MJ kg⁻¹) indicating its higher energy consumption per unit grain yield, whereas the lowest was observed under WDSR (5.9 MJ kg⁻¹). Similarly, in 2022, TPR (6.2 MJ kg⁻¹) remained inferior to WDSR (5.7 MJ kg⁻¹) with DDSR being intermediate. The mean values across years confirmed the superiority of WDSR (5.8 MJ kg⁻¹) in minimizing energy requirement compared to DDSR (6.2 MJ kg⁻¹) and TPR (6.4 MJ kg⁻¹). Among irrigation regimes, AWDI consistently recorded lower specific energy values (6.0 in 2021 and 5.7 in 2022) compared to CS (Table 4). However, the irrigation effect was statistically non-significant. This suggests that WDSR combined with AWDI was energy efficient, while TPR incurred higher energy costs. The reduced specific energy in WDSR can be attributed to the elimination of puddling and transplanting, which require significant energy inputs for labour and machinery (22). AWDI lowered specific energy by reducing pumping and water management costs, making it a viable option for energy-efficient rice cultivation (23). Statistical analysis showed that planting methods and irrigation scheduling significantly influenced specific energy ($p < 0.05$), but their interaction was not significant, indicating that their effects were independent.

Energy Productivity (MJ kg⁻¹ ha⁻¹)

Energy productivity followed a reverse trend to specific energy. In 2021, the highest productivity was recorded under WDSR (0.17 kg MJ⁻¹) and AWDI (0.17 kg MJ⁻¹), while TPR (0.15 kg MJ⁻¹) remained the least productive. The trend was similar in 2022, where WDSR and AWDI produced 0.18 kg MJ⁻¹ compared to 0.16 kg MJ⁻¹ in TPR and CS. The pooled mean across years clearly established the superiority of WDSR (0.18 kg MJ⁻¹) followed by DDSR (0.16 kg MJ⁻¹), while TPR was consistently inferior (Table 4). Irrigation regimes had no significant effect statistically; however, AWDI numerically enhanced energy productivity over CS and saturation. Thus, WDSR with AWDI

maximized energy productivity, highlighting its advantage in resource use efficiency. The superior energy productivity in WDSR can be linked to higher grain yield with lower energy inputs, confirming previous research indicating that direct-seeded rice systems enhance energy productivity (24). AWDI led to increased energy productivity due to optimized water use, minimizing water-related energy losses while maintaining yield levels (23). The statistical analysis confirmed significant effects of planting method and irrigation, but no significant interaction effect, suggesting that their influence on energy productivity operates independently.

Energy Efficiency Ratio (EER)

The energy efficiency ratio was highest under WDSR (2.5 in 2021 and 2.6 in 2022) compared to DDSR (2.3 and 2.4) and TPR (2.2 and 2.4). The pooled mean values also reinforced the superiority of WDSR (2.6) in converting input energy into output (Table 4). Among irrigation regimes, AWDI (2.4 in 2021 and 2.6 in 2022) performed better than CS and saturation, though the effect was statistically non-significant. The consistent improvement under AWDI may be attributed to optimized water and energy inputs, which increased output returns. Hence, WDSR coupled with AWDI was most efficient, whereas TPR under CS remained the least energy efficient. The higher EER in WDSR suggests that reduced tillage and direct seeding methods contribute to higher net energy gain which is in line with previous studies (22). AWDI resulted in the highest energy efficiency due to reduced water pumping and management energy costs, aligning with improvements in energy efficiency under alternate irrigation strategies (23).

The statistical analysis showed significant differences in planting methods and irrigation scheduling, but no significant interaction effect, indicating that the effects of these factors were independent. It is summarised that, among the treatment combinations, WDSR with AWDI consistently recorded higher energy productivity and energy efficiency ratio, reflecting superior conversion of input energy into economic yield. This can be attributed to reduced energy expenditure on transplanting operations, better root aeration and improved soil-water-plant interactions under AWDI, which minimized unproductive water loss. The synergy of WDSR with AWDI not only optimized resource use but also reduced methane emissions by avoiding prolonged anaerobic

Table 4. Specific energy, energy productivity and energy efficiency ratio of rice as influenced by different planting methods and irrigation scheduling during kharif 2021 and 2022

Treatments	Specific energy (MJ kg ⁻¹ ha ⁻¹)			Energy productivity (kg MJ ⁻¹ ha ⁻¹)			Energy efficiency ratio			
	Main	2021	2022	Mean	2021	2022	Mean	2021	2022	Mean
M ₁ : DDSR		6.3	6.1	6.2	0.16	0.17	0.16	2.3	2.4	2.4
M ₂ : WDSR		5.9	5.7	5.8	0.17	0.18	0.18	2.5	2.6	2.6
M ₃ : TPR		6.7	6.2	6.4	0.15	0.16	0.16	2.2	2.4	2.3
SEm±		0.100	0.089	0.084	0.002	0.003	0.002	0.023	0.044	0.027
CD ($p = 0.05$)		0.394	0.347	0.329	0.006	0.012	0.007	0.089	0.172	0.107
Sub										
I ₁ : CS		6.5	6.3	6.4	0.16	0.16	0.16	2.3	2.3	2.3
I ₂ : Saturation		6.3	6.0	6.1	0.16	0.17	0.17	2.3	2.5	2.4
I ₃ : AWDI		6.0	5.7	5.9	0.17	0.18	0.17	2.4	2.6	2.5
SEm±		0.22	0.27	0.20	0.006	0.007	0.005	0.09	0.10	0.08
CD ($p = 0.05$)		NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction										
SEm±		0.33	0.39	0.30	0.009	0.010	0.008	0.13	0.15	0.12
CD ($p = 0.05$)		NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction										
SEm±		0.38	0.46	0.35	0.010	0.012	0.009	0.15	0.18	0.14
CD ($p = 0.05$)		NS	NS	NS	NS	NS	NS	NS	NS	NS

DDSR: dry direct seeding of rice with seed drill; CS: continuous submergence; WDSR: wet direct seeding of rice with drum-seeder; AWDI: alternate wetting and drying irrigation; TPR: manual transplanted puddled rice.

conditions, thereby contributing to eco-friendly and climate-smart rice cultivation. These findings reinforce the potential of WDSR + AWDI as a sustainable practice that ensures higher energy returns while promoting environmental stewardship.

Interaction effects

The interaction effect between crop establishment methods and irrigation regimes on energy indices was found to be non-significant during both years of study. This indicates that the influence of establishment methods (DDSR, WDSR and TPR) and irrigation regimes (CS, saturation and AWDI) operated independently without mutually modifying each other's effects. In other words, the choice of establishment method primarily determined the energy inputs and outputs, while the irrigation schedule independently influenced water use and energy productivity. The absence of significant interaction suggests that the two factors contributed additively rather than synergistically, thereby highlighting the robustness of their individual effects on energy use efficiency, net energy gain and energy productivity. This also implies that farmers can optimize establishment methods and irrigation regimes separately based on resource availability and management goals without expecting combined interactive benefits on energetics.

Conclusion

The study demonstrated that WDSR consistently outperformed other establishment methods in EUE. WDSR reduced specific energy requirement by 15–18 % compared to TPR and achieved the highest energy productivity and efficiency ratio over both years. Among irrigation practices, AWDI enhanced energy utilization compared to conventional submergence and saturation, though differences were not statistically significant. TPR remained the most energy-intensive method. Overall, WDSR combined with AWDI emerged as the most energy-efficient, water-saving and economically viable approach, promoting climate-resilient rice cultivation under semi-arid conditions. Future research should examine the long-term effects on soil health, nutrient dynamics and mechanization potential to further strengthen sustainable rice production systems.

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Authors' contributions

PN conducted experiment, investigation, did formal data analysis and written the original draft. KAK and TLN participated in development of the concept, supervision and editing of the manuscript. MG provided the resources to conduct research at Kampasagar, Nalgonda District and TRP provided the editing of manuscript. KC developed the software and editing.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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