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Evaluation of energy and exergy efficiency of different rice planting methods in Khuzestan province, Iran

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Abstract

This study examines the efficiency and sustainability of various rice planting methods in Khuzestan province, focusing on their energy consumption and exergy indicators. Findings reveal notable differences in energy use and cumulative exergy among methods. Notably, the no-tillage approach has the lowest Cumulative Exergy Consumption (CExC) due to reduced diesel fuel use, while transplanting is the most energy-intensive, relying heavily on manpower and electricity for irrigation. The greatest Cumulative Energy Consumption (CEnC) arises from electricity for irrigation and chemical fertilizers. The analysis highlights fuel and electricity as primary contributors to CExC across treatments. Efficient irrigation methods yield higher Energy Return ratios and lower energy intensities, signifying better energy input efficiency. Data show varying cumulative energy demands, with direct dry seeding and no-tillage exhibiting higher energy efficiency. Cumulative Production Energy (CDP) values reveal differences in the energy performance of planting systems. The Renewability Index (RI) indicates Treatment 5 has the minimal environmental impact. Direct dry seeding on raised beds is favorable for production energy, while dry bed no-till-drill methods excel in exergy efficiency and renewability. Overall, the research underscores the need for improved irrigation management to enhance water and electricity efficiency in rice production, advocating for the adoption of more efficient irrigation techniques to boost energy usage and sustainability in rice cultivation.

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Introduction

Rice (Oryza sativa) is the hugely important staple food crop for more than half of the world's population, especially in Asia and Latin America, and it is the grain with the third highest worldwide production, after maize and wheat (Surendran et al., 2021). In many countries, rice accounts for more than 70% of human caloric intake. The great importance of rice in Asia has led to an increase in the awareness of policy makers and the general public about rice in their food program. In addition to providing food, rice has other uses, such as raw material for food processing industries like pasta and bread, raw material for pharmaceutical industries, feed for bioenergy production, and animal feed (Phitsuwan and Ratanakhanokchai, 2014). Therefore, the forecast indicates a significant increase in rice demand in the future (Chaudhary et al., 2017). Currently, the largest amount and area under rice cultivation belongs to India and China. In Iran, rice with 800 thousand hectares cultivated area and average yield of 4.5 t ha^{-1}, is one of the most important food crops after wheat. However, the demand and amount of rice production in Iran is not in balance, and its higher demand has made Iran the second rice importer country after Philippine with amount of 1.7 Mt. Khuzestan province with more than 12% share of total rice crop production is among the main rice production areas in Iran. In order to create a balance between the consumption and production of rice in the country, planning and efforts should be made to increase production at the same time as managing its consumption (Ministry of Jihad-e-Agriculture of Iran, 2022).

Rice production is associated with many environmental issues, such as heavy consumption of chemical entities and non-renewable energy, environmental pollution, greenhouse gas emissions, and human health (Bartzas and Komnitsas, 2018; Demircan et al., 2006; Esmaeilpour-Troujeni et al., 2021). There are different ways to cultivate rice. Studies show that choosing the right method of rice cultivation, reduces the consumption of inputs, energy and the harmful effects of the environment. Rice cultivation is well-suited to countries and regions with low labor costs and high rainfall, as it is labor-intensive to cultivate and requires plenty of water. Rice also can be grown practically anywhere (under various soil conditions (salt, alkali, peat) and different water and temperature regimes), even on a steep hill or mountain (Cherati et al., 2011; Pishgar-Komleh et al., 2011). The common method of rice cultivation in Iran is transplanting with permanent flood irrigation. In this method, in addition to consuming a lot of water, tillage and land preparation are done with high intensity and require the consumption of non-renewable energy sources. Irrigation activity, especially for rice, is the main energy consumer in agricultural production systems (Pishgar-Komleh et al., 2011). Direct seeding method with intermittent irrigation instead of permanent flooding is a solution that can reduce water consumption in rice production. Although it has failed due to limitations and specific problems in some areas, research has shown that it is generally possible to reduce water consumption in rice cultivation by direct seeding method. In addition, the use of reduced and no tillage systems instead of conventional tillage, significantly reduce the energy consumption of fossil fuels for running agricultural machines, which is one of the main energies consumed in the production of agricultural products (Esmaeilpour-Troujeni et al., 2021; A. Kaab et al., 2019; Ordikhani et al., 2021).

In recent years, rice cultivation is carried out as direct seeding in some areas of Iran, and it has been supported by the Ministry of Agriculture due to the lake of water. In direct seeding systems, as compared to transplanting which required huge amount of water for seedling production, puddling, and 15 days continuous irrigation after transplanting, about 25-30% of the water used can be saved (Mahajan et al., 2013). In many literatures and studies mention potential of direct seeded rice, such as leads to less labor requirement and facilitates interculture and harvesting operations, better mechanical weed control, low fertilizers and chemicals consumption, saving production costs, increasing economic profitability (LÜ et al., 2010), shortening the plant growth period (Farooq et al., 2006), and reduces water consumption and environmental pollution (Nabavi-Pelesaraei et al., 2019). The only challenge confronted from using this method is reported to be the weed pressure. But, if weeds are well managed, direct seeding of rice gives comparable yield to transplanted rice (Akhgari and Kaviani, 2011). Through long term experiment proved that direct seeding could be a potential substitute for transplanted rice if proper and weed management techniques were followed. In addition to direct seeding, the effort is made by policy makers in Iran to extend the use of conservation tillage methods such as no-tillage for rice production systems. However, there are few studies that have examined and evaluated different rice cultivation methods in Iran, especially in terms of input efficiency and sustainability. One of the effective ways to achieve sustainable production, is the efficient use of energy, which leads to preserving nonrenewable resources, reducing adverse environmental effects, and production (Demircan et al., 2006).

Due to development of agricultural mechanization and the extensive use of chemical inputs especially, fertilizers and pesticides to produce agricultural products, it has led to a sharp increase in energy consumption, decrease in the production efficiency of agricultural systems, creating severe environmental problems and a sustainable decrease in production (Nemecek et al., 2011; Nikkhah et al., 2015a). Many researchers indicate that inefficient use of energy for producing higher yield can cause various environmental impacts (Bartzas and Komnitsas, 2018). Despite less inputs of and non-renewable energy consumption and more sustainability, traditional systems have low performance and cannot meet the food demand of the world’s growing population. Therefore, the use of energy-intensive systems with higher performance is inevitable (Kizilaslan, 2009). One of the most important ways to optimize energy consumption in agricultural systems is to increase production efficiency by carefully examining and improving the consumption of inputs in the production process (Esmaeilpour-Troujeni et al., 2021). In this regard, and to provide sufficient information about the quality of energy use and the losses of input energies, exergy analysis method was presented (Özilgen and Sorgüven, 2011; Sartor and Dewallef, 2017). Exergy as an indicator of thermodynamic balance is equal to the maximum useful work that can be obtained from a system in the process of thermodynamic balance (Juárez-Hernández et al., 2019). Exergy provides a single scale of various forms of energy and material carriers according to the second law of thermodynamics (Xiao et al., 2019). Exergy analysis can be a powerful tool to analyze and identify inefficiencies in the production process (Jawad et al., 2018). The cumulative exergy consumption (CExC) approach, which includes the total exergy of agricultural inputs, is a suitable method for evaluating energy consumption and its efficiency in the agricultural systems (Asakereh et al., 2023; Noorani et al., 2023; Yildizhan and Taki, 2018). In this regard, in recent years, various studies have been conducted in this field. For example, (Özilgen and Sorgüven, 2011) compared the sunflower and soybean production in Turkey. They reported that diesel fuel and chemical fertilizers had the largest share in CExC and CCO_2E, respectively and recommended soil analysis to reduce the use of chemical fertilizers. The results of this study indicated that by replacing diesel fuel with renewable energy sources, the total amount of CExC significantly reduced. In evaluating the production of greenhouse cucumber, Taki and Yildizhan (2018) also reported that by replacing nonrenewable energies by renewable ones, the cumulative degree of perfection (CDP) rose from 0.2 to 0.47 and the RI inclined from − 3.32 to − 1.09. This analysis has been also used to calculate the overall exergy efficiency of the Malaysian agricultural sector (Ahamed et al., 2011), tomato (Yildizhan and Taki, 2018), canola (Amiri et al., 2020), Sugarcane and sugar beet (Asakereh et al., 2023) and rice production (Taheri-Rad et al., 2017).

Exergy analysis will pave the way for further improvement in true efficiency by reducing thermodynamic losses via applying feasible technologies. Policy makers can compare their country’s energy use and exergy efficiencies with other countries and take measures to improve the efficiencies of the machines used in this sector. These comparisons will serve as benchmark with other studies as well (Dendup and Chhogyel, 2018). The paper evaluates environmental, economic, and energy aspects of paddy production systems in Iran—conventional, low external input, and organic. Findings show that diesel fuel and nitrogen significantly impact environmental damage, with organic systems achieving the lowest life cycle cost and highest net profit. Organic systems offer long-term sustainability advantages (Saber et al., 2020). The research analyzes four rice straw valorization alternatives for energy in Cuba using exergy analysis. Alternative 4 achieves 66.6% exergetic efficiency, increasing exergy flow from 13.2% to 21.9%, reducing greenhouse gas emissions, and attaining a sustainability index of 2.994. A new indicator, CExCGEI, is proposed to assess accumulated exergy destruction in greenhouse gases (Saber et al., 2020).

The novelty of this research lies in its comprehensive evaluation of multiple rice planting methods in Khuzestan province through the lens of energy and exergy analysis, emphasizing both efficiency and environmental sustainability. Specifically, it offers new insights by comparing the energy consumption and exergy indicators across diverse planting techniques, including no-tillage, transplanting, direct dry seeding, and dry bed no-till-drill. It identifies that no-tillage methods significantly reduce cumulative exergy consumption due to lower diesel usage, a nuanced finding that emphasizes sustainability. The study highlights the dominant role of irrigation electricity and chemical fertilizers in overall energy demands, underscoring the critical need for efficient water management. It demonstrates that certain methods, like direct dry seeding on raised beds and no-till-drill techniques, outperform others in energy efficiency and renewability, thus guiding sustainable practices. Additionally, it introduces the use of the Renewability Index (RI) in this context to assess environmental impacts, with Treatment 5 showing a minimal ecological footprint. The research emphasizes the importance of optimizing irrigation practices to improve overall energy efficiency and sustainability in rice production. This integrated approach, focusing on both energy and exergy metrics along with renewability assessment, adds a valuable dimension to existing studies by promoting sustainable rice cultivation strategies tailored to environmental and resource conservation priorities.

Methodology

Location of the studied area

This research was carried out in the Khuzestan province, situated in the southwest of Iran at coordinates 29°57'-33°04' N and 47°38'-50°32' E. The region is influenced by five significant river flows—Karkheh, Dez, Karun, Maroon, and Zohreh—all regulated by reservoir dams. Khuzestan experiences varied climates, with most areas being arid and an average annual precipitation of 266 mm. The primary period of rainfall occurs towards the end of autumn and winter, while summer temperatures soar above 50°C in many parts (Masoudi and Elhaeesahar, 2016). Holding 33% of the country's surface water and 1.5 million hectares of suitable agricultural land, this province leads in agricultural production in Iran. Khuzestan boasts the cultivation of 138 crops and an annual output of 16.2 million tons of agricultural products, livestock, poultry, and fisheries. Rice farming in Khuzestan has deep cultural roots, with fluctuations in cultivation area and yield per unit area across different crop seasons based on available irrigation water. Presently, the rice cultivation area in Khuzestan ranges from 80,000 to 120,000 hectares, with an average yield of 2.4 tons per hectare (Ministry of Jihad-e-Agriculture of Iran, 2022).

Calculation of cumulative energy consumption and exergy

In this study, the efficiency of exergy and energy consumption in achieving sustainability was investigated by comparing five different rice planting methods using the cumulative exergy consumption (CExC) and cumulative energy (ECnC) approaches. Data were collected from experimental plots at a research farm with a completely randomized block design in three replications. The compared methods included direct seeding by seed drill in flat bed (T1), direct seeding by seed drill on raised bed (T2), direct seeding by no-till-drill in flat bed (T3), direct seeding by hill planter on raised bed (T4), and transplanting in paddled bed (T5). Seed bed preparation involved chisel plowing and disc harrowing to a depth of 30 cm in all treatments except T4, where in addition to chiseling and discing, paddling was done manually before transplanting the seedlings from the nursery.

Total direct and indirect inputs from land preparation to harvesting stages were measured for all planting methods, considering energy sources used directly and indirectly for rice production. Outputs included paddy grains and harvested straw. Special equivalents for CEnC and CExC were used to calculate energy consumption and cumulative exergy, categorizing inputs into renewable/non-renewable and direct/indirect sources. Non-renewable CEnC and CExC involved agricultural machinery, diesel fuel, chemical fertilizers, biocides, and electricity. Indirect inputs like farm machinery, fertilizers, chemicals, and seeds accounted for total energy and exergy consumed in their production processes.

Cumulative energy and exergy of farm machinery, fertilizers, chemicals, and seeds were calculated based on their production energy and exergy, expressed per unit (MJ ha^{-1} or MJ kg^{-1}). The study considered cumulative direct energy and exergy sources like diesel fuel and electricity, calculated using the full tank method for fuel measurement and an equation (1) for irrigation electrical energy calculation (Khanali et al., 2025).

$$DE = \frac{\gamma g H Q}{\varepsilon_q} \quad (1)$$

Where DE is direct energy (J ha^{-1}), γ is density of water (1000 kg m^{-3}), g is acceleration of gravity (m s^{-2}), Q is total water consumed by the crop (m^3 ha^{-1}), H is the pump dynamic head, εq is the total efficiency of energy and power conversion, which is usually considered equal to 0.2-0.18 for electric pumps.

Table 1. Specific of CEnC and CExC of rice inputs.

Items	CEnC	CExC
Diesel fuel	56.30 MJ lit^{-1} (Erdal et al., 2007)	53.20 (Esmaeilpour-Troujeni et al., 2021)
Electricity	12 MJ kWh^{-1} (Kaab et al., 2019)	4.17 MJ kWh^{-1} (Amiri et al., 2020)
Nitrogen (N)	76.14 MJ kg^{-1} (Yilmaz et al., 2005)	32.7 MJ kg^{-1} (Amiri et al., 2020)
Phosphate(P_2O_5)	12.4 MJ kg^{-1} (Yilmaz et al., 2005)	7.52 MJ kg^{-1} (Amiri et al., 2020)
Potassium (K_2O)	11.15 (Ordikhani et al., 2021)	4.7 MJ kg^{-1} (Kaab et al., 2019b)
Herbicides	120 MJ lit^{-1} (Beheshti Tabar et al., 2010)	32.7 MJ kg^{-1} (Esmaeilpour-Troujeni et al., 2021)
Pesticides	363.6 MJ lit^{-1} (Kaab et al., 2024)	7.52 MJ kg^{-1} (Yildizhan and Taki, 2018)
Fungicides	198 MJ lit^{-1} (Yildizhan and Taki, 2018)	4.56 MJ kg^{-1} (Yildizhan and Taki, 2018)
Machinery	9 MJ kg^{-1} $year^{-1}$ (Taherzadeh-Shalmaei et al., 2023)	7.1 MJ kg^{-1} (Michalakakis et al., 2021)
Irrigation	0.00102 MJ kg^{-1} (Yildizhan and Taki, 2018)	0.00425 MJ kg^{-1} (Amiri et al., 2020)
Human labor	1.96 MJ h^{-1} (Kaab et al., 2019a)	-
Rice seed	100 MJ kg^{-1} (Kitani, 1999)	21.7 MJ kg^{-1} (Juárez-Hernández et al., 2019)

A stop watch was used to record the machine operation useful and non-useful times. Then, the effective field capacity of each rice planting method was obtained with the help of equations 2 and 3.

$$C_n = \frac{Swe}{10} \quad (2)$$

$$C_a = \frac{1}{\sum_{i=1}^{n} \frac{1}{C_{ni}}} \quad (3)$$

Where C_n is effective field capacity of a machine operation (ha h^{-1}), C_a is total effective field capacity of the machines involved in a crop production system (ha h^{-1}), S is machine forward speed (km h^{-1}), W is machine working width (m), and e is machine efficiency.

For yield analysis, a crop cut was conducted on an area measuring 6×15 m^2. Calculation of grain yield was done following the standard formula and grain yield adjusted to 14% moisture level as given below:

$$grain\ yield\ (kg\ ha^{-1}) = \frac{plot\ yield\ (kg) \times MC\ adj \times 10{,}000}{plot\ size\ (m^2)} \quad (4)$$

Where MC adj $MC\ adj = \frac{100-MC}{100-86}$, and MC is the grain moisture at harvest.

Energy and exergy indicators

In crop production systems, the ratio of output energy to input energy is used as an important index to measure energy efficiency and calculated by equation 5 (Yuan et al., 2018). A value greater than one for this index indicates that the output energy is greater than the cumulative energy consumption in a given system (Ordikhani et al., 2021). So, a higher index for a rice production system implies a higher efficiency of energy use in that system. Another important indicator that evaluates CEnC is energy productivity, which shows the amount of product production per unit of CEnC is expressed in terms of kg MJ^{-1}, which is calculated from equation 6. Cumulative net energy index, which is obtained from equation 7, shows the difference between the energy produced and the cumulative energy consumed. A positive value for this index indicates that the production energy is more than the cumulative consumption energy in the production system and the system has produced more energy than the cumulative consumption energy (Asakereh et al., 2023).

$$Energy\ ratio\ (ER) = \frac{Output\ energy\ (MJ/ha)}{\text{CEnC}\ (MJ/ha)} \quad (5)$$

$$Energy\ productivity\ (EP) = \frac{Yield\ (kg/ha)}{\text{CEnC}\ (MJ/ha)} \quad (6)$$

$$\text{Cumulative net energy gain}(CNEnG) = Output\ energy\ \text{CEnC}\ (MJ/ha) - CEnC\text{CEnC}\ (MJ/ha) \quad (7)$$

To evaluate the sustainability of crop production, this study employed three measures, including Cumulative Degree of perfection (CDP), Exergy Intensity (ExI) and Renewability Index (RI) (Ahamed et al., 2011; Esmaeilpour-Troujeni et al., 2021). CDP (Equation 8) is calculated on the basis of the exergy rate resultant from the chemical crop structure and the cumulative exergy rate consumed in the crop production process. CDP refers to the exergy use efficiency in a production system. The indicator determines how much exergy is gained from the final product per unit of exergy consumed in the production process. The higher values of the indicator claim the higher values of exergy use efficiency in the system (Noorani et al., 2023). In this research, since the rice production system was considered as a closed system, only the rates of controllable inputs were needed in CDP computation, and the energies of the soil and sun were neglected. According to Equation (9), the CDP index is equivalent to the ratio of the chemical crop exergy to the total exergy consumed in the production of that crop (Rasoolizadeh et al., 2022). ExI, which shows the amount of CExC per unit of produced crop, is also calculated from Equation 8 (Juárez-Hernández et al., 2019).

$$\text{CDP} = \frac{\text{Exergy in products}\ ((\text{m} \times \text{b})_{\text{products}})}{\sum(m \times CExC)_{raw\ materials} + \sum(m \times CExC)_{fuels}} \quad (8)$$

$$Exergy\ intensity(ExI) = \frac{\text{CExC}\ (MJha^{-1})}{Yield\ (kgha^{-1})} \quad (9)$$

where m and b represent mass and chemical exergy respectively.

The other measured factor for examining the sustainability of rice production systems was RI, which reflected the ratio of the rate of consumed renewable energies to the total energy generated by the final product, calculated according to Equation (10). In this relation, E_{ch} equals the total chemical exergy of the final product, and W_r equals the entire renewable energy resources consumed in the crop production process (Rasoolizadeh et al., 2022). In fact, RI donates how much exergy is consumed from renewable energy sources per unit of gained exergy from the final product (Kaab et al., 2025). Closer values to one refer to the more environmentally-friendly process. The renewability rate of the production process is displayed by RI in four general conditions. If the RI value equals 1, it will indicate the complete renewability of the production process. In this condition, the consumption of renewable energies is zeroed. If the RI value ranges from 0 to 1, it will depict the relative renewability of the production process. Accordingly, the consumption of renewable energies does not approximate zero; however, it is smaller than the total chemical exergy of the final product. In case the RI value equals zero, it will indicate the equality of the consumed and generated energy rates in the system. However, if the RI value becomes negative, the non-renewability of the production process will be implied. In this condition, the rates of the consumed renewable energies exceed even the total chemical exergy of the final product (Troujeni et al., 2018).

$$RI = \frac{E_{ch} - W_r}{E_{ch}} \quad (10)$$

Cumulative net exergy gain index (CNExG) in $MJha^{-1}$ of the rice planting methods was calculated by equation 11.

$$Cumulative\ net\ exergy\ gain(CNExG) = Output\ exergy\ \mathrm{CEnC} - \mathrm{CExC} \quad (11)$$

Results and discussion

Analysis of variance

The variance analysis (ANOVA) of the cumulative consumption of energy and exergy of inputs in different rice cultivation methods is given in Table 2. Because the required chemical fertilizers were determined based on the soil test, they were used the same for all treatments. Chemical pesticides, including herbicides and fungicides, were also applied similarly in all treatments. Therefore, the energy consumption and cumulative exergy of these two inputs were the same for all treatments. But the effect of rice planting methods on the energy consumption and cumulative exergy of other inputs (fuel, electricity, irrigation, machinery, manpower and seeds) and the total energy consumption and cumulative exergy was significant at P 0.01 level of significance.

Table 2. Variance analysis of the effect of different rice planting methods on the cumulative energy consumption of inputs

		CExC			CEnC		
Treatments	df	Mean Square	F	Sig	Mean Square	F	Sig
Fuel	4	2329888.60	221.10**	0.00	2712585.80	221.40**	0.00
Labor	4	-	-	-	57271.80	396.10**	0.00
Machinery	4	3570529.70	246.60**	0.00	173081.50	260.10**	0.00
Electricity	4	104703.60	260.10**	0.00	29568074.10	246.60**	0.00
Irrigation	4	142821.20	246.60**	0.00	1182722.90	246.60**	0.00
Seed	4	1594586.40	206.20**	0.00	985370.40	198.60**	0.00
Total	4	5668712.50	151.90**	0.00	42715622.50	207.40**	0.00

** Significant at the 1% level

Comparing different rice cultivation systems reveals that direct seeding typically consumes less energy than transplanting, as noted by (Cherati et al., 2011). Chaudhary et al. (2017) found that manual transplanting in India was the most energy-intensive method among those they examined. In a study comparing various rice production scenarios in the northern region of Iran, it was observed that the highest energy consumption occurred in the scenario involving the use of well water with a high-yielding rice variety and full mechanized operation. Conversely, the scenario utilizing river water for low-yielding rice variety production in a conventional method had the lowest energy requirement (Jamali et al., 2021). A comparison of cumulative energy consumption and exergy of inputs across different rice cultivation methods was conducted using Duncan's test at a significance level of 0.05, as indicated in Table 3. The results show that the lowest energy consumption and fuel cumulative exergy were significantly associated with the no-till-drill treatment. This method involves planting seeds directly into unprepared soil, thereby reducing the need for heavy tillage machinery and consequent fuel consumption. Studies have demonstrated that the no-till-drill approach leads to notable fuel savings compared to conventional tillage practices by minimizing the use of machinery and agricultural operations (Filipovic et al., 2006; Ordikhani et al., 2021). The application of no-till-drill cultivation has been shown to decrease energy usage in wheat, corn, and soybean production when compared to conventional tillage methods (Rusu, 2014). Additionally, it reduces both time and energy requirements relative to traditional methods (Khaledian et al., 2012).

Table 3. Comparison of average energy consumption and cumulative exergy input in different rice cultivation methods with Duncan's test at a significance level of 5%.

	CExC					CEnC				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
Fuel	3983.70^{c}	3981.80^{c}	4622.10^{d}	4283.7^{b}	2076.30^{a}	4298.50^{c}	4296.40^{c}	4622.10^{d}	4058.50^{b}	2240.40^{a}
Labor	-	-	-	-	-	213.20^{b}	164.40^{a}	164.00^{a}	490.80^{c}	201.50^{b}
Electricity	3546.40^{b}	2735.40^{a}	2727.80^{a}	5397.60^{c}	3450.80^{b}	10205.50^{b}	7849.70^{a}	7849.70^{a}	15532.60^{c}	9930.40^{b}
Machinery	793.60^{c}	780.90^{bc}	878.70^{d}	753.20^{b}	397.20^{a}	1020.30^{c}	1004.10^{bc}	1129.70^{d}	968.40^{b}	510.70^{a}
Fertilizers	2425.20	2425.20	2425.20	2425.20	2425.20	2422.20	5422.20	5422.20	5422.20	5422.20
Irrigation	709.30^{b}	547.10^{a}	545.60^{a}	1079.50^{c}	690.20^{b}	2041.10^{b}	1574.30^{a}	1569.90^{a}	3106.50^{c}	1986.10^{b}
Biocides	69.96	69.96	69.96	69.96	69.96	603.40^{a}	603.40^{a}	603.40^{a}	603.40^{a}	603.40^{a}
Seed	1440.00^{c}	1440.00^{c}	288.00^{a}	576.00^{b}	1440.00^{c}	1470.00^{c}	1470.00^{c}	294.00^{a}	588.00^{b}	1470.00^{c}
Total	12968.20^{c}	11980.40^{b}	11218.80^{a}	14062.80^{d}	10549.70^{a}	25274.10^{b}	22406.50^{a}	21655.00^{a}	30770.50^{c}	22364.70^{a}

Figure 1 (a) illustrates the impact of tillage and planting operations on the overall cumulative fuel exergy consumption across various treatments. In treatments T1 to T4, approximately 65%, 67%, 69%, and 63% of the total cumulative fuel energy consumption can be attributed to plowing and planting operations, respectively. In contrast, the no-tillage system accounts for around 32% of this total, indicating significant fuel energy savings. The adoption of reduced tillage practices in methods T1 to T4 leads to a lesser degree of soil mechanical disturbance and reduced fuel consumption compared to traditional tillage methods. Several studies, such as those by Rusu (2014) and Sørensen et al. (2014), have demonstrated that transitioning from conventional tillage to reduced or minimum tillage techniques decreases the energy demand. Sørensen and Nielsen (2005) have noted that minimum and no tillage approaches can lower energy consumption by 18-53% and 75-83%, respectively, compared to conventional tillage. The findings reveal that Treatment 3 (T3) exhibits the highest fuel consumption primarily due to the increased use of machinery in plowing and planting activities. Conversely, Treatment 4 (T4), where paddling and transplanting are carried out manually by labor, shows lower energy and exergy consumption compared to Treatments 1 and 2, which are more mechanized. Statistical analysis and mean comparisons underscore significant disparities in energy consumption and cumulative machine exergy among the various treatments. Treatment 5 (T5) stands out for having the lowest cumulative energy consumption, approximately half that of the other treatments. This reduction in energy consumption and exergy usage in Treatment 5 is primarily attributed to the utilization of a no-till-drill machine for rice planting.

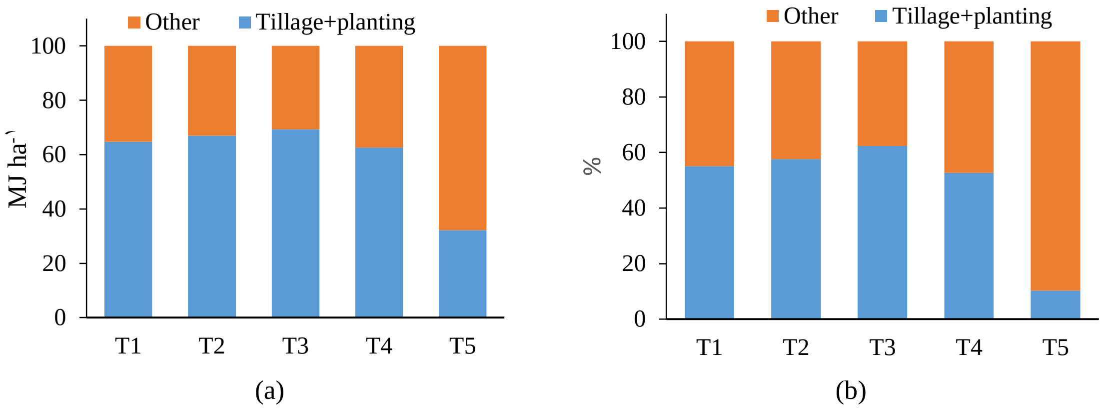

Figure 1. The contribution of tillage and planting to the cumulative exergy consumption of fuel (a), the contribution of tillage and planting to the cumulative exergy consumption of machines (b)

Analyzing various operations reveals that tillage and planting activities are the primary consumers of energy and exergy in machinery. Figure 1 (b) illustrates that in T1 to T4, 55.11%, 57.67%, 62.38%, and 52.71% of the cumulative exergy of machines were utilized in tillage and planting operations, respectively. Conversely, in T5, tillage and planting operations only accounted for 10.32% of the total machinery exergy, indicating that the adoption of a no-till method can significantly reduce machinery exergy consumption. Electricity was employed for pumping rice irrigation water, a process directly linked to irrigation water consumption and the dynamic head of the pumping system. The extent of irrigation water pumped was uniform across all treatments due to the utilization of a common water source. However, water consumption varied significantly based on the irrigation system employed. T2 and T3 treatments, utilizing furrow irrigation, required the least water, while T1 and T5, utilizing the flooding method, exhibited the highest water consumption. Notably, furrow irrigation has the potential to reduce water consumption by 30% compared to flood irrigation. Treatment T4, with continuous irrigation, experienced a notable surge in water and energy consumption, recording the highest energy consumption at 15.53 GJ and cumulative exergy at 53.97 GJ. The utilization of electricity, as shown in various studies, is substantially higher in rice transplanting with continuous flood irrigation compared to direct dry seeding systems. Water losses in flooded rice transplanting systems result from surface evaporation, paddling, and infiltration, leading to increased pumping duration and electricity consumption. Notably, the adoption of rice direct dry seeding methods can reduce irrigation water usage by up to 45%, consequently decreasing overall energy consumption. Factors such as fuel input and indirect energy and exergy due to irrigation infrastructure play vital roles in total energy consumption for rice production. The choice of irrigation method significantly impacts energy efficiency, with furrow irrigation methods exhibiting lower cumulative exergy consumption, while treatments like T5, utilizing permanent flooding, show higher indirect exergy consumption. Human labor energy consumption varied across treatments, with treatment T4 displaying the highest consumption at 334 MJ ha^{-1}, attributed to manual activities like paddling and transplanting. Labor-intensive operations like irrigation significantly contribute to overall human energy consumption in all treatments. Implementing modern irrigation systems and mechanized equipment can help reduce labor requirements in rice production. The study analyzes exergy flow in paddy rice production by evaluating nine varieties in Italy. Results show cumulative exergy consumption ranges from 16.09 to 25.80 GJ ha^{-1}, with fossil fuels and fertilizers being the main contributors. The Luna variety proved most exergy-efficient (Nikkhah et al., 2021).

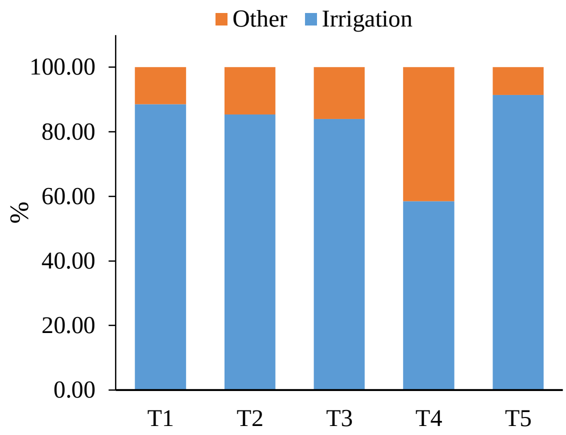

Figure 2. Irrigation operation share of total labor consumption.

As previously mentioned, in T2 and T3, the adoption of furrow irrigation led to reductions in both water and electricity consumption. As a result, the proportions of total cumulative energy and total cumulative exergy consumption were 35.13% and 36.25%, and 22.83% and 24.31% lower than those of other treatments, respectively. On the other hand, in T1 and T5, which utilized flood irrigation, 40.38% and 44.40% of their total cumulative energy consumption, and 27.35% and 32.71% of their total cumulative exergy consumption were attributed to electricity, respectively. Across all treatments, chemical fertilizers and fuel were identified as the second and third major inputs contributing to cumulative energy consumption. However, in terms of cumulative exergy consumption, chemical fertilizers ranked third in treatments T1 to T4 and second in treatment T5. Previous studies have also highlighted electricity, diesel fuel, and chemical fertilizers as primary energy and exergy inputs in agricultural product production (Banaeian and Zangeneh, 2011; Pishgar-Komleh et al., 2012; Yousefi et al., 2014). The utilization of chemical fertilizers stands out as a key method to enhance agricultural productivity. Among these fertilizers, nitrogen fertilizer accounts for the majority of the Cumulative Exergy Consumption (CExC) of fertilizers, representing approximately 76.05% of the total CExC. Nitrogen, an essential element for plant growth and development, plays a crucial role in various biological processes such as protein synthesis, nucleic acid formation, and other biological compound production. Notably, in a relevant study, nitrogen fertilizer emerged as the primary exergy component among chemical fertilizers in rice production (Nikkhah et al., 2015b). Energy efficiency in agriculture is vital for sustainable production. This study uses life cycle assessment (LCA) to analyze paddy production in Iran's Khuzestan province, comparing three cultivation methods: PTS, PFS, and PDS. PTS had the highest energy input (79069.80 MJ ha^{-1}) and output (105400 MJ ha^{-1}), while PDS showed the lowest energy production. Diesel fuel and nitrogen fertilizers were primary energy consumers. The benefit-cost ratio for PTS was highest (6.60), indicating significant profitability. Environmental impacts varied, with resource depletion highest in PDS, followed by PFS and PTS (Molaee Jafrodi et al., 2022).

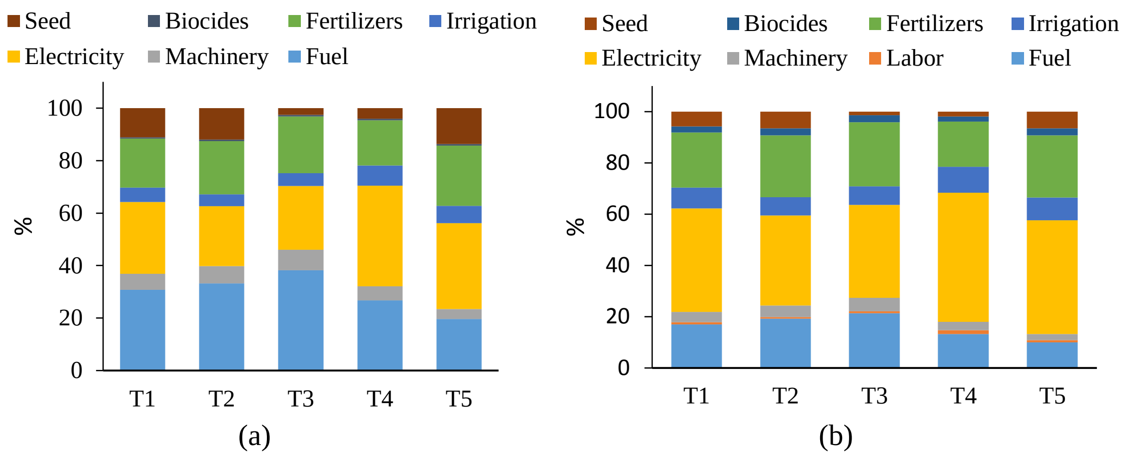

Figure 3. The share of inputs from the total cumulative exergy consumption in rice production (a), the share of inputs from the total cumulative energy consumption in rice production (b)

Indexes

The analysis of variance (ANOVA) indicated that the planting method did not have a significant impact on the final yield, energy, and exergy of the rice produced at a significance level of P0.001 (refer to Table 4). The average energy and exergy produced under different treatments are illustrated in Figure 4. The average yield of rice varied among treatments, from 3435 to 3742 kg ha^{-1} in T2 and T4, respectively, with corresponding energy outputs ranging from 50.49 to 55.01 GJ ha^{-1} and chemical exergy from 49.46 to 53.88 GJ ha^{-1}. In the variance analysis, it was observed that the effect of the rice planting method on Energy Return (ER) was statistically significant at P0.001. The ER values across all treatments were greater than 1, ranging from 1.65 to 2.47, indicating that the energy produced in rice cultivation exceeded the Cumulative Energy of controllable inputs (CEnC) (Figure 5). Since only commercial inputs were considered in the energy calculations, an ER above 1 is feasible. A higher ER signifies a more efficient utilization of energy inputs within the production system, as noted by previous studies (Asl and Asakereh, 2023; Yuan et al., 2018). The research prioritized paddy cultivation areas in Iran—Mazandaran, Fars, and Khuzestan—based on sustainability criteria using the Best-Worst Method (BWM). Evaluating eco-efficiency, Mazandaran emerged as the most sustainable region, followed by Fars and Khuzestan, with final indices of 0.98, 0.93, and 0.85, respectively (Alijani et al., 2025).

Table 4. Variance analysis of the effect of rice production methods on performance indicators, energy and exergy

Treatments	df	Mean Square	F	Sig
Yield	4	37838.90	1.091	0.412
Energyratio	4	0.354	21.891	0.00
EnI	4	4.659	24.448	0.00
CNEnG	4	78377797.174	9.420	0.002
CDP	4	0.892	16.124	0.00
ExI	4	0.651	14.96	0.00
RI	4	0.004	22.096	0.00
CNExG		20269373.656	2.734	0.09

Based on the comparison of ER average using Duncan's test, T2, T3 and T5 with the highest amount of ER (2.46, 2.47 and 2.34 respectively) were statistically placed in the same group, but their difference with T1 and T4 was significant. Because of using direct seeding system with furrow irrigation method in T2 and T3, which reduced electricity and man power consumption, as well as no-till-drill in T5, which reduced the need for farm equipment and diesel fuel, led to an increase in their input energy productivity. Due to higher CEnC and lower yield, the minimum ER with 1.65 belonged to T4. ER of T1 was equal to 2.09, which significantly differed with T4. This shows that the use of direct seeding method, even in the form of flood irrigation, is more efficient than the traditional transplanting method. ER of rice produced in direct seeding and transplanting systems in Ramhormoz region of Iran is reported to be 2.31 and 2.84, respectively (Cherati et al., 2011). In a similar study on rice production systems, (Chaudhary et al., 2017) indicated that ER of direct seeding is more than transplanting method. In their study, the ER for all cultivation methods was expressed between 1.98 and 2.79. In India, the ER in transplanting and direct seeding of rice production systems has calculated to be 4.4 and 7.3 respectively (Basavalingaiah et al., 2020). The ER of rice production has reported to be 6.58 to 7.62 in Nigeria (Kosemani and Bamgboye, 2020), 1.83 in Mazandaran province of Iran (Firouzi et al., 2016), and 1.33 to 2.81 in northern of Iran (Jamali et al., 2021).

The obtained net cumulative energy ranged from 19.88 to 32.60 GJha^{-1}, which indicates the existence of a positive energy production balance in the studied rice planting systems. From Table 4, it can be seen that the rice planting method has a significant effect on the net cumulative energy at P0.001. According to Duncan's test, the net cumulative energy obtained in T4 is significantly lower than other treatments. The value of this index with 32.60 GJha^{-1} was the highest in P2, which had not significant difference with the rest of treatments, i.e. T1, T2, T3 and T5. The average of energy intensity, which indicates the amount of cumulative energy consumption per unit of the final product, was obtained from 5.96 to 8.93 MJkg^{-1} in evaluated rice planting systems. The effect of planting methods on the energy intensity values was significant at P0.001. The energy intensity of treatment T4 with 8.93 MJkg^{-1} was higher than the other treatments. The lowest energy intensity was related to the T3 with 5.96 MJkg^{-1}, and did not have a significant difference at P0.005 with the T2 and T5 treatments.

The energy intensity shows that 7.08, 5.99, 5.96, 8.93, and 6.30 MJ of cumulative energy of controllable inputs was used to produce 1 kg of rice in treatments T1 to T5, respectively, which indicates the better conditions of T2 and T3 compared to other treatments. In similar studies, the energy intensity of rice production in transplanting system has been obtained more than direct cultivation (Basavalingaiah et al., 2020; Chaudhary et al., 2017; Cherati et al., 2011). Different amounts of energy consumption have been obtained to produce 1 kg of rice, such as 3.75 to 7.39 MJ (Chaudhary et al., 2017), 8.71 MJ (Firouzi et al., 2016), 6.31 to 13.4 (Jamali et al., 2021), and 6.4 to 4.1 (Basavalingaiah et al., 2020).

CDP of different rice planting systems was between 3.52 and 4.85, which indicates that the chemical exergy of produced rice is more than the CExC of controllable inputs. as higher as this index, indicates the higher efficiency of inputs exergy consumption, stability and more compatibility (Firouzi et al., 2016).

Planting method had a significant effect on CDP at P0.001. P5 with 4.85 had the highest CDP value and was in the same statistical group with P2 and P3. Compared to the other two treatments (i.e., P1 and P4), this group of treatments has higher exergy consumption efficiency and greater compatibility with the environment. The lowest amount of exergy production per unit of CExC was related to T4, which shows that rice transplanting method has the lowest efficiency in terms of exergy and the least compatibility with the environment (Figure 5). In a study on exergy flow in the production of different varieties of rice in Italy, CDP was reported from 3.98 to

7.96, and the difference in cumulative exergy consumption and yield was one of the important reasons for the difference in CDP in the production of different varieties. In the study of exergy flow in the production of different rice varieties in Italy, CDP was reported from 3.98 to 7.96. The difference in cumulative exergy consumption and yield among rice varieties has been the main reason for CDP variations (Nikkhah et al., 2021). In sesame production systems in south of Iran, the CDP of the mechanized system, due to its higher exergy output, was reported to be 14 percent more than the traditional system (Noorani et al., 2023). CDP index for sugarcane and sugar beet production system in Khuzestan province of Iran was calculated as 6.21 and 6.42 respectively (Asakereh et al., 2023). In corn production systems in Mexico, the value of this index has been reported as 1.6 to 14.1, which the difference in CExC and output exergy was the main reason for the high range of this index (Juarez-Hernandez et al., 2019). In the current study, the CDP index of rice production has been found to be higher than the CDP of such products as irrigated wheat with 0.72 (Asl and Asakereh, 2023), rapeseed with 1.8 (Amiri et al., 2020), banana with 1.62 (Rasoolizadeh et al., 2022), tomato with 1.62 (Yildizhan and Taki, 2018), and black tea with 0.425 (Özilgen and Sorgüven, 2011). This can be due to the different needs of crops for inputs, growth conditions, and their yield and chemical exergies.

The findings of the current study show that the exergy efficiency in direct dry seeding is more than that of the transplanting method, and moreover different tillage and irrigation applied in direct dry seeding treatments have also affected the exergy efficiency. Exergy efficiency of furrow irrigation in T2 and T3 was more than that of flood irrigation T1 (Figure 5). Also, calculated CDP shows that the replacing of minimum tillage by no-tillage has increased the exergy efficiency. The difference in the CExC, especially due to the energy required for irrigation and fuel in different rice planting methods, was the most important factor for the significant difference in the CDP of the treatments. Treatments T1, T2, T3 and T5 had no significant difference at P0.005 in terms of cumulative net exergy and were placed in the same statistical group. However, the highest value was related to T2 with 41.90 GJha^{-1}. The lowest cumulative net exergy was related to T4, which had a significant difference at P0.005 with other treatments except T1 (Figure 4).

The intensity of cumulative exergy consumption was 2.97 to 4.10 MJkg^{-1} and the lowest value significantly was related to T5. Similar to CDP, treatments T2, T3 and T5 were placed in a statistical group in terms of intensity of cumulative exergy consumption, which shows that less exergy is consumed per kilogram of rice produced in these treatments compared to T1 and T4. T4 had the highest cumulative exergy consumption by consuming 4.10 MJ to produce 1 kg of rice.

The RI obtained in current study ranged from 0.727 to 0.822, indicating that the rice production system in all treatments is a relatively renewable process. As stated, the higher of this index indicates the lower pressure and stress on the environment as a result of the production process, so it is an important criterion for comparing the sustainability of production processes. Table 4 shows that the effect of planting method on RI is significant at P0.001. Figure 5 shows the average comparisons of this index at P0.005. The lowest value of RI with 0.727 was related to T4, which, like energy indices, has weaker conditions in exergy indices than other treatments. The highest value of the renewable index with 0.822 was related to T5 followed by T2, which have the least stress on the environment. Therefore, these rice cultivation methods have the most sustainable process in production. The difference in non-renewable exergy consumption in different treatments is the main reason for the difference in RI. The difference in non-renewable exergy consumption of the treatments is the main reason for the difference in their RI. As observed, the RI of T5 with the lowest CExC of non-renewable inputs (diesel fuel, electricity) had the highest value. While T4, where CExC values of non-renewable inputs, especially electricity, were higher, had the lowest RI. This index for the production of sugar cane, sugar beet

(Asakereh et al., 2023), and canola (Esmaeilpour-Troujeni et al., 2021) were reported 0.86, 0.84, and 0.72 respectively. As compared to wheat with RI=-0.185 (Asl and Asakereh, 2023), black tea with RI=-1.35 (Özilgen and Sorgüven, 2011), and Sesame with RI=-0.72 (Noorani et al., 2023), Rice production has a higher renewable index. The findings of this study show that although T5 has weaker conditions in terms of yield, production energy and energy indicators compared to T2 and T3, but it is better in terms of exergy indicators and has higher exergy efficiency and a more renewable process.

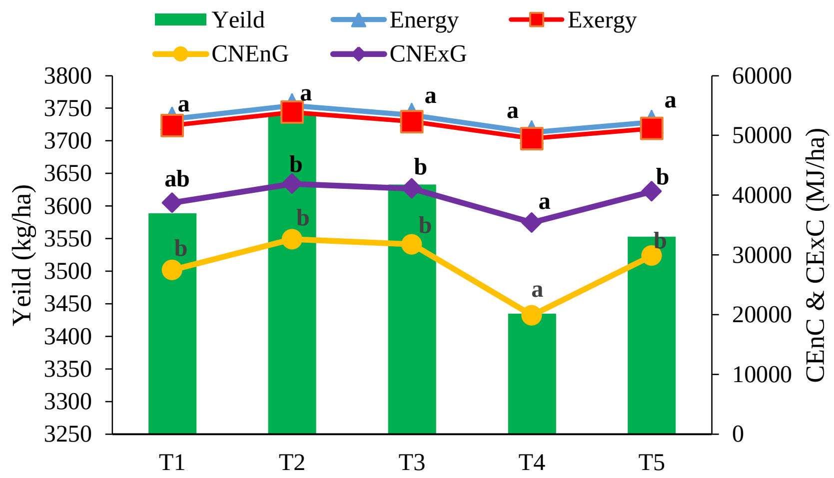

Figure 4. Yield, energy and chemical exergy of produced rice and cumulative net energy and exergy obtained

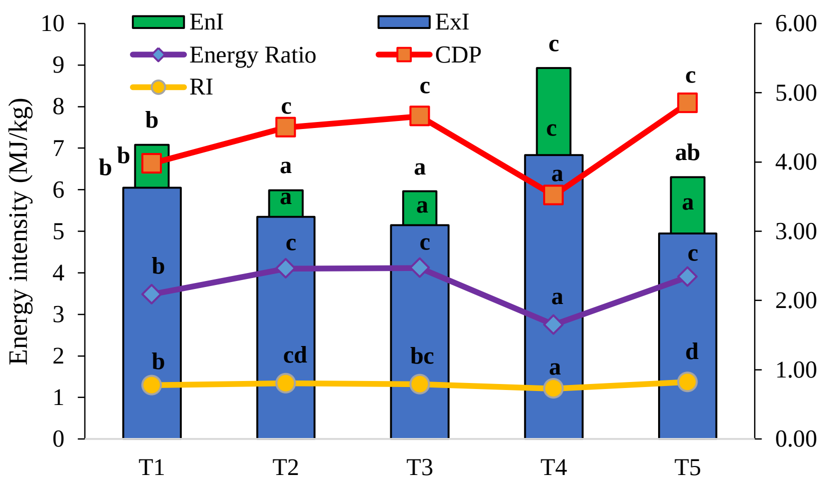

Figure 5. Cumulative energy and exergy indicators in rice production

Conclusions

This study assessed the efficiency and sustainability of different rice planting methods by examining their impact on energy use and exergy measures. Results showed that the choice of planting technique significantly influences both energy consumption and total exergy. The no-tillage method had the lowest cumulative exergy demand, mainly due to reduced diesel fuel use for machinery. In contrast, transplanting registered the highest energy and exergy consumption, largely because of increased labor for paddling and greater irrigation electricity use. Across all methods, electricity for irrigation water pumping was the largest contributor to energy use, followed by chemical fertilizer application. For exergy, fuel resources were dominant in treatments T1, T2, and T3, while electricity was the main contributor in T4 and T5. Treatments T2, T3, and T5 demonstrated a good balance of high energy return and low energy intensity, indicating that improved practices—such as efficient irrigation, direct dry seeding, and no-tillage—can enhance energy input efficiency. The energy input per kilogram of rice varied across treatments, with values of 7.08, 5.99, 5.96, 8.93, and 6.30 MJ for T1 to T5, respectively. The energy performance coefficients ranged from 3.52 to 4.85, with T5 achieving the highest efficiency and T4 the lowest. The Renewable Index (RI) analysis indicated that all methods are fairly sustainable, with T5 reaching the highest RI of 0.83, reflecting a reduced environmental impact. Overall, direct dry seeding on raised beds proved most effective for energy and production efficiency, while no-till dry bed methods excelled in exergy performance, exergy efficiency, and overall sustainability. Since irrigation water pumping accounts for the majority of energy and exergy use in rice cultivation, adopting more efficient irrigation practices is strongly recommended to improve water and electricity productivity in rice farming.

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