



RESEARCH ARTICLE

Energy productivity and system performance of diversified rice-based cropping systems

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Abstract

The traditional rice-wheat system is a century-old practice that diminishes the potential of natural wealth and relies on energy-intensive methods in most rice-wheat growing regions. This system has grown year after year, explicitly showing a deterioration in total factor productivity. Hence, to determine the effective cropping system that achieves sustainability, energy efficiency and system productivity, a field study was conducted to analyse energy usage in relation to various desired farm input necessities and the amount of a crop or resource gathered after crop matured, specially the final yield under diversified rice-based cropping systems over four years from 2021-22 to 2024-25. The study focused on a rice-based system that involved 8 different crop sequences, utilizing diversification, zero-tillage sowing of wheat and green gram to analyse the energy dynamics, such as energy moves, transforms and is utilized within the studied systems of a choice of cropping systems. The study exposed that the sum of total energy utilised was observed to be highest in the cropping system of rice + potato + green gram, which utilised 65,750 MJ ha⁻¹, next to the rice + vegetable pea + wheat (zero tillage) system with utilisation of 38,670 MJ ha⁻¹ and the rice-wheat (zero tillage)-green gram (zero tillage) system, which recorded 37887 MJ ha⁻¹. Overall, the rice + vegetable + green gram cropping system used 11 % less energy than the conventional rice-wheat cropping system (RWCS). The use of the rice + potato + green gram pattern yielded a significantly higher total output energy, estimated at 207,708 MJ ha⁻¹, compared to the rice-wheat system, which yielded 34,330 MJ ha⁻¹. The net energy returns are estimated to be significantly higher for the rice + potato + green gram system than for other fallowed systems. This adopted system consumed approximately 91 % more input resource energy, although it delivered 60 % higher energy productivity than the traditional rice-wheat cropping model. Overall, the rice-potato-green gram system achieved a 1.83-fold increase in total system productivity and a 1.48-fold increase in profitability over traditional rice-wheat methods.

Keywords: cropping system; energy; harvested output; minimum tillage; system productivity

Introduction

The rice-wheat cropping system (RWCS) is the most widely adopted vital agricultural practice worldwide, playing a key role in providing food security. Across Asia, this system covered over 13.5 million hectares, with South Asia contributing around 57 % of the total cultivated area (1–3). Rice-Wheat Cropping System is most prominent in India, covering about 9.2 million hectares and serving as a cornerstone of the nation's food production strategy (4, 5). Specifically, rice cultivation occupies about 51.4 million hectares, yielding 149.0 million tonnes, providing an average productivity of 2899 kg ha⁻¹ in farmers' fields. Wheat, on the other hand, is grown on 32.76 million hectares, producing 117.51 million tonnes at a productivity of 3,587 kg ha⁻¹ (6).

Under the Indian rice + wheat model, farmers cultivated rice in flooded lowlands from June through October, then switched to wheat in upland fields from November through April. The puddling operation used to prepare rice paddies disrupts soil structure, reducing aeration and increasing compaction (7-9). Over successive cycles, these practices lead to the formation of a shallow hardpan

that limits root expansion and hampers the growth of the following wheat crop. Studies showed that wheat sown after puddled (transplanted) rice yields about 8 % reduced grain than wheat sown after direct-seeded rice practices (10). Poor management and overexploitation of groundwater have led to a drastic decline in groundwater tables across key agricultural regions (11). Moreover, rice and wheat are known for their high nutrient demands, which leads to significant soil nutrient depletion. This issue is exacerbated when farmers burn the rice residue left after mechanical harvesting. The presence of leftover straw in the fields complicates tillage and sowing for subsequent wheat crops, leading farmers to strongly prefer burning this residue. India produces about 500 million tonnes of crop residues each year, most of which are utilised as fodder, fuel and for various domestic and industrial purposes. However, 92 million tonnes of crop residues are estimated to be burnt each year (12). The practice of burning crop residues significantly contributes to air pollution, which is linked to higher rates of premature mortality. Consequently, managing residues from the rice-wheat cropping model, particularly rice straw, poses a key challenge for efficient, timely management. The sustainability and profitability of

traditional rice-wheat production systems across various regions of India are being called into question due to unsustainable energy practices, ongoing natural resource degradation, climate variability and suboptimal crop yields (13, 14). Given these challenges, farmers require innovative alternatives to replace the conventional rice-wheat system. Therefore, a diversified cropping system or model is a panacea to address several challenges that persist in agriculture.

Crop diversification is a vital strategy for sustainable agricultural practices and enhanced energy productivity. As the agricultural sector faces challenges posed by climate change, soil degradation and uneven market demands, the adoption of diverse cropping practices has emerged as a key solution to both environmental and economic pressures. By cultivating a variety of crops, farmers can improve biodiversity, enhance ecosystem resilience and mitigate risks associated with monoculture systems (15, 16). Sustainable cropping systems that prioritise diversification can lead to increased soil health, pest and disease resistance and improved overall productivity (17). This not only supports the ecological integrity of agricultural landscapes but also enhances food security by providing a broad range of products and reducing dependence on a few staple crops. In addition, diversification plays a key role in energy productivity by optimizing the use of natural resources and promoting more efficient energy cycles within farming systems (18).

The use of energy inputs is a critical component in achieving sustainable agricultural cultivation in India, as significant energy is required for the production of crops such as pulses, sugarcane, rice, wheat, potatoes and oilseeds. Energy is important for all forms of agricultural inputs (labor, seeds, fertilisers, irrigation and insecticides for pest management) as well as for the operation of machinery, which is directly correlated with technological advancement in India. The relationship between energy and agriculture is increasingly pertinent as cropping systems intensify in resource-constrained environments. Research suggests that crop production systems are well observed to be energy-intensive. In the eastern plateau region, rice + rice cropping systems and rice + fallow + fallow modal estimated energy consumption levels of 2.14 and 1.91 MJ kg⁻¹, respectively (19). The assessment of energy flows within diverse production systems gained prominence among researchers in the 1970s, driven by the global fossil fuel crisis and the rising demand for food to meet a continuously expanding population (20). The effective use of energy in agriculture is crucial for achieving sustainable agricultural production, increasing yields and efficiency, conserving financial resources and protecting fossil fuel reserves. Since the Green Revolution period, agriculture in India has seen a rise in the use of high-input, mechanised and irrigated farming systems. This shift has resulted in significant energy use, both directly and indirectly, due to the energy-intensive nature of production activities, inputs and additional necessities (21). Consequently, improving energy efficiency has become a key objective for both farmers and policymakers.

Among field crops, legumes and oilseeds exhibit lower energy requirements compared to other crop types. In contrast, crops such as rice, wheat, maize and sugarcane require higher energy inputs, primarily due to their significant needs for irrigation, fertilisers and various cultural practices (22). The realization of diversified crop production alongside advanced yield targets is not feasible without substantial energy inputs. An increase in crop

productivity necessitates enhanced mechanical power supply in conjunction with adequate chemical energy (23). Consequently, increasing cropping intensity beyond current levels requires a greater supply of energy for essential inputs, including manpower, seeds, fertilisers, irrigation and implements for tillage, harvesting and threshing (24). The evolving factors of production have led to increased energy inputs aimed at maximizing yields and reducing labor-intensive practices (25). Thus, there is an urgent imperative to sustain the productivity of various crops in India by incorporating profitable, energy-efficient crops. This objective can be achieved by integrating traditional energy inputs, specifically human labor, alongside significant investments in machinery, irrigation, fertilisers and soil and water conservation practices. The various inputs and methodologies represent different forms of energy that require careful evaluation to assess their effectiveness and devise strategies for their conservation (26). Energy computing plays a vital role in the efficient management of limited resources, enhancing crop production in India, which is crucial given the pressing issues of rapid resource depletion and climate change. Establishing a highly energy-efficient output system that requires minimal energy input would provide a sustainable and economically viable livelihood for Indian farmers. As such, energy budgeting is crucial for the prudent management of scarce resources, aiming to enhance agricultural yields. Unfortunately, there is insufficient information on energy consumption across diverse cropping systems in the study area. Therefore, this research article aims to investigate the potential of crop diversification as a pathway to sustainable agriculture while enhancing energy productivity.

Materials and Methods

Site and climate

The field experiments were conducted at the College of Agriculture, Azamgarh, Uttar Pradesh, India, from 2021-22 to 2024-25. The site was located in the Sub-tropical region of the middle Indo-Gangetic plains at 26°1'36" N latitude, 83°8'24" E longitude and 64 m above MSL in the eastern parts of Uttar Pradesh. In the Kharif season, the major crop is rice, but other crops are also grown. In this region, rice is transplanted with high yields. Rice is grown mostly in rice-wheat or rice-rapeseed-sugarcane ratoon + wheat sequence. The soils are medium- to heavy-textured (silty clay loam), with high cation exchange capacity, nutrient content and water-holding potential. These soils are generally medium to low in organic matter, available nitrogen and medium in available phosphorus and potassium. Available sulfur is marginal in some areas and is near the critical level. Available zinc levels are below the necessary threshold; therefore, zinc deficiency in rice is widespread.

Experimental details

The experiment was conducted to estimate the energy input, energy output, energy use and net return of various existing cropping systems. Eight (8) sequential treatments were involved, like (i) Rice-Wheat (Conventional), (ii) Rice + Vegetable Pea+ Wheat [Zero Tillage (ZT)], (iii) Rice + Vegetable Pea-Green gram, (iv) Rice-Rapeseed + Green gram, (v) Rice + Mustard + Green gram (ZT), (vi) Rice + Potato-Green gram, (vii) Rice + Rapeseed-French Bean and (viii) Rice-Wheat (ZT)+ Greengram (ZT). The experimental plots were arranged in a randomized block design (RBD) with four replications.

For the kharif rice crop, all plots were twice harrowed and tilled once with a tiller, then sown by direct seeding. The field was prepared for a wheat crop with four harrowings, planking and leveling for conventional sowing. In the case of zero tillage, wheat seed was sown after harvesting the rice crop without tilling. In the same way, the field of green gram was prepared and sown. The other crops were prepared in the same manner as in the conventional land preparation method. In conventional systems, the field remained vacant during the summer. In contrast, in improved diversified systems, crops were grown according to their respective treatments with a tractor-drawn vertical disc plow after the rabi harvest during the summer. All crops were grown following the treatments and the standard package of practices.

Method of energy calculation

Evaluation of manual energy input

The manual energy (E_m) was estimated using the standard formula (27).

$$E_m = 1.96 N_m \times T_m \text{ MJ} \quad (\text{Eqn. 1})$$

Where N_m = the number of laborers spent on a farm activity;
 T_m = useful time spent by a laborer on a farm activity expressed in hr.

The energy coefficients used in the formula are given in Table 1. The total manual labor for each operation was estimated in working hours, then converted to man-hours. Only the primary variables were used in estimating manual energy; all secondary factors were neglected.

Evaluation of mechanical energy use

Mechanical energy input was estimated by measuring the diesel fuel used during tillage, sowing, threshing and winnowing, following the standard methodology (27). The total time spent on each action was recorded. Diesel consumption at the pump was observed during irrigation practice. Therefore, for each farm operation, the diesel fuel energy input was calculated by:

$$E_r = 56.31 \times D \text{ MJ} \quad (\text{Eqn. 2})$$

Where 56.31 = unit energy value of diesel, MJ L^{-1} ; D = diesel consumed.

Table 1. Energy conversion factors as adopted during the experiment (28, 29)

Particulars	Unit	Energy equivalent (MJ)
Human power		
Man	Man hour	1.96
Woman (female)	Woman hour	1.57
Tractor	hour	332.0
Diesel	Litre	56.31
Chemical input		
Nitrogen (N)	Kg	60.60
Phosphorus (P)	Kg	11.10
Potash (K)	Kg	6.70
Protection		
Standard chemical (Granular)	Kg	120
Non-standard chemical	Kg	10
Liquid pesticide	mL	0.102
Crop produce		
Rice grain	Kg	14.70
Wheat grain	Kg	15.70
Vegetable pea	Kg	3.91
Green gram	Kg	13.96
Mustard and Rapeseed	Kg	22.72
Potato	Kg	4.07
French bean	Kg	18.14

Energy for other inputs

The inputs applied for different operations in crop sequences, along with the resulting yields, were estimated to calculate energy use in the systems. The other field operations necessary to complete each activity in the experiment were measured by the time taken by both humans and machinery, as well as the fuel consumed during various activities. This information was shown as energy input in megajoules (MJ) using the relevant constants detailed in Table 1. Farm production, represented by grain yield, was converted into energy output (MJ) using the four-year average yield for various crops in the selected sequences and the available energy units (29). The direct energy use was calculated for each field operation, like (i) land preparation, (ii) nursery raising and transplanting, (iii) sowing or planting, (iv) intercultural operations and weeding, (v) crop management and (vi) harvesting and threshing. Moreover, the energy inputs were premeditated based on the sources of inputs throughout the crop period, such as (i) seeds, (ii) chemical fertilisers, (iii) insecticides, pesticides and herbicides, (iv) diesel and (v) human labor, among others.

Net energy returns (NER)

Net energy return represents the surplus energy remaining after subtracting the necessary production energy (the energy output) from the total energy generated. When applied to farming systems, this metric is commonly reported relative to a standard unit of land area, for example, 1 ha.

Energy ratio (ER)

This metric is calculated by dividing the total caloric energy yielded by the output products by the total energy sequestered in the production factors (inputs). This index illustrates the impact of inputs, expressed in energy units, on the process of producing consumer goods, often associated with food production. Still, it can also be suitably applied to the energy balance of biomass production. This index was calculated as energy output divided by input,

$$ER = \frac{E_o}{E_i} \quad (\text{Eqn.3})$$

Where,

ER = energy ratio

E_o = energy output

E_i = energy input

Additionally, energy profitability was computed as

$$PE = \frac{NER}{E_i} \quad (\text{Eqn.4})$$

Where,

PE = energy profitability

NER = net energy return

E_i = total energy input

Energy productivity (EP)

Energy productivity is defined as the volume of output derived from a single unit of input energy. Its correlation with the energy efficiency ratio is linear and direct; dividing the energy efficiency ratio by EP results in the calorific value of the final product.

Specific energy (SE)

It was estimated by energy input (MJ ha^{-1}) divided by crop yield (kg ha^{-1}).

$$E = \frac{\text{Energy input (MJ ha}^{-1}\text{)}}{\text{Crop yield (kg ha}^{-1}\text{)}} \quad (\text{Eqn.5})$$

System productivity

Grain yield was measured throughout the season from a net plot area of 10 square meter and then converted to a hectare basis. Total system productivity and profitability were calculated to assess and identify the best cropping system for this locality.

Since the data collected over the years at the same experimental site passed the homogeneity test, they were pooled over the seasons and mean values are presented. The observed data were statistically analysed according to the standardised procedure (30).

Results and Discussion

Operation-wise input energy utilization pattern

The energy practice for rice-based cropping systems, as detailed in Table 2, highlights the distribution of energy across various farm operations. Crop management activities required the most energy, accounting for 69 % to 74 % of total energy consumption. This was followed by land preparation, which accounted for 9 % to 14 % of the energy use. Sowing and planting consumed 5 % to 7 %, while harvesting and threshing operations utilised 6 % to 9 % of the energy. Remarkably, intercultural operations such as weeding accounted for only 2 % to 3 % of the total energy input in these systems. The significant allocation of energy to crop management operations highlights a crucial area for intervention, particularly given the escalating energy costs faced by farmers in major rice-producing regions. These findings demonstrated the vital importance of optimizing energy-intensive field activities to improve the overall energy efficiency and sustainability of rice production systems (31, 32).

The highest management operations utilised the most input energy across the entire system. This intensive energy consumption, particularly in mechanised processes such as tillage, sowing/transplanting, harvesting and threshing, underscores the critical need to optimise these operations to enhance overall energy efficiency in rice-based cropping systems (33). This ranged from 16832 MJ ha⁻¹ in the conventional rice-wheat method to 32171 MJ ha⁻¹ in the rice-potato+green gram cropping system. In land preparation, energy use varied significantly, from 2473 MJ ha⁻¹ in the rice-wheat (zero tillage) and green gram (zero tillage) system to 5854 MJ ha⁻¹ in the rice+potato-green gram cropping system modal. During sowing and planting, energy consumption ranged from 1676 MJ in the conventional rice-wheat system to 1959 MJ ha⁻¹ in the rice+potato-green gram cropping system. Harvesting and threshing operations also exhibited variations in energy use, ranging from 1254 MJ in the rice-wheat system to 1975 MJ ha⁻¹ in the rice-potato-green gram system. Notably, in the rice-potato-green gram cropping

system, land preparation consumed 5854 MJ ha⁻¹, ranking second in energy use after crop management. This was attributed to the additional energy required for earthing-up operations. The higher input energy in crop management can be attributed to increased energy consumption for irrigation and chemical fertiliser production. Among the various chemical fertilisers, nitrogen accounted for the largest share of total fertiliser energy input, followed by phosphorus, while potash contributed the least. This trend is primarily due to the higher energy equivalent of nitrogen fertilisers (≈60–66 MJ kg⁻¹) compared to phosphorus (≈11–15 MJ kg⁻¹) and potash (≈6–8 MJ kg⁻¹), as reported in previous studies. Consequently, nitrogen application accounts for the majority of total fertiliser energy consumption in cropping systems. It was also reported that fertiliser contributes the largest energy input (45–50 %) across different cropping systems (34). A comparison of cropping systems for various operations reveals that land preparation consumes the highest energy in the rice-potato-green gram system (5,854 MJ ha⁻¹). In contrast, the lowest energy use was observed in the rice-wheat (zero tillage) and green gram (zero tillage) systems (2473 MJ ha⁻¹). For harvesting and threshing, the highest energy consumption was again observed in the rice-potato-green gram system, followed by the rice-vegetable pea + wheat (zero tillage) and rice-wheat (zero tillage) systems and the green gram (zero tillage) system. This increased energy requirement was due to the greater labor required to harvest the potato crop. Intercultural and weeding operations devoted significantly less energy, ranging from 825 MJ ha⁻¹ to 1624 MJ ha⁻¹. The mechanised crop production system was associated with lower input energy consumption, consistent with findings from other studies (35, 36). The rice-potato + green gram cropping system required the highest percentage of input energy across all operations (Fig. 1), followed by the rice-vegetable pea-green gram system for land preparation and the rice-vegetable pea-wheat (zero tillage) system for sowing/planting, intercultural/weeding and harvesting/threshing. The rice-rapeseed-french bean system was noted for crop management operations.

The rice-potato-green gram sequence required the most human labor because more workers were needed for tasks such as sowing potatoes, earthing up and harvesting green gram. This combination also showed the highest overall energy input among various rice-based cropping sequences. Another study indicated that potato production requires a significant amount of energy, aligning with peak irrigation demands in potato farming (37). Since the potato plantation required a large number of seed tubers per unit area, it involved a greater energy input. The same result also aligns with % of a previous investigation, which reported that the potato seed material accounted for 10200.0 MJ ha⁻¹, representing 40.98 % of the total energy (35). A separate study found that seed materials and field operations accounted for a significant portion of the energy required (38). Research conducted in Japan and Iran found energy inputs for potato cultivation consistent with the figures presented in this study. In the study, rice-wheat (ZT) + greengram

Table 2. Input energy use in different cropping systems with operation (MJ ha⁻¹)

Cropping system	Land preparation	Sowing/ planting/ transplanting	Interculture/ weeding	Crop management	Harvesting/ threshing
Rice-Wheat (Conventional)	3624	1676	825	16832	1254
Rice-Vegetable pea-Wheat (ZT)	4054	1786	1396	21145	1926
Rice-Vegetable pea-Green gram	5633	1911	1388	20802	1768
Rice-Rapeseed-Green gram	4986	1896	1310	23710	1833
Rice-Mustard-Green gram (ZT)	3378	1864	1231	21838	1833
Rice-Potato-Green gram	5854	1959	1624	32171	1975
Rice-Rapeseed-French bean	4955	1875	1310	23923	1833
Rice-Wheat (ZT)-Green gram (ZT)	2473	1802	1317	20956	1926

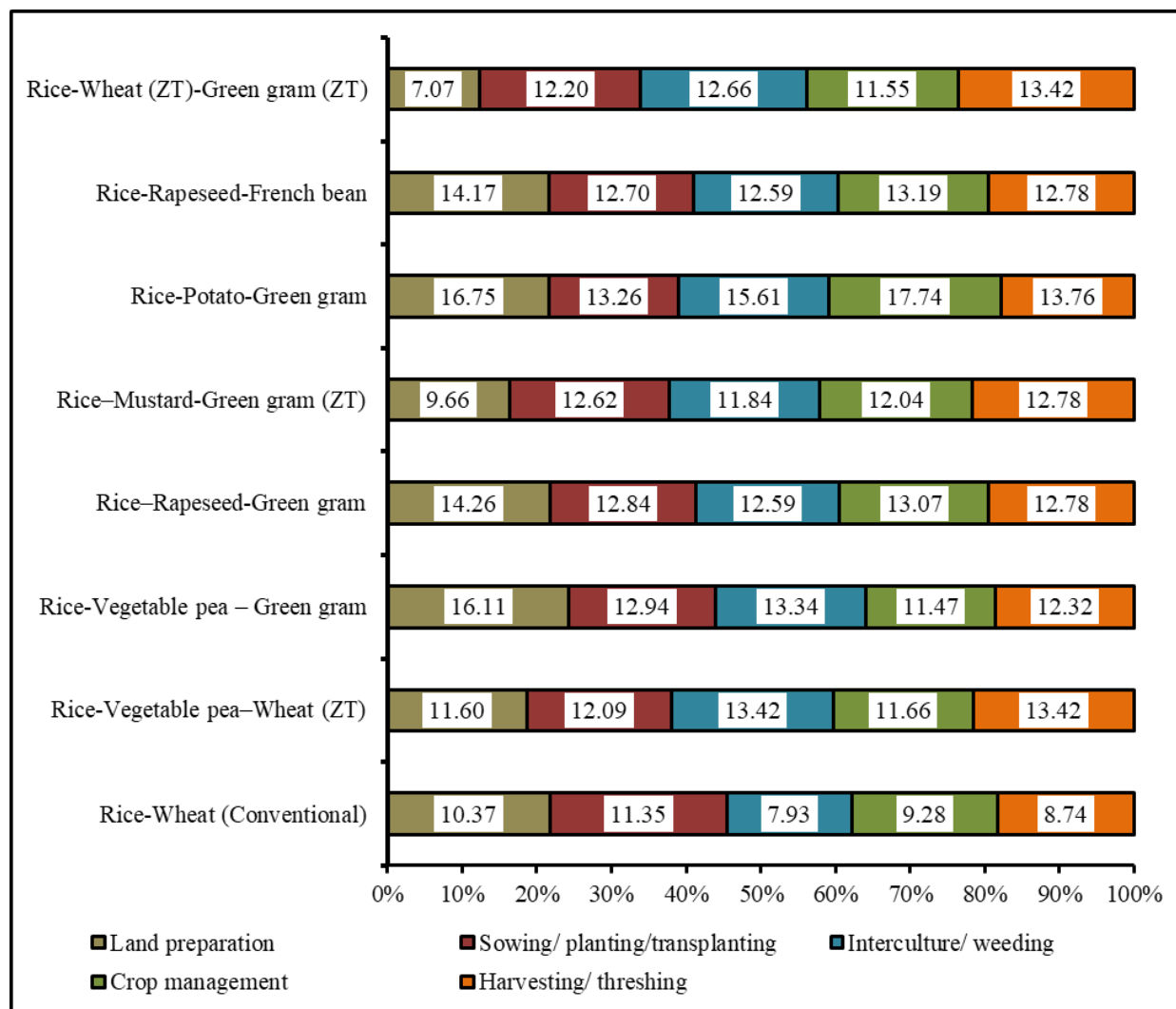


Fig. 1. Energy use (Input %) of various cropping practices for various operations out of the total energy.

(ZT) exhibits lower input energy across most field operations (39). Completely removing tillage in rice-wheat (ZT)-green gram (ZT) systems may help reduce reliance on non-renewable energy sources, such as diesel. Consequently, the reduced use of fossil fuels in ZT techniques is expected to lower greenhouse gas emissions, thereby supporting ecosystem services (40, 41). The reduced irrigation needs associated with conservation tillage compared to conventional tillage also help explain its energy-saving benefits (42).

Energy production (input-output) pattern

Average energy output calculated from converting the crop yield of one hectare in various cropping systems to Mega Joules (MJ). Table 3 showed that the net energy was superior in the rice+potato+green gram system (i.e., 141958 MJ ha⁻¹) compared to other systems such as rice-wheat (ZT)-green gram (ZT) (i.e., 103787 MJ ha⁻¹), rice-wheat conventional (i.e., 95453 MJ ha⁻¹), rice-vegetable pea-wheat (ZT) (i.e., 95100 MJ ha⁻¹), rice-rapeseed+french bean (i.e., 91216 MJ ha⁻¹), rice-rapeseed+green gram (i.e., 81053 MJ ha⁻¹), rice-mustard+green gram (ZT) (i.e., 80883 MJ ha⁻¹) and rice-vegetable-green gram (i.e., 69532 MJ ha⁻¹). The rice+vegetable pea+green gram system yielded a lower net return energy than other cropping systems. The higher output-input energy difference may be possible due to the potato crop in the system, which contributed approximately 46 % of the total output energy, followed by rice (37 %) and green gram (17 %) in the rice+potato+green gram cropping system. Another study reported that the rice+potato+maize cropping system yielded 89.6 % more energy than the conventional rice-wheat system (43). The

energy efficiency was found to be more or less the same in rice+wheat (conventional), rice+rapeseed+french bean and rice-wheat (ZT)-green gram (ZT) (i.e., 3.78, 3.74 and 3.74, respectively) compared to rice-potato-green gram (3.16). Numerically, the maximum net return energy was estimated in the rice+potato+green gram system compared to other systems. This showed that approximately 49 % higher energy output was achieved in the rice+potato+wheat system compared to the conventional system (rice-wheat), with the inclusion of potato. The net energy return will increase by growing more crops in the field. Similar findings were also reported by (44-46).

It is evident from Table 3 that more input energy was consumed, 65750 MJ ha⁻¹ in the rice-potato-green gram system, resulting in more output energy for this system, i.e., 207708 MJ ha⁻¹, followed by the rice-vegetable pea-wheat (ZT), i.e., 38670 MJ ha⁻¹ and rice-wheat (ZT)-green gram (ZT), i.e., 37887 MJ ha⁻¹. The lowest energy was found in the rice-vegetable pea-green gram system, i.e., 30855 MJ ha⁻¹. While output energy was calculated based on final crop yields, the maximum output energy was observed in the rice-potato-green gram system (i.e., 207708 MJ ha⁻¹), likely due to the high yield mass of potato. This was followed by the rice-wheat (ZT)-green gram (ZT) system (141674 MJ ha⁻¹), with the lowest yield in the rice-vegetable pea-green gram system (100387 MJ ha⁻¹).

Higher energy productivity and specific energy were 0.40 kg MJ⁻¹ in the rice-vegetable pea-green gram system and 3.82 MJ kg⁻¹ in the rice-potato-green gram cropping system. The lowest average

Table 3. Various indices of energy efficiency are involved in different cropping systems

Cropping system	Input energy (MJ ha ⁻¹)	Output energy (MJ ha ⁻¹)	Energy ratio (MJ ha ⁻¹)	Net energy return (MJ ha ⁻¹)	Energy productivity (kg MJ ⁻¹)	Specific energy (MJ kg ⁻¹)	Energy profitability (MJ ha ⁻¹)
Rice-Wheat (Conventional)	34330	129783	3.78	95453	0.27	3.76	2.78
Rice-Vegetable pea-Wheat (ZT)	38670	133770	3.46	95100	0.35	2.83	2.46
Rice-Vegetable pea – Green gram	30855	100387	3.25	69532	0.41	2.44	2.25
Rice-Rapeseed-Green gram	32616	113669	3.49	81053	0.34	2.96	2.49
Rice-Mustard-Green gram (ZT)	31993	112876	3.53	80883	0.36	2.77	2.53
Rice-Potato-Green gram	65750	207708	3.16	141958	0.26	3.82	2.16
Rice-Rapeseed-French bean	33277	124493	3.74	91216	0.32	3.08	2.74
Rice-Wheat (ZT)-Green gram (ZT)	37887	141674	3.74	103787	0.29	3.43	2.74
SEm. ±	482	1659	0.06	1776	0.002	0.04	0.02
LSD (p=0.05)	1427	4911	0.18	5258	0.006	0.11	0.05

energy productivity was recorded in the rice–potato–green gram system (0.26 kg/MJ), followed by the conventional rice–wheat system. The system with the lowest specific energy was the rice–vegetable pea–green gram system (2.44 MJ kg⁻¹). Similarly, the rice–wheat system achieved the highest energy profitability, followed by the rice–rapeseed–French bean and rice–wheat–green gram systems. The calculation of energy productivity is well documented in the literature, as evidenced by studies on stake–tomato (1.0), cotton (0.06) and sugar beet (1.53). A separate study reported specific energy values for various crops and vegetables in Turkey, including 16.21 for sesame, 11.24 for cotton, 5.24 for wheat, 3.88 for maize, 1.14 for tomatoes, 0.98 for melons and 0.97 for watermelons (47).

Although the rice–potato–green gram system recorded the highest net energy return, its energy productivity and energy profitability were comparatively lower. This is because energy productivity is expressed as output per unit of input energy (kg MJ⁻¹) and the rice–potato–green gram system involved substantially higher input energy due to intensive operations, higher fertiliser use and energy-intensive potato cultivation. Similarly, energy profitability (output energy/input energy) was lower due to the disproportionately high energy inputs. Thus, despite generating higher total output energy, efficiency per unit energy input decreased. This indicates that high-output systems are not necessarily the most energy-efficient systems.

The input energy presented in Table 2 reflects operation-wise energy consumption, whereas Table 3 represents total input energy, which includes both operational energy and input energy from fertilizers, seeds, irrigation and agrochemicals. Therefore, slight differences between the tables may occur.

System productivity

In the Kharif season, the average rice grain yield over four years was estimated to be significantly higher under the rice+vegetable pea+wheat (ZT) cropping system (4653 kg ha⁻¹) (Table 4). However, this was on par with the rice+toria+greengram system (4646 kg ha⁻¹), followed by the rice+potato+greengram system (4607 kg/ha). Similarly, the rice-toria-french bean and rice-wheat (ZT)-green gram (ZT) systems, which showed a higher and nearly similar yield trend, were observed. The inclusion of legumes in any cropping system could increase crop productivity by fixing atmospheric nitrogen in the soil, thereby improving soil nitrogen content. This N is competently used by succeeding crops. This biological nitrogen fixation not only enriches the soil's nitrogen reserves but also benefits subsequent non-leguminous crops in the rotation, reducing the need for external nitrogen inputs and promoting a more sustainable nutrient cycle (48). This natural process also contributes to the enhancement of soil organic matter and improved soil structure, thereby fostering a healthier rhizosphere that promotes overall crop vigor and resilience (49, 50). Beyond this, the functional

diversity of pulse crops, encompassing a vast array of species, offers considerable potential for developing resilient cropping systems tailored to diverse environmental constraints (51). It was also reported that rice and wheat yields were positively affected by the inclusion of legumes in rice and wheat cropping systems (52). Additionally, pulse crops stimulate soil microbial activity, thereby enhancing the accumulation of soil organic matter and accelerating the mineralization of fixed nitrogen. Therefore, our results were also positively correlated with rice grain yield when pulse was included as one of the crops in the cropping system.

Cropping systems were diversified during the rabi season. A higher yield of vegetable pea was recorded significantly in rice-vegetable pea–wheat (ZT) cropping system (5448 kg ha⁻¹) than rice-vegetable pea–green gram (5219 kg ha⁻¹) system (Table 4). Even though two more legume crops were included in the cropping system, there was no positive effect. This might be due to the soil's higher nitrogen content, which is partly harmful to pulse crops. Accordingly, the results demonstrated that the rice–vegetable–pea–wheat cropping system yielded significantly higher than the rice–vegetable–pea–green gram cropping system. This finding aligns with previous research highlighting the intricate relationship between soil nutrient availability and pulse crop productivity, suggesting that excesses of certain nutrients, such as nitrogen, can suppress the symbiotic nitrogen fixation process crucial for optimal legume growth. This implies a critical need for balanced nutrient management strategies that account for the specific requirements of pulse crops in diversified cropping systems, especially in environments where prior agricultural practices have elevated nitrogen levels (53). Furthermore, while pulses are critical for diversifying cropping systems and enhancing soil fertility, their optimal integration requires careful consideration of site-specific conditions and the existing nutrient profiles to maximize their benefits without inadvertently hindering their yield potential (54). Similarly, a higher grain yield of wheat crop was recorded in the rice–wheat (ZT) – green gram (ZT) system (4286 kg ha⁻¹) than the rice–wheat (conventional method) system (4225 kg ha⁻¹). This may be due to the adoption of zero-tillage and the inclusion of green gram, which improved soil conditions and nutrient availability, ultimately increasing wheat grain yield in the rice–wheat (ZT)–green gram (ZT) system. The enhanced soil health and nitrogen contribution from the preceding green gram crop likely contributed to this observed increase, reinforcing the benefits of legume integration into cereal-based rotations (55). This further emphasizes the broader advantages of legumes beyond nitrogen fixation, including improvements in overall soil health and the potential to enhance yields of subsequent crops in the rotation (56). In the case of toria crop, a higher yield of toria was obtained from the rice–toria–french bean system (1304 kg ha⁻¹) than from the rice–toria–green gram cropping system. The potato yield was 11,706 kg ha⁻¹ and the

Table 4. Yield, total system productivity and system profitability as influenced by various diversified cropping systems

Treatment	Grain/ Pod/ Tuber yield (kg ha ⁻¹)			Total system productivity (t ha ⁻¹)	System profitability (Rs ha ⁻¹ day ⁻¹)
	Kharif	Rabi	Summer		
Rice-Wheat (Conv.)	4317	4225	0	9.13	139
Rice-Veg-Pea-Wheat (ZT)	4653	5448	2807	13.67	205
Rice-Veg-Pea- Green Gram	4325	5219	1169	12.65	206
Rice-Toria-Green Gram.	4646	1288	1148	11.02	158
Rice-Mustard-Green Gram (ZT)	4289	1462	1184	11.54	175
Rice-Potato-Green Gram	4607	11706	1168	17.20	255
Rice-Toria-French bean	4463	1304	2085	10.81	141
Rice-Wheat(ZT)-Green Gram (ZT)	4433	4286	651	11.05	158
SEm.±	29.99	43.58	17.32	0.14	1.88
LSD (p=0.05)	88.80	129.02	51.27	0.43	5.56

mustard yield was 1,462 kg ha⁻¹.

During the summer season, the cropping system was also diversified. The green gram yield was nearly equal across all cropping systems, except in the rice-wheat (ZT)-green gram system. The maximum yield of green gram was recorded in the rice-mustard-green gram (ZT) system (1,184 kg ha⁻¹). However, this was on par with rice-vegetable pea-green gram, rice-potato-green gram and rice-toria-green gram cropping systems. French bean and summer wheat yields were 2085 kg ha⁻¹ and 2807 kg ha⁻¹. The summer wheat crop yield was lower than that of wheat grown in the rabi season. However, this yield was higher than that of other crops in the summer season.

Total system productivity was examined to compare all cropping systems on a monetary basis, expressed in terms of rice equivalents (Table 4). The significantly higher total system productivity was recorded in the rice-potato-green gram system (17.20 t ha⁻¹) because a massive potato yield and lump-sum profit were possible, resulting in a higher value than other cropping systems and a 1.88-fold increase over the rice-wheat conventional system. The rice-vegetable pea-wheat (ZT) and rice-vegetable pea green gram systems recorded the next highest total system productivity. However, these two cropping systems are on par. All other cropping systems exhibited similar total system productivity values and were on par with one another. The low system productivity recorded in the rice + wheat (conventional) system (9.13 t ha⁻¹) was due to the absence of a summer crop. AEI integrates biodiversity management and ecological principles into farming practices. According to previous reports this strategy aims to boost agricultural output, reduce reliance on external resources and either preserve or enhance vital ecosystem services (57, 58). Crucially, AEI also contributes to raising farmer incomes through a sustainable framework.

The rice-potato-green gram system demonstrated lower energy productivity but higher economic profitability. This apparent contradiction arises because energy productivity is measured as physical output per unit of energy input, whereas profitability depends on market value. Potato, being a high-value crop, significantly increases economic returns despite requiring high energy inputs. Therefore, while energy efficiency declines, economic gains improve, highlighting a trade-off between energy efficiency and profitability.

Economic analysis of diversified cropping systems

Economic evaluation of different rice-based cropping systems was conducted using system profitability (Rs/ha/day) as the indicator (Table 4). The results indicated that the rice-potato-green gram system recorded the highest system profitability (Rs. 255 ha⁻¹ day⁻¹), which was 1.83 times higher than the conventional rice-wheat system (Rs. 139 ha⁻¹ day⁻¹). Similarly, the rice-vegetable pea-green gram system also showed higher profitability (Rs. 206 ha⁻¹ day⁻¹), representing a 1.48-fold increase over the conventional system.

The increased profitability in diversified systems is primarily attributed to the inclusion of high-value crops such as potato and vegetable pea, along with additional seasonal cropping, which enhanced total system productivity. Diversification also improves resource-use efficiency and income stability. Although the detailed cost of cultivation and benefit-cost ratio were not calculated, system profitability provides a reliable comparative economic indicator

across cropping systems under similar experimental conditions. The inclusion of legumes not only improved soil fertility through biological nitrogen fixation but also reduced dependence on synthetic fertilizers, thereby lowering input energy requirements and enhancing the system's overall energy-use efficiency.

Similarly, the same trend was followed in system profitability. Rice-potato-green gram cropping system has been recorded significantly higher than any other system (Rs. 255 ha⁻¹ day⁻¹) and 1.83 times increased over rice-wheat conventional system, followed by rice-vegetable pea-green gram (Rs. 206 ha⁻¹ day⁻¹), which was 1.48 times increased over rice-wheat conventional system. Low system profitability was observed in the rice + wheat cropping system. This outcome highlights the synergistic benefits of crop diversification, particularly with high-value crops like potatoes, which can significantly enhance farmers' economic returns, thereby incentivizing the adoption of more sustainable agricultural practices. Other studies have observed that implementing certain agricultural practices alongside soil and water conservation measures in the transboundary region of Kenya and Uganda improves local farmers' commitment to and understanding of sustainable crop cultivation and land-use management (59, 60).

The observed improvements in energy efficiency and system productivity in diversified cropping systems can be attributed to complementary interactions among component crops, particularly the inclusion of legumes and high-value crops. Legumes contribute to biological nitrogen fixation, reducing dependence on external inputs, while crops like potatoes enhance biomass and economic output. Similar findings have been reported across diverse rice-based systems, where crop diversification improved energy efficiency, profitability and sustainability compared with monocropping systems. The integration of zero tillage further enhances energy savings by reducing fuel consumption and improving soil structure.

Conclusion

Assessing energy efficiency in cropping systems offers significant potential to optimize net energy gains in agricultural production. Remarkably, the rice-potato-green gram cropping system, although requiring a slightly higher energy input, delivers approximately 46 % more energy output than the conventional rice-wheat system with potato. The addition of green gram in rice-wheat (ZT)-green gram (ZT) systems also contributes to improved energy outcomes. System productivity in the rice-potato-green gram cropping system is 1.83 times that of conventional rice-wheat, while system profitability is 1.48 times higher.

Overall, the results demonstrate that diversified cropping systems offer significant advantages in terms of energy output, system productivity and economic returns. While some systems may be less energy-efficient, they provide higher profitability due to the inclusion of high-value crops. For farmers, this underscores the importance of selecting cropping systems not only for energy efficiency but also for economic returns. For policymakers, promoting diversified systems with legumes and conservation practices, such as zero tillage, can enhance sustainability, reduce dependence on external inputs and improve farm income under changing climatic conditions.

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Authors' contributions

PT and PY designed the study and arranged the data. VK and DKS prepared the manuscript, while VY, AY and AS edited the manuscript and refined the design. All authors read and approved the final manuscript.

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