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Research article

Advanced technological adaptations can improve the energy-cum-carbon-efficiency of diverse rice production systems

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ABSTRACT

Worldwide, there is an urgent need to develop energy-cum-carbon smart and cost-effective rice production systems for farmer's adoption. Data were collected from 280 farmer's fields representing the South Asia rice production system. Out of these 75 fields following transplanted rice (TPR), 55 fields of wet direct seeded rice (WDSR), 60 fields of drill sown direct seeded rice in line (DSR L), 60 fields of traditional direct seeded rice (DSR) and 30 fields of DSR + *beushning* (DSR + B). Results show that grain and straw yields in the TPR were 6056 and 7752 kg ha^{-1}, respectively; however, they were neither profitable, energy efficient, or eco-friendly. At the same time, the grain and straw yields in DSR L were recorded by 5832 and 7757 kg ha^{-1}, respectively. It was profitable with the highest net returns (1111.5 US$ ha^{-1}), energy use efficiency (12.77), energy productivity (0.41 kg MJ^{-1}), energy profitability (11.77 US$ MJ^{-1}), energy output efficiency (1314.3 MJ day^{-1}) environment friendly in terms of carbon efficiency 7.20, carbon sustainability index (6.20) and had most diminutive carbon footprint (0.14 kg CO_2 eq kg^{-1} grain) with a comparable carbon credit. DSR L is productive, economically viable, energy efficient, and environmentally safer among rice production systems.

1. Introduction

Rice (*Oryza sativa* L.) is a staple diet to most of the world's energy supply. It is grown on ~170 million hectares (Mha) in South Asia, yielding 782 million tonnes (MT) [1]. India has 43.8 million hectares of rice-growing land, producing 117.5 MT of rice, accounting for 24% of global rice output [2]. Of the total rice area, ~53.9% is irrigated, ~27.1% is rainfed, ~6% is flood-prone, and ~13% is upland [3]. The rice-based production system is wasting infinitive natural resources and causing many problems for developing countries and the rest of the globe, including soil sickness, economic and environmental unsustainable, and human health problems. It's because of stagnant production at a high cost, declining farm profitability, excessive agricultural energy consumption, and unsustainable management of scarce natural resources [4].

Traditional agricultural practices have a significant impact on greenhouse gas (GHG) emissions, accounting for 60% of nitrous oxide (N_2O), 39% of methane (CH_4), and 1% of carbon dioxide (CO_2) emissions [5]. CH_4 is the major contributor to rice production, whereas N_2O and CO_2 emissions are also significant in some systems [6]. The impounding of water in puddle transplantation of rice

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(TPR) favors anaerobic conditions, leading to CH_4 emission. The Indian rice field emits 96.2 MT CO_2 equivalent (eq); these contributed to 18.4% of the world during 2016 [1].

A comprehensive solution for productivity, profitability, environmental, soil, and human health security may be used to ensure agricultural sustainability in the future [7]. It may be possible to develop an eco-friendly, carbon-cum-energy-efficient, rice-based production system for future sustainability by assessing all production techniques used by farmers [8]. Realizing the optimal use of existing agricultural resources is a significant challenge in agriculture for an energy-efficient production system compared to traditional rice-growing approaches [9]. As a result, it is committed to developing an energy-efficient, commercially viable, and ecologically responsible system [10,11]. The relationships between crop productivity, economics, and energy are closely linked [7]. Different production systems have been adopted in rice based on resource availability, considerably influencing the energy consumption pattern and GHG emissions. The evaluation of economic feasibility, energy efficiency, and carbon footprint (CF) may give insights into the environmental implications of agricultural production [12–15]. An organized energy flow analysis helps describe various activities and is also required for identifying and developing an effective and efficient rice production system. Because the area under traditional direct-seeded rice (DSR and DSR with *beushning* (DSR + B) has a substantial yield variability, efforts are being made to replace it with advanced drill-sown direct-seeded rice (DSR L) [16–21].

A quantum shifts towards DSR L to cherish the potential advantage of 12–40% water saving [22], reduced drudgery, 11–66% labor saving eliminating TPR [23], diesel energy (60%), 2–16% cost saving [24], and sustainable soil properties [25,26]. The conventional rice production systems' energy use efficiency (EUE) has been declining, owing to higher energy input than energy output and environmental consequences [27]. The DSR L helps to earn more carbon credits than TPR, mainly by a 6–92% reduction in CH_4 emission [28]. Furthermore, carbon-efficient agricultural activities would aid in developing a carbon-efficient production system and reducing CF, which has been used as a quantitative measure of GHG emissions [29]. The CF is a valuable index for designing a climate-smart, sustainable, and eco-friendly production system [30], similar to techniques aimed at reducing CO_2 emissions, increasing CH_4 oxidation, minimizing CH_4 production in submerged fields, and reducing N_2O output [31].

Farming in rice-growing areas of India is representative of South Asia, with fragmented land ownership, little investment, inadequate irrigation systems, and insufficient money. The rice-growing system used is highly dynamic and diversified. Monsoon-dependent rice is grown by most rice producers in a considerable region. Therefore, an attempt has yet to be made to assess productivity, profitability, energy usage, or CF for rice production systems in South Asia. The energy efficiency of five established or semi-developed rice production systems with various management approaches and varying levels of energy and carbon inputs were assessed in this study. To evaluate the energy and carbon fluxes of a rice production system, data were collected from 280 rice producer field sites. The study's goals were to 1) identify the most productive and economic rice-growing system, 2) analyze energy-cum-carbon-efficient rice-growing systems, and 3) explore alternative management techniques for establishing a sustainable rice-growing system. Because information on these topics is limited, the current study focused on all rice-cultivating techniques to determine practice for per-unit productivity, economic feasibility, energy, and carbon budgeting for long-term sustainability and to save the costly natural resources exploited in South Asia's rice-dominant belt. Also, it will achieve the targets set out by the United Nations to battle climate change, generate a zero-carbon sink, and enhance above- and below-ground ecosystem services.

2. Materials and methods

Designing experiments based on traditional agricultural techniques has not been financially feasible or environmentally sustainable

Table 1
Major activities followed in the rice production system.

Rice production system	Abbreviation	Description	Tillage	Seedbed	Seed environment	Seeding method
Transplanted rice	TPR	Nursery land: Land is plowed, leveled and seeds are sown in dry condition Main field: Land is plowed and puddle and 20–25 days old seedlings are transplanted, seedlings get transplanting sock and get recovers after 5–8 days	Dry and wet	Wet	Dry and wet	Manual transplanting
Wet- Direct seeded rice	WDSR	Land is plowed and puddle, pre-germinated seeds (with 24 h soaking and 24 h incubation) are sown by manually, immediately after puddling, seeds settle down with suspended mud and protect the seeds	Dry and wet	Wet (puddle)	Anaerobic	Random broadcasting
Drill sown direct seeded rice	DSR L	Land is plowed, harrowed but not puddle, leveled then dry seeds are drilled through seed drill, before the onset of monsoon for effective use of rain	Conventional dry tillage	Dry soil	Aerobic	Drilled through seed drill
Direct seeded rice	DSR	Land is plowed, harrowed but not puddle, leveled then dry seeds are broadcasted before the onset of monsoon for effective use of rain	Conventional dry tillage	Dry soil	Aerobic	Manually broadcasted
Direct seeded rice with *beushning*	DSR + B	Land is plowed, harrowed but not puddle, leveled then dry seeds are broadcasted before the onset of monsoon for effective use of rain	Conventional dry tillage	Dry soil	Aerobic	Manually broadcasted

since the 1960s. Individual farmers have adopted semi-advanced rice cultivation methods (Table 1) such as TPR, wet DSR (WDSR), DSR, DSR L, and DSR + B based on farm resource richness and affluence.

2.1. Study location and climatic parameters

Under the Indian Council of Agricultural Research (ICAR)-National Institute of Biotic Stress Management (from now on, ICAR-NIBSM), Raipur, Chhattisgarh, India, the current study was replicated on 280 fields between 2013 and 2016 for data gathering during four years (Fig. 1). The climate was sub-tropical, and weather conditions were stable during both years. The annual average rainfall received during the study period (15 June to 15 November) was 1084.2–1798.2 mm. The maximum weekly average temperature varied from 26.5 to 41.2 °C, respectively, whereas the minimum average temperature ranged from 11.0 to 28.6 °C. In 0–20 cm soil depth, the soil is an Arang Series loamy texture (30–35% sand, 39–45% silt, and 20–23% clay), with 0.34–0.38% organic carbon, near-neutral pH (6.5–7.2), 1.40–1.42 Mg m^{-3} bulk density (ρb) and low to medium in $KMnO_4$ oxidisable nitrogen (205.8–350.6 kg ha^{-1}), medium in 0.5 N $NaHCO_3$ extractable phosphorus (15.5–18.5 kg ha^{-1}), and high in 1.0 N NH_4OAc exchangeable potassium (321.5–362.6 kg ha^{-1}).

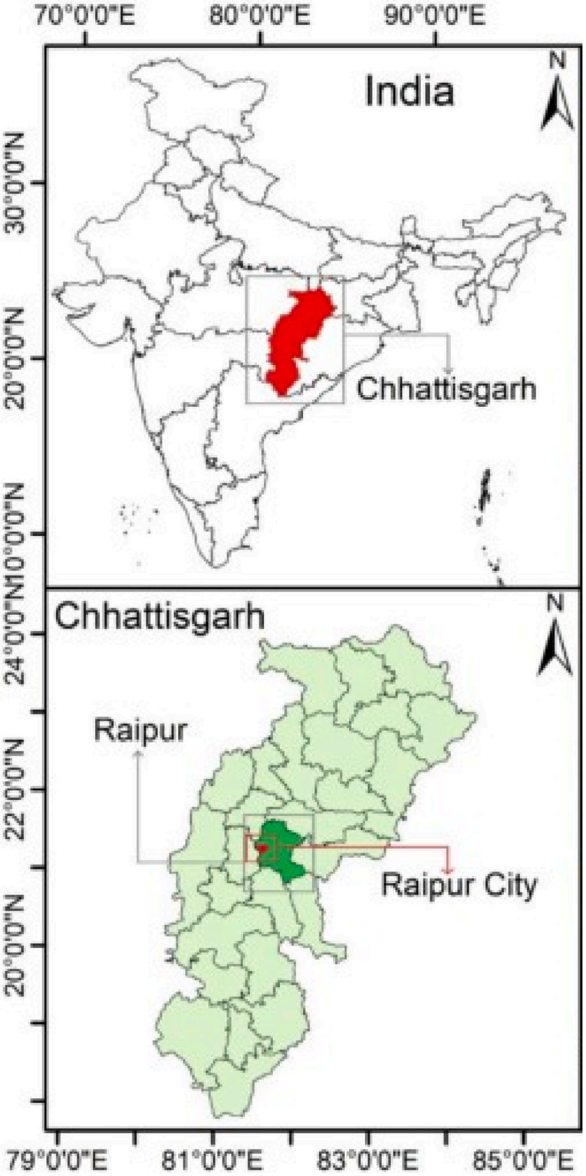

Fig. 1. Location map of the study area.

2.2. Experimental procedures

The study area was selected for the adoption of the different rice production systems and uniformity in cultivation practices. Data was collected from a total of 280 farmers' fields consisting of 75 fields of TPR, 55 fields of WDSR, 60 fields of DSR L, 60 fields of DSR, and 30 fields of DSR following *beushning* (wet cross-ploughing with country plough ~25–35 DAS of the dry seeded rice field, when ~20 cm of water gets impounded in the crop field followed by laddering and seedling redistribution) [32,33] were included in the study. The data on crop production was collected by input used during the production process. The grain and straw yields were obtained by crop cutting at 25 m^2 area (5 m × 5 m) at three places of each field and averaged for interpretation. In the study area, farmers irrigated crops mainly through tube wells. Farmers growing rice cv. 'Swarna' (140–145 days, high yielding) was selected for the investigation to eliminate the varietal disparity. The details of agricultural practices adopted during the cropping season with different rice production systems are presented in Table 1. Although, at ICAR-NIBSM, all the rice production systems were adopted in three replications. Data were entered as three sites where every input was quantified and used for estimation. These were almost similar to the inputs used by rice growers in different production systems.

2.3. Economic parameters

As the majority of the farmers use the farm resources as inputs available free of cost, these are not considered while estimating the cost of production. The economic parameters of rice cultivation only consider the variable production cost. The inputs include machinery (tractor, cultivator, harrow, rotavator, sprayer, *etc.*), seed, fertilizer, pesticides, irrigation, harvesting, threshing and bagging, and human labor, excluding the cost of land were considered while estimating the cost of production. The various economic parameters were calculated based on the following equations (1)–(3)

$$GR = (GYxPR) + (SYxPS) \tag{1}$$

$$NR = GR - PC \tag{2}$$

$$B : C = GR/PC \tag{3}$$

where, GR, gross returns (US\$ ha^{-1}); GY, grain yield (kg ha^{-1}); PR, the market price of rice grain; SY, straw yield (kg ha^{-1}); PS, the market price of rice straw; NR, net returns (US\$ ha^{-1}); PC, production cost; B: C, the benefit–cost ratio.

For better comparisons, all the economic values were converted from Indian rupees (INR) to US\$, using an exchange rate of 2015–16 (65 INR = 1 US\$).

2.4. Energy analysis

The energy analysis compared the performance of five rice production systems managed according to different energy inputs. The energy inputs are referred to as non-renewable and renewable. Manual labor, fuel, types of machinery, agrochemicals (herbicide, fungicide, and insecticide), and inorganic fertilizers (N, P_2O_5 and K_2O) were non-renewable energy inputs, whereas seed, water etc., were renewable energy inputs. The energy output was computed using grain and straw yields of rice. The energy equivalents used during the study are presented in Supplementary Table 1. The energy indices were calculated using the formula [34–36] and equations (4)–(12).

$$EO = (GYxEcg) + (SYxEcs) \tag{4}$$

$$NER = EO - EI \tag{5}$$

$$EUE = EO/EI \tag{6}$$

$$EP = GY/EI \tag{7}$$

$$EPf = NER/EI \tag{8}$$

$$HEPf = EO/LE \tag{9}$$

$$EIn = EI/PC \tag{10}$$

$$SE = EI/Y \tag{11}$$

$$EOE = EO/D \tag{12}$$

where, EO, energy output (MJ ha^{-1}); Ecg, energy coefficient grain; Ecs, energy coefficient straw; NER, net energy returns (MJ ha^{-1}); EI, energy input (MJ ha^{-1}); EUE, energy use efficiency; EP, energy productivity (kg MJ^{-1}); EPf, energy profitability (US\$ MJ^{-1}), HEPf, human energy profitability; LE, labor energy (MJ ha^{-1}); EIn, energy intensity (MJ US\$$^{-1}$); SE, specific energy (MJ kg^{-1}); Y, yield (kg ha^{-1}); EOE, energy output efficiency (MJ ha^{-1} day^{-1}); D, duration (day).

Grain and straw were used to estimate energy output. In contrast, the rest of the energy parameters were calculated based on grain yield, as farmers sell to estimate energy output. Farmers sold rice grain in the market, and straw was used for domestic purposes or burnt in the field.

2.5. Carbon footprint analysis

The carbon equivalent (kg CO$_2$eq ha^{-1}) of input used in the rice production system (Supplementary Tables 2 and 3) was used to estimate different carbon parameters as suggested by Lal [11]. The following equations were calculated using the following equations: the carbon input and output, carbon efficiency, carbon sustainability index, carbon credit, and CF.

$$CO = BMx\ 0.44 \tag{13}$$

where CO, carbon output (kg CO$_2$eq ha^{-1}); BM, biomass (grain + straw) in kg ha^{-1}; 0.44, is carbon content (44%) each plant biomass does contain as suggested by Lal [11] and Singh and Ahlawat [20].

$$CE = \frac{CO}{CI} \tag{14}$$

$$CSI = (CO - CI)/CI \tag{15}$$

$$\text{C credit (US\$ ha}^{-1}\text{ yr}^{-1}) = \text{Rate (t}^{-1}\text{ ha}^{-1}\text{ yr}^{-1}) \times 15 \ldots \tag{16}$$

where, CE, carbon efficiency; CI, carbon input (kg CO$_2$eq ha^{-1}); CSI, carbon sustainability index; price per ton of CO$_2$eq was 15 US$ (2015-16).

The CF (kg CO$_2$eq kg^{-1} grain) of the rice production system was calculated as per the methodologies suggested by Gan et al. [42], Ma et al. [43] and Singh and Ahlawat [20].

$$CF = \frac{CI}{GY} \tag{17}$$

2.6. Statistical analysis

The collected data underwent statistical analysis following the methodology outlined by Cochran and Cox [51]. To compare means, a Fisher's protected least significant difference (LSD) test with a significance level set at $p = 0.05$ was employed, utilizing IBM SPSS Statistics version 24.0. Before conducting the analysis of variance (ANOVA), normality and homogeneity of variance were evaluated for rice yield, energy, and carbon parameters. The assessment was performed using the Shapiro-Wilk test for normality and the Bartlett test for homogeneity of variance, both conducted at a significance level of $p = 0.05$. Following these assessments, mean values were differentiated using Duncan's Multiple Range Test (DMRT).

3. Results and discussion

3.1. Rice productivity

Fig. 2 depicts that rice's grain and straw yields tended to be higher on the TPR (6056 and 7752 kg ha^{-1}, respectively) but were on

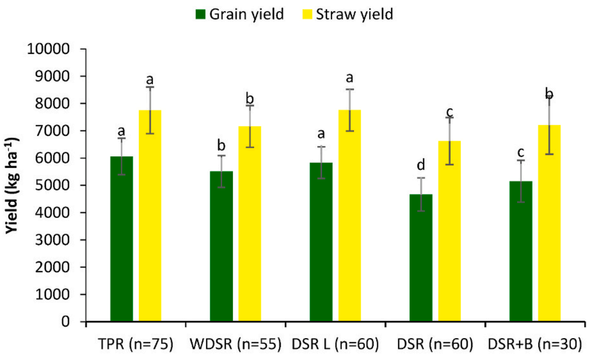

Fig. 2. Grain and straw yield (kg ha^{-1}) as influenced by different rice production systems (transplanted rice, TPR; wet-direct seeded rice, WDSR; drill sown direct seeded rice, DSR L; direct seeded rice, DSR; direct seeded rice with *beushning*, DSR + B) (same letters are statistically comparable to each other in similar color bar). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

par with DSR L (5832 and 7757 kg ha^{-1}, respectively). In contrast, the traditional DSR system had considerably lower yields (4664 and 6623 kg ha^{-1}, respectively). The rest of the rice production systems had significantly higher grain and straw yields, yet their effect was less concerning to TPR and DSR L. The higher grain and straw yields in TPR and DSR L were mainly due to optimum plant population, more tillers, and longer and heavier panicles with more grain panicle^{-1} [15]. Furthermore, TPR, DSR L, and WDSR have been semi-evolved cultivation systems where plants were responsive to external inputs such as water, nutrients, and plant protection measures, and helped in synthesizing longer and broader leaves resulting in larger leaf area, and ultimately higher leaf area index (LAI). These trapped more solar radiation led to synthesizing additional photosynthesis, translocated to different plant parts, producing higher yield attributes and leading to higher yield [26,52,53]. In contrast, traditional DSR plots had an inappropriate plant population (at some places, a dense population and another thin population), shorter panicles, lighter, and fewer grains panicle^{-1} (data not presented), resulting in lower grain and straw yields. The TPR and DSR L production systems had optimum plant population and better microclimates for growth and development, hence utilizing solar radiation more efficiently. They produced higher rice grain yield [54]. In conformity with our results, reduction in yield under DSR was also recorded by Clerget et al. [55] and Yadav et al. [56]. Similar to our result, Bhushan et al. [57] reported no yield advantage in DSR L compared to TPR. These provided insight into redesigning the rice production system to increase the yield under DSR L.

3.2. Energy utilization pattern

The source-wise energy utilization pattern differed with different rice production systems (Table 2). The highest mean energy was consumed under TPR (17201.1 MJ ha^{-1}), followed by DSR + B (17103.9 MJ ha^{-1}), and the least in DSR (13666.4 MJ ha^{-1}). The WDSR and DSR L utilized reasonably lower energy inputs but were higher than DSR. The energy utilization of renewable and non-renewable energy under different rice production systems was varied. TPR utilized the highest indirect non-renewable energy comprising fertilizer, pesticides, and farm machinery (9318 MJ ha^{-1}), and subsequently WDSR (9015 MJ ha^{-1}), whereas the lowest non-renewable energy under DSR (7601 MJ ha^{-1}). Seeds were an indirect renewable energy source, consumed highest with DSR + B (1900 MJ ha^{-1}) afterward in DSR (1520 MJ ha^{-1}) and lowest under TPR (608 MJ ha^{-1}). Likewise, diesel contributed 2393–3153 MJ ha^{-1}, the highest with TPR, whereas it was similar in WDSR, DSR, and DSR + B (Fig. 3). Direct renewable energy, viz. human labor, water, and animal power, was higher in DSR + B (4762 MJ ha^{-1}) after TPR (4122 MJ ha^{-1}), whereas it was lowest in DSR L (2083 MJ ha^{-1}). Thus, the data indicated that the percent contributions of indirect non-renewable energy ranged between 47 and 57%. The higher contribution was recorded with WDSR and the lowest with DSR + B. The rest of the rice production system lies between TPR and DSR + B. The energy contribution of seed ranged between 4 and 11%, the highest in DSR + B and DSR and the lowest with TPR. Direct renewable energy contributed 15–28%, higher under DSR + B and the weakest in DSR L. Further, the percentage contribution of these input energy in the rice production system illustrated that energy consumption was highest in fertilizer management (33.8–44.5%) subsequently consumption of diesel (14.0–21.6%), irrigation (11.4–21.5%), seeds (3.5–11.1%), machinery used for various operations (8.9–10.6%), application of plant protection chemicals (3.5–4.5%), and the least by animal power (Fig. 4). The contributions of commercial energy, viz. machine, diesel, fertilizer, plant protection chemicals, etc., in different rice production systems ranged between 72.2 and 85.4%, being the highest in DSR L and the lowest in DSR + B. On the contrary, non-commercial energy, viz. animal power, labor, water, etc., ranged between 14.6 and 27.8%, with the highest in DSR + B and lowest in DSR L (Fig. 5). Jat et al. [58] stated that fertilizer application could contribute ~50% of the total energy in conventional tilled maize-wheat cropping systems. A slightly improved rice production system, i.e. DSR + B, relies more on animal power. Additionally, human laborers were engaged in various operations, maintaining a uniform plant population that consumed considerably more energy than DSR. Furthermore, this system additionally required 2000 m^3 of water to be impounded to impose *beushning*. It has been observed that DSR + B utilized higher seed energy, mainly due to some of the plants being uprooted and drying while ploughing with a country plough. Also, trampling while maintaining the plant population further kills certain plants. Therefore, a higher seed rate (20–25%) has been suggested [32,33].

Modern or improvised rice production systems depended not on animal power but more on mechanical power. Nursery management and field preparation are additional desired activities for TPR. Furthermore, TPR consumed higher fertilizer energy with the lowest seed energy. Therefore, overall energy input was highest in TPR over many other rice production systems [54]. Likewise, WDSR essentially requires puddling before sowing sprouted seeds. The improvised rice production system has depended much on non-renewable energy; hence, it has been suggested to adopt agriculture systems requiring less tillage, water, fertilizers, and energy in a larger area to minimize the use of non-renewable energy [6,59]. Crews and Peoples [60] also stated that non-renewable energy, like fertilizers alone, contributed >40% of total energy input. Fertilizers, land preparation, sowing management, and plant protection further increased the share of total energy input. Laik et al. [61] estimated 20.6–34.4 GJ ha^{-1} of energy inputs in rice production in the

Table 2
Energy input (MJ ha^{-1}) used in different rice production systems.

Rice production system	Bullock power 1	Machinery 2	Diesel 3	Labor 4	Water 5	Seed 6	Fertilizer 7	Plant protection 8	Total 9
TPR	0.0	1715.4	3153.4	957.0	3164.6	608.0	6994.0	608.7	17201.1
WDSR	0.0	1411.8	2393.2	549.0	2552.6	1216.0	6994.0	608.7	15725.2
DSR L	0.0	1523.9	3097.1	448.6	1634.6	1216.0	5782.0	608.7	14310.8
DSR	0.0	1210.4	2393.2	517.6	1634.6	1520.0	5782.0	608.7	13666.4
DSR + B	350.4	1658.0	2393.2	737.0	3674.6	1900.0	5782.0	608.7	17103.9

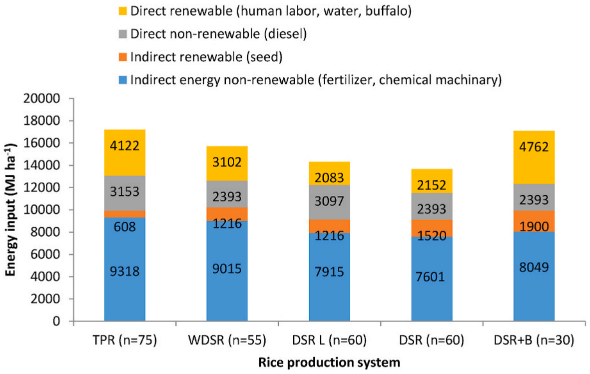

Fig. 3. Renewable and non-renewable energy inputs (MJ ha^{-1}) used in different rice production systems a).

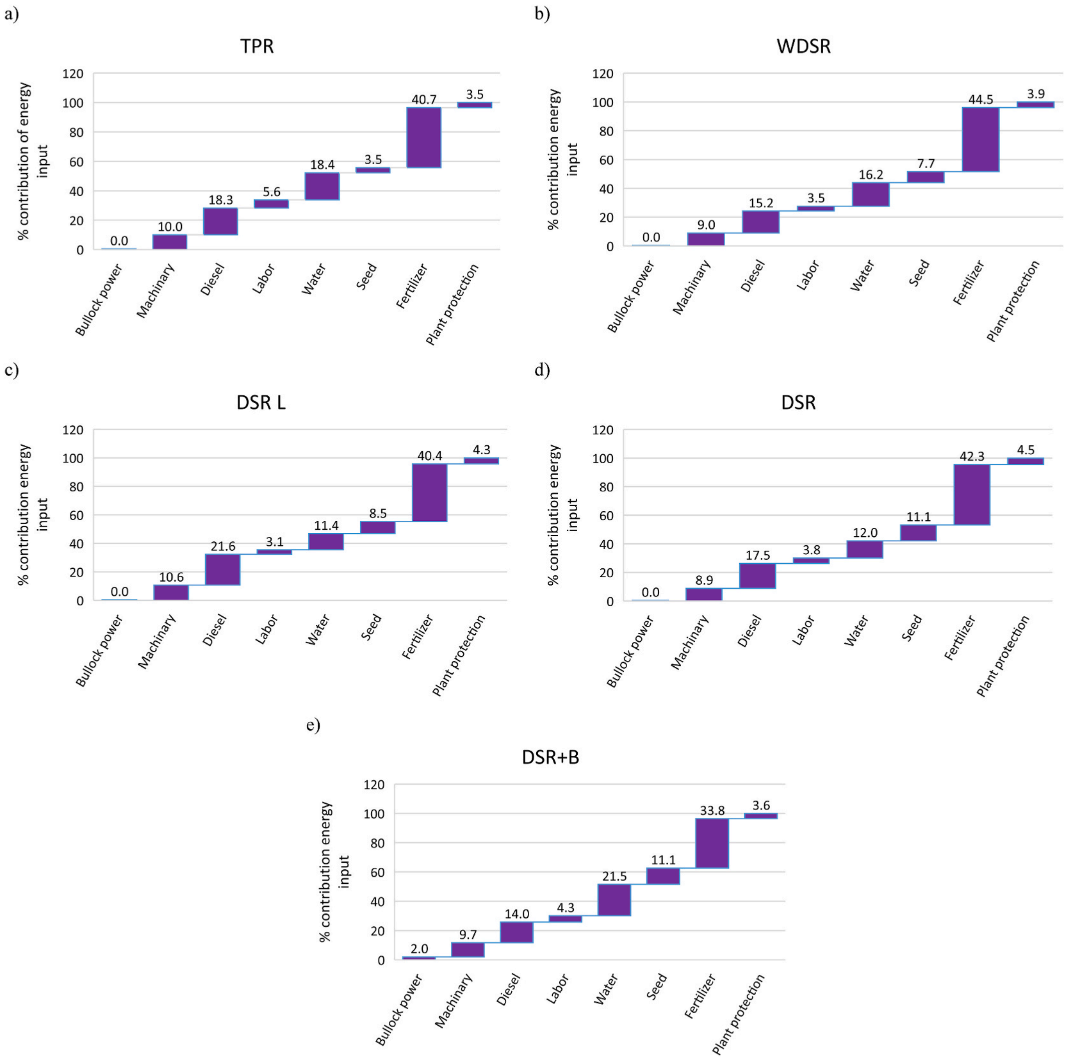

Fig. 4. Source-wise energy input in rice production system a) transplanted rice (TPR), b) wet-direct seeded rice (WDSR), c) drill sown direct seeded rice (DSR L), d) direct seeded rice and e) direct seeded rice with *bueshning* (DSR + B).

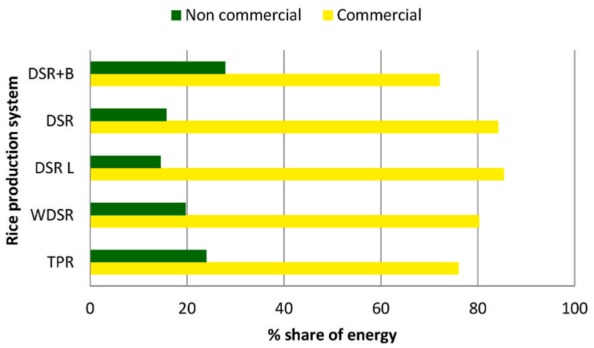

Fig. 5. Source-wise share of commercial and non-commercial energy inputs (%) used in different rice production system.

Eastern Indo-Gangetic Plain of India. Similar to our finding, the consumption of non-renewable energy like diesel, over 60% in Iran [40] and more than 50% in the Philippines [62] had been observed. Efforts must be made to substitute the complete production system with less demanding utilizing local resources and site-specific agricultural practices like conservation tillage where >30% of input energy can be saved [63,64]. In the DSR L rice production system, the number of tillage operations can be considerably reduced. In the study site, the energy consumed in various field operations in the rice production system was moderate because of renewable and non-renewable energy sources. This was lower than many other cereal-based systems [49,65] and also higher than traditional intensive cropping [62] (Quality et al., 2014). Like our findings, Jat et al. [58] found that fertilizer was the primary carbon input in the rice production system, followed by fossil fuel, i.e., diesel. DSR L has the least CF as it remarkably utilizes the resources to convert into economic output with a climate-smart production system [67].

3.3. *Energy parameters*

The data in Table 3 illustrate that the rice production system significantly influenced the energy parameters; the total output energy produced ranged from 151358 MJ ha^{-1} (DSR) to as high as 185927 MJ ha^{-1} (TPR). Energy output relies on economic yield harvested under the rice production systems. The TPR produced significantly higher energy output (185927 MJ ha^{-1}) and net energy returns (168726 MJ ha^{-1}) than other rice production systems. The DSR L was the next best rice production system regarding energy output and net energy returns (182687 and 168377 MJ ha^{-1}, respectively). The traditional DSR production system yielded the most negligible energy output and net energy returns (151358 and 137691 MJ ha^{-1}, respectively). Furthermore, WDSR and DSR + B produced more energy, yet their effect on TPR was less. The increment in energy production (output and net) with TPR was 23% more, followed by DSR L (21 and 22%, respectively) compared to DSR. The WDSR and DSR + B recorded 10–13 and 8–12% more energy than DSR. The maximum energy output and net energy under TPR and DSR L were mainly due to the higher energy output in crop yield and comparatively lower energy expenditure [27,67]. In agreement with our findings, Nagarjun et al. [68] reported higher energy output and net energy return with thrice hand weeding at 20, 40, and 60 DAS (171614 and 160825 MJ ha^{-1}, respectively) in DSR mainly due to higher grain and straw yield. They also found that the variables where lower yield was recorded had the least energy productivity and vice-versa with thrice hand weeding. Syhamlal et al. [69] also corroborated that lower yield led to the least EUE.

Table 3
Energy input, output, net energy return, energy ratio, specific energy, energy intensiveness, and human energy profitability of different rice production systems.

Production system	Total energy input (MJ ha^{-1})	Energy output (MJ ha^{-1})	Net energy return (MJ ha^{-1})	Energy use efficiency	Energy productivity (kg MJ^{-1})	Energy profitability	Energy intensiveness (MJ US\$$^{-1}$)	Human energy profitability
Transplanted rice (n = 75)	17201.1	185927a ±20547	168726a ±20547	10.81b ± 1.19	0.35b ± 0.04	9.81b ± 1.19	24.8c	194.3e±21.5
Wet seeded rice (n = 55)	15725.2	170489b ± 18157	154764b ± 18157	10.84b ± 1.15	0.35b ± 0.04	9.84b ± 1.15	29.5a	310.6b ± 33.1
Drill sown direct seeded rice (n = 60)	14310.8	182687a ±18073	168377a ±18073	12.77a ±1.26	0.41a±0.04	11.77a±1.26	26.8b	407.3a±40.3
Direct seeded rice (broadcasting) (n = 60)	13666.4	151358c ±19706	137691c ±19706	11.08b ± 1.44	0.34b ± 0.05	10.08b ± 1.44	27.1b	292.4c±38.1
Direct seeded rice with *Beushning* (n = 30)	17103.9	165851b ± 24641	148748b ± 24641	9.70c ±1.44	0.30c±0.05	8.70c±1.44	26.7b	216.6d ± 32.2

±, standard deviation; different letters in same column are significant different at $p < 0.05$ and same letters are comparable to each other.

Likewise, EUE was tented to be higher by 32% with DSR L (12.77) than DSR + B (9.7). The rest of the rice production systems also improved the EUE to 11–14% over DSR + B. Barut et al. [70] found higher EUE under no-till DSR than the conventional tilled DSR; as a conventional tilled desired more tractor traffic, it further increased under TPR [54]. Adoption of DSR L recorded 35% more EP than DSR + B (0.30 kg MJ^{-1}). In addition, other rice production systems also recorded an improvement in EP by 13–17% more than DSR + B, according to those reported earlier [59,71]. Among rice production systems, the EPf was improved by 13–35% than DSR + B (8.70), the highest with DSR L (11.77) and the lowest in TPR (9.81), though they were considerably higher than DSR + B. The EIn was improved by 8–19% in different rice production systems over TPR (24.8 MJ $US\$^{-1}$). The highest was recorded with WDSR (29.5 MJ US $\$^{-1}$), followed by DSR (27.1 MJ $US\$^{-1}$). The HEPf acquired was the lowest in TPR (194.3), although there was an improvement in it by 12–110% as compared to TPR. The HEPf was higher in DSR L (407.3), followed by WDSR (310.6) and DSR (292.4), whereas a lower value was obtained under DSR + B (216.6) but was 12% more than TPR (Table 3). The SE was significantly higher in DSR + B (3.4 MJ kg^{-1}); it was 27.2% higher over DSR L and 15.5% over TPR, whereas DSR was lower by 12.3% than DSR + B. These indicated that DSR L had the least energy expended to produce a unit quantity of output, and DSR + B spent the highest point. DSR L was the energy-efficient production system with 1314.3 MJ ha^{-1}, even 3.9% more than TPR, whereas the rest of the rice production systems had lower EOE (Fig. 6). This was mainly due to the minor fertilizer and irrigation energy consumption. Tuti et al. [19] stated a similar trend of energy parameters in colocasia–based cropping systems. Based on the findings, energy, economics and agriculture are interdependent and have a close relationship Nagarjun et al. [68].

3.4. Carbon budgeting

Almost all rice production systems have followed the same trend on various carbon inputs used for various agricultural operations. Fertilizers used in crop production consumed the highest carbon input (52.5–60.6%), followed by water as irrigation (11.9–23.3%) and diesel used in various field operations (11.5–13.7%), plant protection used to manage disease, weeds, and insects (5.2–6.9%) in different rice production systems (Fig. 7). The TPR production system consumed the highest carbon (1095.8 kg CO_2eq ha^{-1}), with which 54.8% alone from fertilizer, 17.5% from water, and 15.7% from diesel, followed by WDSR (991.1 kg CO_2eq ha^{-1}) in which fertilizer consumed 60.6% and water (15.6%), diesel (13%) of total carbon. The least carbon was consumed in DSR L (830.2 kg CO_2eq ha^{-1}) compared to other rice production systems. Adopting a DSR-based rice production system has consumed considerably less carbon inputs. Surprisingly, WDSR has consumed 19.4% more carbon, by applying a higher fertilizer, water, and labor rate. Likewise, further modification in the rice production system finished 32.0% more carbon in TPR over DSR L. This was due to higher fertilizer, water, labor, puddling, and nursery management. Hence, it can be inferred that improvement in the rice production system consumed more carbon. However, DSR L has been recently adopted in a larger area with the lowest carbon consumption over other rice production systems. Similar findings were reported in the pigeonpea–castor cropping system [71], diversified cropping system [7], rice [54], and the upland rice–toria cropping system [59].

3.5. Carbon parameters

The rice production system significantly influenced the carbon output, efficiency, and CF (Table 4). Among the different rice production systems, TPR maintained significantly higher carbon output (6075.6 kg CO_2eq ha^{-1}) after that in DSR L (5979.0 kg CO_2eq ha^{-1}), whereas the lowest carbon output was recorded in DSR (4966.6 kg CO_2eq ha^{-1}). The TPR had 22% more carbon output, followed by DSR L (20%) > WDSR (12%) > DSR + B (10%) than that of DSR. Likewise, carbon efficiency was the highest with DSR L (7.20), followed by DSR (5.95) > DSR + B (5.70) > WDSR (5.62) > TPR (5.54). DSR L production system had the highest carbon efficiency, and it recorded a higher trend of TPR (23%) > WDSR (22%) > DSR + B (21%) > DSR (17%). The higher carbon efficiency was mainly attributed to lower carbon input by the rice production system than that of others. The CSI was recorded as the highest in DSR L (6.2), with 36.5% more than the TPR; DSR was the next best rice production system with a 9.0% improvement over TPR. DSR + B and WDSR were comparable to TPR. The carbon credit explains how many carbon units can be sold; TPR was recorded with the highest carbon credit (91.1 \$ t^{-1} ha^{-1} yr^{-1}) and was comparable to DSR L (89.7 \$ t^{-1} ha^{-1} yr^{-1}). The rest of the rice production system had considerably lower carbon credit by 8.2% in WDSR, 10.5% in DSR + B, and 18.3% in DSR over TPR. This exhibited that TPR is the

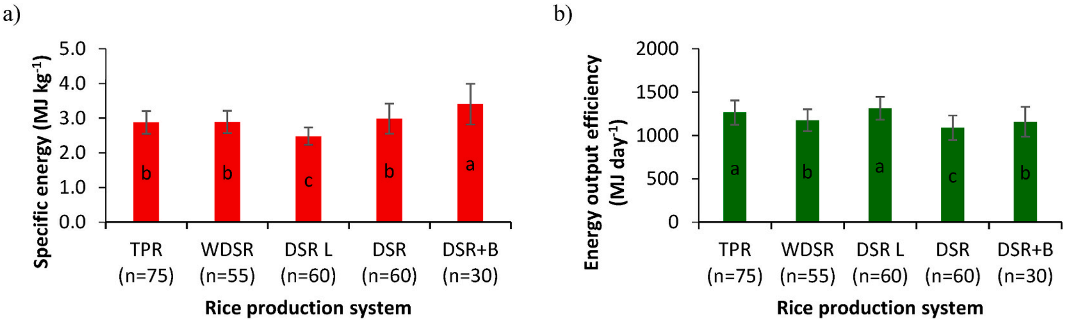

Fig. 6. Rice production system influences a) specific energy and b) energy output efficiency (same letters are statistically comparable).

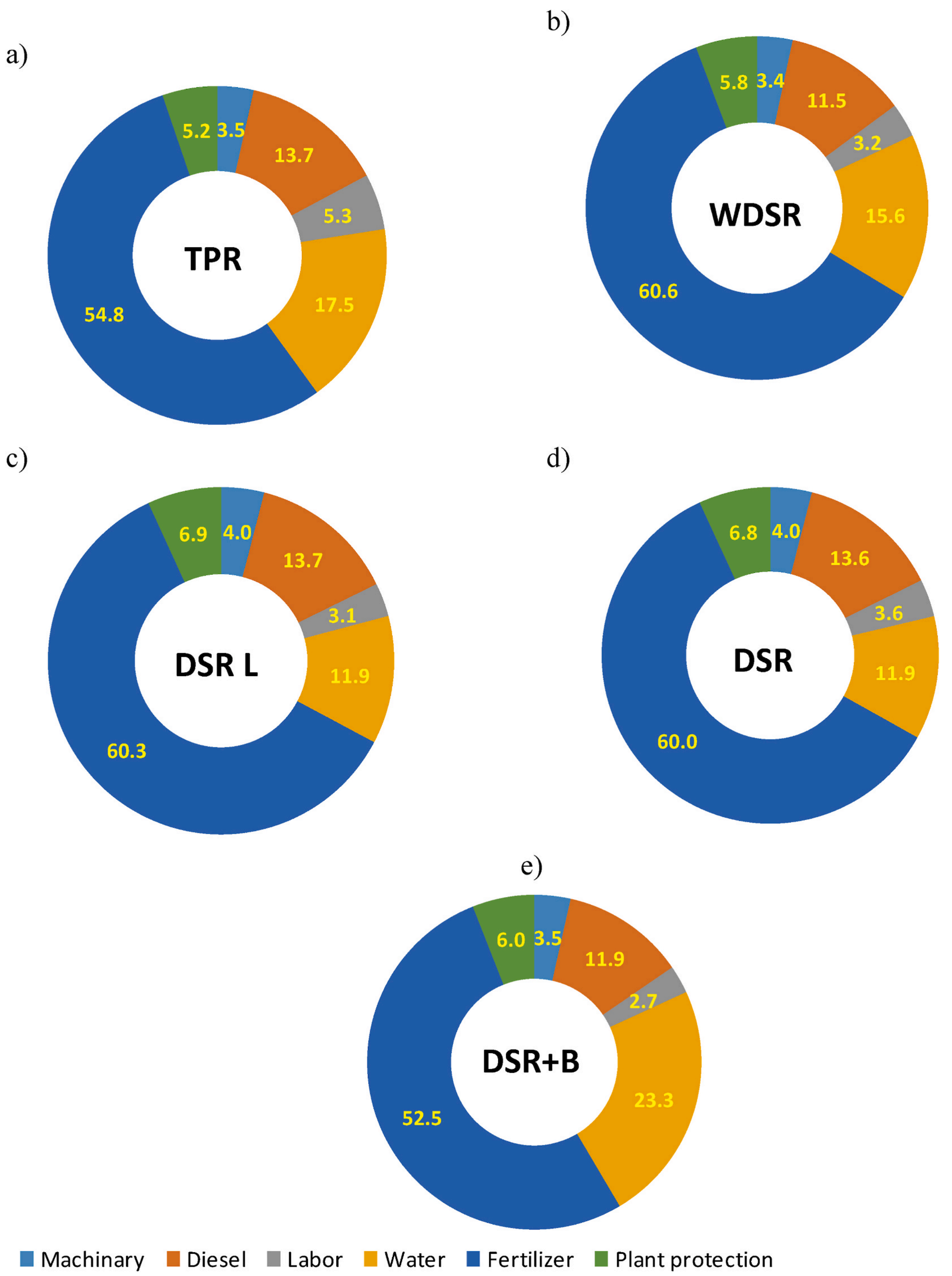

Fig. 7. Contribution of carbon input (%) in different rice production systems a) transplanted rice, b) wet-direct seeded rice, c) drill sown direct seeded rice, d) direct seeded rice and e) direct seeded rice with *beushning*.

efficient production system along with DSR L (Fig. 8). The DSR L has significantly lower CF (0.14 kg CO_2eq kg^{-1} grain) than the other rice production system. Although it was 32% lower than DSR + B, followed by 27% lower than DSR, TPR, and WDSR as these had similar CF (0.18 kg CO_2eq kg^{-1} grain). It has been stated that management practices influenced the CF; the consumption of non-renewable energy has lesser carbon credit Choudhary [54]. Singh et al. [7] found the highest CF in the rice–wheat cropping system (0.114 kg CO_2eq ha^{-1}) followed by the maize–wheat system; it was mainly due to the application and conversion efficiency of nitrogen

Table 4
Carbon budgeting under different rice production systems.

Production system	Carbon input (kg CO_2eq ha^{-1})	Carbon output (kg CO_2eq ha^{-1})	Carbon efficiency	Carbon footprint (kg CO_2eq kg^{-1} grain)
Transplanted rice (n = 75)	1095.8	6075.6a±671.4	5.54c±0.61	0.18a±0.02
Wet seeded rice (n = 55)	991.1	5574.6b ± 593.7	5.62c±0.60	0.18a±0.02
Drill sown direct seeded rice (n = 60)	830.2	5979.0a±591.5	7.20a±0.71	0.14b ± 0.01
Direct seeded rice (broadcasting) (n = 60)	834.5	4966.6c±646.6	5.95b ± 0.77	0.18a±0.03
Direct seeded rice with *Beushning* (n = 30)	953.9	5439.1b ± 808.1	5.70BCE±0.85	0.19a±0.03

±, standard deviation; different letters in same column are significant different at $p < 0.05$ and same letters are comparable to each other.

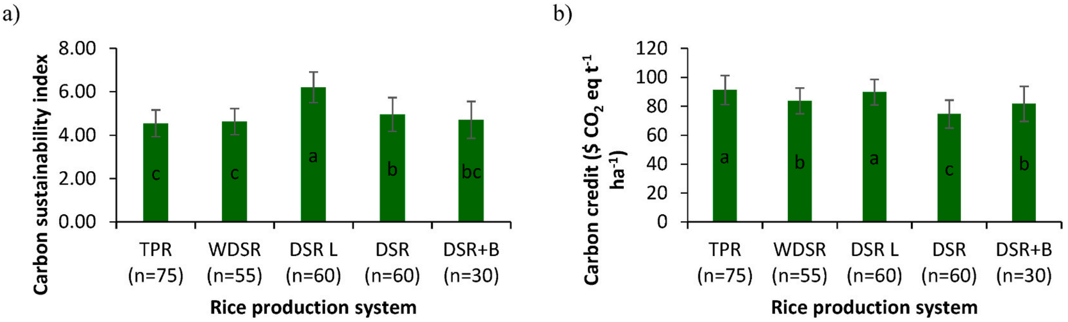

Fig. 8. Rice production system influences a) carbon sustainability index and b) carbon credit (same letter represents statistically comparable).

fertilizer to economic yield [20,43,72]. Yadav et al. [59] revealed that the no-till field had~74% less GHG emissions from diesel and higher carbon efficiency (10.36) than the conventional till area. This was mainly associated with higher carbon input than that of carbon output. Adoption of good agronomic practices in crop production, helps in minimizing CF and also improves the crop yield. This can be further improved by adopting conservation tillage, placement of mulch, use of organic fertilizer, and diversifying crop rotations [73,74]. Environmental sustainability is a major concern in the modern production system; but it also adversely influences climate [75]. Adopting the DSR L production system is climate-smart and climate-resilient, attaining comparable economic yield to the TPR production system; it will resolve the issue of ecological sustainability [76]. It was also recorded that DSR L has the least CF with lower energy input. The areas where irrigation is being supplied through lifting underground water could be further improvised by adopting rainwater harvesting structures.

Adopting resource, energy, and carbon-efficient rice production systems is paramount in the present-day situation [77]. The DSR L production system requires less water, diesel, machinery, and fertilizer over TPR and others, and comparable yield, resulting in profitable, energy, and carbon-efficiency. DSR L production should be disseminated on a large scale emphasizing the precise utilization of inputs. In the DSR L system, further energy and carbon efficiency can be improvised by altering agronomic management practices [78].

3.6. *Economics parameters*

The data on production cost, gross and net returns, and B: C were analyzed (Table 5). TPR had a higher mean production cost (691.8 US$ ha^{-1}) followed by DSR + B (640.7 US$ ha^{-1}). The lowest cost of production was observed for DSR (503.8 US$ ha^{-1}) and DSR L (533.0 US$ ha^{-1}). The gross returns were largely dependent on grain and straw rice yields; TPR had higher gross returns (1703.1 US$ ha^{-1}) and the lowest in DSR (1321.7 US$ ha^{-1}). The rest of the rice production system had a gross return between these two. Based on the data, DSR L was the second-best rice production system comparable to TPR but superior to DSR, DSR + B, and WDSR. The net returns tended to be highest in DSR L (1111.5 US$ ha^{-1}). The next best rice production system regarding net returns was WDSR (1016.8 US$ ha^{-1}), followed by TPR (1011.3 US$ ha^{-1}). The lowest net returns were obtained in DSR + B (817.2 US$ ha^{-1}), and DSR (817.9 US$ ha^{-1}). The net returns largely depended on the economic yield harvested and the production cost involved. The DSR L had a considerably higher yield with comparatively lower production costs, which led to higher net returns. Our findings are corroborated by earlier findings of Chaudhary et al. [15], Yadav et al. [6], Yadav et al. [59]. It has been stated that in DSR L, a better growth environment helped the plants synthesize more yield attributes and resulted in higher yield, with considerably less production cost ultimately guided to obtain net returns. Likewise, the B: C obtained was the highest in DSR L (3.09), followed by WDSR (2.90), although both were comparable. But it had considerably more than that of other rice production systems. Nevertheless, TPR produced a higher economic yield but was also associated with higher production costs, thus recording a lower B: C. The TPR rice production was found to be the most input intensive, such as water-guzzling, deterioration of soil health, and environmental pollution by exhaustive tillage, less responsive to nutrients, and energy-expensive [79]; therefore, the cost of production was comparatively higher [54].

Table 5
Economic parameters under different rice production systems.

Production system	Cost of cultivation (US\$ ha^{-1})	Gross return (US\$ ha^{-1})	Net return (US\$ ha^{-1})	Benefit: cost
Transplanted rice (n = 75)	691.8	1703.1a±188.2	1011.3b ± 188.2	2.46d ± 0.27
Wet seeded rice (n = 55)	533.9	1550.8b ± 165.2	1016.8b ± 165.2	2.90b ± 0.31
Drill sown direct seeded rice (n = 60)	533.0	1644.5a±162.7	1111.5a±162.7	3.09a±0.31
Direct seeded rice (broadcasting) (n = 60)	503.8	1321.7d ± 172.1	817.9c±172.1	2.62c±0.34
Direct seeded rice with *Bueshning* (n = 30)	640.7	1457.9c±216.6	817.2c±216.6	2.28e±0.34

Exchange of rate 1US\$ = 65 INR (2015-16).
Price of produce, rice grain: 261.5 US\$ t^{-1}; straw: 15.4 US\$ t^{-1}.
±, standard deviation; different letters in same column are significant different at $p < 0.05$ and same letters are comparable to each other.

Correspondingly, some rice production systems also required inputs to perform specific operations such as nursery management, puddling and transplanting in TPR; puddling in WDSR, *bueshning* in DSR + B, and drill sowing in DSR L than the traditional DSR.

The adoption of DSR L unequivocally demands reduced energy inputs while delivering superior EO and NER, thus ensuring the highest levels of energy efficiency, productivity, and profitability. Moreover, DSR L boasts the lowest carbon inputs while yielding the highest carbon output and efficiency, coupled with reduced CF. These combined attributes culminate in reduced production costs, maximized NR, and an impressive B: C. Consequently, DSR L emerges as an exemplary rice production system, excelling in productivity, profitability, and carbon and energy efficiency.

4. Conclusions

The farmers' adopted approaches were reported on the findings from 280 farmer locations. This study measures carbon and energy inputs and outputs for per unit productivity, profitability, energy consumption efficiency, and environmental indices to create a safer, more ecologically friendly rice production system in South Asia. The data also supports the following conclusions.

1. TPR had a 29% better grain yield than regular DSR, followed by DSR L with a 25% higher yield. Conversely, TPR used the most significant amount of agricultural input, resulting in higher production costs (691.8 US\$ ha^{-1}) and energy use (17201.1 MJ ha^{-1}). Compared to standard DSR, DSR L is used more wisely per unit inputs, resulting in lower production costs (533.0 US\$ ha^{-1}) and energy utilization (14310.8 MJ ha^{-1}).
2. The DSR L had a greater net returns (1111.5 US\$ ha^{-1}) and B: C (3.09), which was 35.9% and 17.6% higher than traditional DSR, respectively, and was lucrative among other rice production methods.
3. TPR had the highest energy net returns (168726 MJ ha^{-1}), followed by DSR L (168377 MJ ha^{-1}). DSR L was found to be an energy-efficient rice production system, with the highest energy use efficiency (12.77), energy productivity (0.41 kg MJ^{-1}), energy profitability (11.77US\$ MJ^{-1}), and human energy profitability (407.3) among the various rice production systems.
4. The DSR L was more ecologically friendly than other rice production systems, with better carbon efficiency (7.20) and a lower carbon footprint (0.14 kg CO_2eq kg^{-1} grain).
   The adoption of DSR L as a practical alternative rice production technique would surely benefit rice farmers, crop models, government planners, and policymakers with the use of this information. DSR L is recommended for widespread deployment, notwithstanding its benefits, such as its relative productivity, economic feasibility, energy-cumulative efficiency, and environmental friendliness. It may be added to several programs for wider application.

Data availability statement

The mean data has been included in the manuscript and supplementary tables. However, a submission to the journal implies that the relevant raw data will be freely available to any researcher wishing to use them for non-commercial purposes, without breaching participant confidentiality.

CRediT authorship contribution statement

V.K. Choudhary: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ram Swaroop Meena:** Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that there is no conflict of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27691.

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