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RESEARCH

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Bio-energy auditing, system productivity, energy efficiencies and economics of different direct-seeded *basmati* rice-based cropping systems and nutrient management options

Rakesh Kumar Verma[1,2], Yashbir Singh Shivay[1*], Radha Prasanna[3], Prakash Chand Ghasal[4], Chiter Mal Parihar[1], Mukesh Choudhary[5] and Raghavendra Madar[2]

Abstract

Background: Diversification, intensification, new water and integrated nutrient management methods of rice-based cropping systems are being advocated as an alternative to the water-intensive nature of conventional rice cultivation in north-western India to address the issues of decline in the productivity, energy and nutritional scarcity and deteriorating soil fertility. Hence, the development of eco-friendly cropping systems with efficient nutrient management is essential for sustainable productivity.

Material and methods: The experiment was conducted with four cropping systems viz. direct-seeded *basmati* rice (DSBR)-wheat-fallow, DSBR-wheat-greengram, DSBR-cabbage-greengram and DSBR-cabbage-onion, being assigned to vertical strips; and 4 nutrient management strategies (MNS), viz. control, 100% RDF (recommended dose of fertilizers), 50% RDF + 25% RDN (recommended dose of nitrogen) through leaf compost + biofertilizers and 50% RDF + 25% RDN through vermicompost + biofertilizers assigned to horizontal strips.

Results: The highest system productivity (20.7 Mg/ha) was registered in DSBR-cabbage-onion and with a nutrient management strategy of 50% RDF + 25% RDN through vermicompost + biofertilizers (13.5 Mg/ha). The highest net energy (269.6×10^3 MJ/ha) was generated under DSBR-wheat-greengram. Among different NMS, the highest energy output efficiency was recorded under NS_3 (0.20×10^3 MJ/ha/day). The CS_2 had 20.4% and 20.2% higher total system protein yield and protein equivalent yield for adults than DSBR-wheat-fallow, respectively. Application of NS_3 had the highest total system protein yield (89.7%) and protein equivalent yield for adults (92.6%) over the control (NS_0). The maximum net return (5755 US$/ha) was obtained under CS_4.

Conclusion: A cropping system involving DSBR-cabbage-onion and application of 50% RDF + 25% RDN through vermicompost + biofertilizers is identified as the most productive, energy efficient and profitable production system.

Keywords: Bio-energy, Nutrient management strategies, Protein yield, Rice equivalent yield

Introduction

In India, Haryana, Punjab, Uttar Pradesh, Uttarakhand, and Jammu & Kashmir are the *basmati* rice growing states with an annual production of about 5.1 million metric tonnes (mt) from 1.5 million hectares (m ha) during 2018–2019 (Udhayakumar et al. 2021). The

*Correspondence: ysshivay@hotmail.com

[1] Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India
Full list of author information is available at the end of the article

conventional puddled transplanted system of rice establishment is water, capital and energy intensive (Gupta et al. 2006). The use of chemical fertilizers, pesticides and excess irrigation are also increasing the energy inputs in conventional rice-based cropping systems, especially rice–wheat (Hatirli et al. 2006; Pishgar-Komleh et al. 2012; Soni et al. 2013; Pratibha et al. 2015). These production practices lead to soil health degradation (Bhandari et al. 2002; Gupta et al. 2006), rapidly declining underground water table (Hira et al. 2004; Gupta et al. 2006; Humphreys et al. 2010), environmental pollution (Singh et al. 2008) and yield stagnation (Busari et al. 2015), which has resulted in a decline in productivity and sustainability of the conventionally followed rice-based cropping systems. Subsequently, direct-seeded rice (DSR) has been receiving much attention because of its low inputs (water and labour) demand (Gupta et al. 2006), the most energy-efficient rice cultivation method (Mandal et al. 2015), and its productivity is often reported as comparable to the conventional transplanting method (Gangwar et al. 2008).

Continuous cultivation of the cereal–cereal system is more exhaustive and the main cause of deterioration of the rhizosphere environment, which leads to the impairment of nutrient availability and poor root growth. Under this situation, it is desirable to diversify or intensify existing cropping systems through the use of different pulses and vegetable crops. This not only helps in achieving the objectives of food security, nutritional security, judicious use of land, and water resources, sustainable agriculture development and environment improvement (Gangwar and Prasad 2005; Hedge et al. 2006; Ali and Kumar 2009; Meena and Meena 2017) but also enhances the below ground diversity of beneficial soil organisms due to different plant–microbial interactions. This improves nutrient cycling within the soil system. Crop diversification/intensification and organic management hold a lot of promise in improving soil quality, conserving natural resources and judicious use of inorganic fertilizers (Gill and Ahlawat 2006; Bhatt, 2013; Laxmipathi Gowda et al. 2013). However, the energy-farming system relationship is more important with the intensification of the existing cropping systems. Traditional, low-energy farming is being replaced by modern mechanized systems, which require more energy use (Chaudhary et al. 2009). Crop diversification as an alternative helps in improving total farm productivity, water, land, energy use efficiency and farm profitability (Das et al. 2014a, b) under the changing climate scenario (Congreves et al. 2015).

Energy is critical to agricultural production (Devasenapathy et al. 2009), and the sustenance of human life (Saad et al. 2016). Energy consumption in agriculture has increased day by day to feed the ever-increasing population (Das 2012; Yuan and Peng 2017). Intensive tillage, indiscriminate use of inorganic fertilizers and reduced use of organic manure has not only affected soil quality but also crop productivity and the quality of agricultural produce (Kamoshita et al. 2010). These factors resulted in a high cost of cultivation due to the rising fuel prices, and inflated labour costs (Ladha et al. 2009; Das et al. 2014a, b), as labor is becoming a scarce resource in recent times.

For a sustainable and cleaner agro-ecosystem functioning, agricultural management practices that involve low energy inputs and improve energy use efficiency are the need of the hour. In this context, the inclusion of legumes in prevailing cropping systems enhances energy use efficiency through savings of nitrogen fertilizer and leads to higher system productivity (Fernandez and Zentner 2005). The integrated use of organic manure with inorganic fertilizers in crop rotations led to significant savings in energy use (Hoeppner et al. 2005; Pimentel et al. 2005); this was more energy efficient than conventionally managed systems (Clancy et al. 1993; Clements et al. 1995; Haas et al. 2001; Gregory et al. 2005).

The specific objective of this study was to evaluate the system productivity, bio-energy efficiency and profitability of different diversified *basmati* rice-based cropping systems under reoriented nutrient management strategies. The experiment was planned to test the hypothesis that integrated nutrient management and inclusion of short-duration legume crops in rice–wheat cropping systems will require less energy input and lead to higher profitability, than conventional managed cereal–cereal based-cropping systems.

Materials and methods

Site description and soil characteristics

A field experiment was conducted comprising crops namely rice, wheat, cabbage, onion and greengram during the rainy (*Kharif*), winter (*Rabi*) and summer seasons of 2014–2015 and 2015–2016 at ICAR-Indian Agricultural Research Institute (IARI), New Delhi (28° 38′ N and 77° 10′ E, 228.6 m above mean sea level). The climate of the location is the sub-tropical and semi-arid type with hot and dry summer and cold winters and falls under the agro-climatic zone of 'The trans-Gangetic plains. Mean metrological parameters during cropping seasons were recorded at ICAR-IARI metrological observatory adjacent to the experimental field (Figs. 1, 2).

The soil of the experimental field was alluvium-derived sandy clay loam (*typic Ustochrept*) with 51.7% sand, 21.9% silt, and 26.4% clay. The soil (0–30 cm layer) had pH 7.9 (1:2.5 soil: water ratio), electrical conductivity 0.76 dS/m, Walkley–Black C (oxidizable-SOC) 0.49%, alkaline $KMnO_4$-oxidizable-N 209.7 kg/ha (Subbiah and

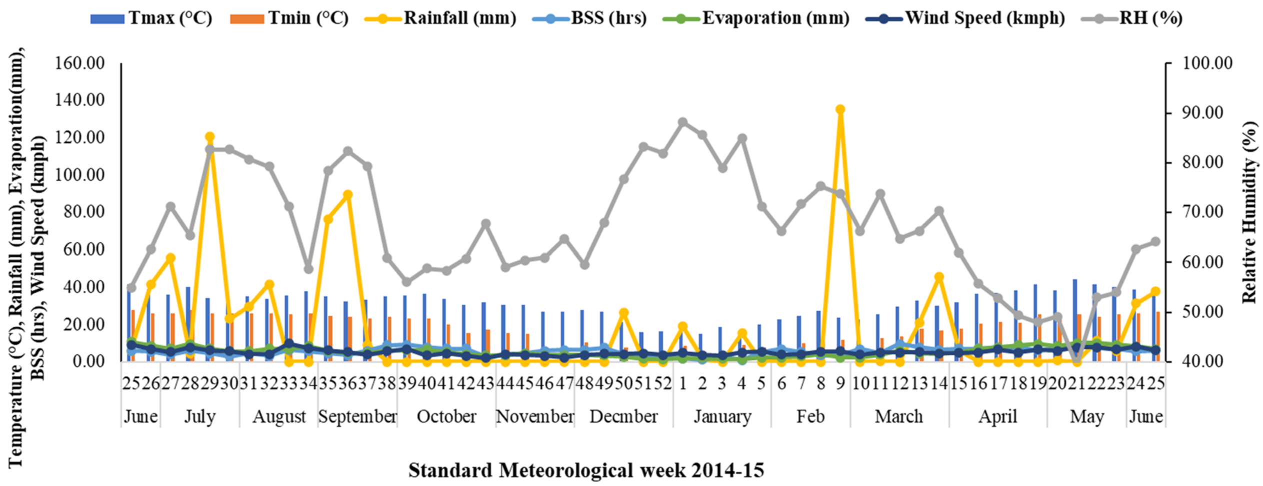

Fig. 1 Mean weekly weather parameters during June 2014 to June 2015

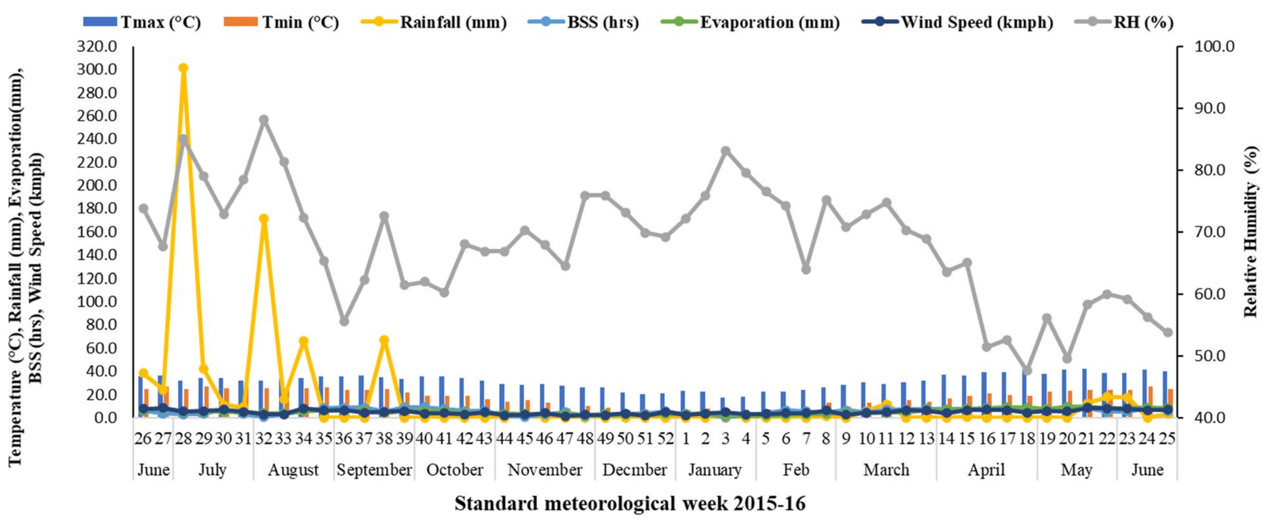

Fig. 2 Mean weekly weather parameters during June 2015 to June 2016

Asija 1956), 0.5M $NaHCO_3$-extractable P 15.3 kg/ha (Olsen et al. 1954), 1N NH_4OAc-extractable K 272.4 kg/ha (Hanway and Heidel 1952), particulate organic carbon 0.86 g/kg soil, light fraction carbon 0.52 g/kg soil, microbial biomass carbon of 211.4 µg/g soil, dehydrogenase activity of 49.3 µg TPF/g soil/day, the alkaline phosphatase activity of 89.6 µg PNP/g/soil/hr, polysaccharide content of 1958.4 µg/g, bulk density (0–15 cm layer) 1.48 Mg/m^3 and water stable aggregates 56.9%.

Experimental setup, design and treatments

The experiment was laid out in a strip-plot design. The 16 treatment combinations with a sub-plot size of 15.0 m^2 (5.0 m length × 3.0 m width) were replicated thrice for both the years of study. Four cropping systems (CS), viz. direct-seeded *basmati* rice (DSBR)-wheat-fallow (CS_1), DSBR-wheat-greengram (CS_2), DSBR-cabbage-greengram (CS_3) and DSBR-cabbage-onion (CS_4) were assigned to vertical strips; and 4 nutrient management strategies (NMS), viz. control (NS_0), 100% RDF (recommended dose of fertilizers) (NS_1), 50% RDF + 25% RDN (recommended dose of nitrogen) through leaf compost (LC) + biofertilizers (NS_2) and 50% RDF + 25% RDN through vermicompost (VC) + biofertilizers (NS_3) were assigned to horizontal strips. The vermicompost, 5.26 t/ha for rice and wheat, 6.55 t/ha for cabbage, 4.53 t/ha for onion and 0.71 t/ha for greengram (0.60% N, 0.30% P, 0.39% K) and leaf compost, 8.33 t/ha for rice and wheat, 10.33 t/ha for cabbage, 6.22 t/ha for onion and 1.03 t/ha for greengram (0.37% N, 0.10% P, and 0.21% K) was applied before sowing of crops based on nitrogen equivalent basis and requirement of crops in respective treatments. Leaf compost was prepared by the heap method after shredding the leaves into small pieces for quick composting. Allocations of the treatments were done by randomization following Fisher and Yates random number tables. All fertilizers (Additional file 1: Table S1) to greengram were applied at sowing. One-third dose of N for rice and wheat and half dose of N for cabbage and onion and a full dose of P and K were applied at planting. Remaining N was applied in two equal splits after the first irrigation at tillering stage in rice and wheat, whereas, in cabbage and onion, it was applied at 45 and 30 days after planting, respectively. Seeds/seedlings of crops were treated with *Rhizobium* in greengram, and *Azotobacter* in wheat and cabbage, and *Azospirillum* in onion, based on the respective treatments at sowing/planting. Details on crop establishment are given in Additional file 1: Table S1.

Measurements and calculations

The rice and wheat were manually harvested with sickles at ripening stages and the produce was left in the field for 3 days for sun-drying. Threshing was done manually for rice and wheat using an ALMACO Pullman Thresher and the grains were cleaned and weighed. The yield per plot was adjusted at 14% moisture for rice and 12% moisture for wheat and expressed as Mg/ha. The weight of rice/wheat straw was also recorded, separately. Cabbage was harvested in the first fortnight of January, while onion was harvested in the first fortnight of May for each year of experimentation. Greengram pods were hand-picked twice, first when pods changed to blackish-brown in colour, and the second when all the pods matured. The yield was expressed in Mg/ha.

To compute the system productivity of the diversified DSBR-based cropping systems, the yield of non-rice crops was converted into rice equivalent yield (Mg/ha) using the equation:

$$\begin{aligned}&\text{Rice equivalent yield}\left(\text{Mg/ha}\right)\\&=\text{rice yield}\left(\text{Mg/ha}\right)\\&\quad+\sum\left(\text{respective crop yield in the system}\right.\\&\quad\times\text{MSP of the respective crop}\left.\left(\text{US\$/Mg}\right)\right)/\\&\quad\text{MSP of rice}\left(\text{US\$/Mg}\right),\end{aligned}$$

MSP stands for Market Sale Price.

Nitrogen content in the produce was determined by modified Kjeldahl's method (Jackson 1958). Grain nitrogen content varied from 1.25–1.50% in rice, 1.42–1.65% in wheat, 1.88–2.25% in cabbage, 1.24–1.40% in onion, and 3.46–3.55% in greengram. Protein content was calculated by multiplying the estimated nitrogen content described by Lindner (1944) with the standard factor given by AOAC (1990) for each crop i.e., for rice-5.95; wheat-5.80; cabbage-5.63; onion-5.63 and greengram-5.70. The system protein yield includes the protein yield of all the crops (rice, wheat, cabbage, onion, and greengram). An annual adult protein demand equivalent is calculated based on the 60 g/person/day as per the recommendations of the Indian Council of Medical Research (1981).

The energy inputs consisted of renewable and non-renewable energy. The energy inputs comprised human labour, fuel, machinery, chemical fertilizers (N, P, and K) and agro-chemicals, etc., whereas, renewable energy included seeds, organic manures (leaf compost, vermicompost, biofertilizers), and crop residues. The primary data on various inputs and agronomic practices were used for the estimation of energy consumption. The energy output from the biomass, grain/seed/head/bulb, and straw/stover yield was also computed. The loss of output was very negligible from aberrant weather conditions and pests. Therefore, not included in the calculations. The energy inputs and energy outputs were calculated using energy equivalents, as suggested by Mandal et al. (2002) and Zangeneh et al. (2010) and given in Additional file 1: Table S2. The following indices are pertinent to evaluate the changes in energy requirements as influenced by rice-based cropping systems and nutrient management. Energy use indices were calculated using the following formula as suggested.

Energy use efficiency = Energy output (MJ/ha)/Energy input (MJ/ha).

Energy efficiency is an indicator of energy demand and the cost involved in production. Hence, improved energy efficiency manifests a reduction in production cost and energy. Further, it helps in decreasing dependence on fossil fuels thereby, diminishing greenhouse gas emissions.

Energy productivity in terms of rice equivalent yield (kg/MJ) = system productivity (kg/ha)/energy input (MJ/ha).

REY is required for the estimation of production efficiency (PE). REY determines the yields of different intercrops/crops, which are converted into an equivalent yield of any one crop based on the price of the produce (Habimana et al. 2021).

Energy intensiveness (MJ/US$) = Energy input ÷ cost of cultivation.

Net energy returns (MJ/ha) = Energy output (MJ/ha) − Energy input (MJ/ha). It is used to access energy surplus-related issues (Rahman et al. 2017).

Energy profitability = Net energy returns (MJ/ha) ÷ Input energy (MJ/ha).

Energy output efficiency (MJ/ha) = Energy output (MJ/ha)/Crop duration (days).

The land and production use efficiencies were calculated using the following formulae:

Production efficiency (kg REY/ha/day) = REY (kg/ha)/crop durations of the system. It signifies the lowest possible cost at which maximum productivity can be obtained.

Production efficiency (US$/ha/day) = System net returns (US$/Crop durations of the system)

Land use efficiency = Crop durations × 100/365. It helps to gain an insight into maximum economic output under a given amount of land input (Qiu et al. 2021).

The economic analysis was done by considering the variable production costs only. The variable costs included human labour, use of machinery (tractor, plough, cultivator, seed drill, sprayer, etc.), the input cost (seed, chemical fertilizer, organic manures, and herbicides), and irrigation, harvesting, and threshing. The production cost, however, did not include the value of the land. The prevailing market price for different key inputs was taken for the calculation of gross returns (GR). Net returns (NR) were calculated by deducting the total cost (TC) of cultivation from gross returns (GR) (NR = GR–TC). The cropping system net returns were computed by adding the net returns of all the crops grown in a sequence within each calendar year. The system net benefit cost (NBC) ratio was calculated by dividing net returns with the total cost (TC) of cultivation (NBC ratio = Net returns ÷ cost of cultivation). For better comparisons, all the economic data (cost of cultivation and net returns) were converted from Indian rupees (INR) to US$ using an exchange rate (INR/US$) of 64 (2014–2015) and 67 (2015–2016).

Statistical analyses

The experiments were taken up in the fixed strip plots during both seasons/years. Analysis of variance was performed using the SAS statistical package version 9.3, SAS Institute., Cary, NC with the general linear model in strip-plot design for 2 years and also the pooled data (SAS Institute Cary, NC, USA). The year was considered as an orthogonal treatment as there were no repeated measures on strips. The least significant difference test at 5% probability was used to decipher the main and interaction effects of treatments through the Fisher least significant differences (LSD) and Tukey's Studentized Range test was used to separate the treatment means. The pooled analysis was done and pooled data are presented in the tables which include the year effect. Details on ANOVA of the statistical analysis used are given in Additional file 1: Tables S3–S5.

Results

The results of the 2-year study were pooled and only the average values are discussed throughout this paper.

Energy relationship

The average input energy consumption of various cropping systems (CS) was the lowest in DSBR-wheat-fallow (30.7×10^3 MJ/ha) and the highest in DSBR-cabbage-onion CS (48.9×10^3 MJ/ha) cropping systems (Table 1). Among nutrient management strategies (NMS), the highest input energy use was registered in 100% RDF (45.8×10^3 MJ/ha) plots and was followed by 50% RDF + 25% RDN-VC + biofertilizers (39.6×10^3 MJ/ha) and 50% RDF + 25% RDN-LC + biofertilizers (41.7×10^3 MJ/ha).

Bio-energy outputs and net energy of different direct-seeded *basmati* rice-based cropping systems and nutrient management strategies are depicted in Table 1. Significantly highest energy output (305.1×10^3 MJ/ha) and net energy (269.6×10^3 MJ/ha) were generated under the DSBR-wheat-greengram system. Among different nutrient management strategies, the highest energy output and net energy were registered under 50% RDF + 25% RDN-VC + biofertilizers (252.7 and 213.0×10^3 MJ/ha), followed by 50% RDF + 25% RDN-LC + biofertilizers (247.5 and 205.8×10^3 MJ/ha) and least under control treatment (169.3 and 143.6×10^3 MJ/ha). Similarly, significantly the highest energy efficiency ratio was registered under DSBR-wheat-fallow CS (8.97) followed by DSBR-wheat-greengram CS (8.67) and minimum under DSBR-cabbage-onion CS (3.37).

On the contrary, the highest energy productivity was registered under DSBR-cabbage-onion CS (0.420 kg REY/MJ) followed by DSBR-cabbage-greengram CS (0.342 kg REY/MJ), and was the least under DSBR-wheat-fallow CS (0.195 kg REY/MJ) (Table 2). However, energy output efficiency (1.08×10^3 MJ/ha/day), energy profitability (7.97) and energy intensiveness (0.387 MJ/US$) was found highest under DSBR-wheat-fallow system and the least under the DSBR-cabbage-onion system. Among NMS, the highest energy output efficiency was recorded under 50% RDF + 25% RDN-VC + biofertilizers (0.92×10^3 MJ/ha/day) and least under control/unfertilized treatment (0.62×10^3 MJ/ha/day). However, the maximum energy profitability (6.03) was recorded under control treatment and the minimum under 100% RDF through fertilizers (4.70). On the contrary, the higher energy intensiveness was registered by

Table 1 Effect of cropping systems and nutrient sources on energy input, output, and net energy considering the rice equivalent yield in direct-seeded *basmati* rice-based cropping system

Treatment	Energy input ($\times 10^3$ MJ/ha)			Energy output ($\times 10^3$ MJ/ha)			Net energy ($\times 10^3$ MJ/ha)			Energy efficiency ratio		
	2014–2015	**2015–2016**	**Pooled**	**2014–2015**	**2015–2016**	**Pooled**	**2014–2015**	**2015–2016**	**Pooled**	**2014–2015**	**2015–2016**	**Pooled**
Cropping systems												
DSBR-wheat	29.7	31.7	30.7^{d}	265.9^{b}	273.2^{b}	269.6^{b}	236.2^{b}	241.5^{b}	238.9^{b}	9.17^{a}	8.78^{a}	8.97^{a}
DSBR-wheat-greengram	35.1	36.3	35.7^{c}	296.0^{a}	314.2^{a}	305.1^{a}	261.0^{a}	278.1^{a}	269.6^{a}	8.57^{b}	8.78^{a}	8.67^{a}
DSBR-cabbage-greengram	37.0	38.2	37.5^{b}	170.1^{c}	183.9^{c}	177.0^{c}	133.2^{c}	145.7^{c}	139.5^{c}	4.63^{c}	4.85^{b}	4.74^{b}
DSBR-cabbage-onion	47.6	50.4	48.9^{a}	159.0^{dc}	170.3^{d}	164.7^{d}	111.5^{d}	119.9^{d}	115.7^{d}	3.35^{d}	3.40^{c}	3.37^{c}
Nutrient management strategies												
Control	24.8	26.6	25.7^{d}	162.6^{b}	175.9^{b}	169.3^{b}	137.8^{d}	149.3^{c}	143.6^{c}	7.03^{a}	7.03^{a}	7.03^{a}
100% RDF through fertilizers	44.9	46.7	45.8^{a}	240.7^{a}	253.6^{a}	247.2^{a}	195.8^{cb}	206.9^{b}	201.4^{b}	5.67^{cb}	5.74^{c}	5.70^{c}
50% RDF + 25% RDN-LC + Bio	40.8	42.6	41.7^{b}	240.7^{a}	254.2^{a}	247.5^{a}	199.9^{b}	211.6^{ab}	205.8^{b}	6.25^{b}	6.31^{b}	6.28^{b}
50% RDF + 25% RDN-VC + Bio	38.8	40.6	39.6^{c}	247.2^{a}	258.2^{a}	252.7^{a}	208.4^{a}	217.6^{a}	213.0^{a}	6.76^{a}	6.73^{a}	6.74^{a}

Data represent mean values (n = 3) within a column followed by means with the same letter are not significantly different ($P < 0.05$) according to Tukey's Studentized Range test

DSBR, Direct-seeded *basmati* rice; RDF, Recommended dose of fertilizers; RDN, Recommended dose of nitrogen; LC, Leaf compost; VC, Vermicompost; Bio, Biofertilizers

Table 2 Effect of cropping systems and nutrient sources on energy use indices considering the rice equivalent yield in direct-seeded *basmati* rice-based cropping systems

Treatment	Energy productivity (kg REY/MJ)			Energy output efficiency ($\times 10^3$ MJ/ha/day)			Energy profitability			Energy intensiveness (MJ/US$)		
	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled
Cropping systems												
DSBR-wheat	0.20^{dc}	0.19^{dc}	0.195^{c}	1.07^{a}	1.10^{a}	1.08^{a}	8.17^{a}	7.78^{a}	7.97^{a}	0.39	0.39	0.387^{a}
DSBR-wheat-greengram	0.20^{c}	0.20^{c}	0.200^{c}	0.96^{b}	1.02^{b}	0.99^{b}	7.57^{b}	7.78^{a}	7.67^{a}	0.38	0.37	0.375^{b}
DSBR-cabbage-greengram	0.34^{b}	0.34^{b}	0.342^{b}	0.71^{c}	0.77^{c}	0.74^{c}	3.63^{c}	3.85^{b}	3.74^{b}	0.37	0.36	0.363^{c}
DSBR-cabbage-onion	0.44^{a}	0.40^{a}	0.420a	0.52^{d}	0.56^{d}	0.54^{d}	2.35^{d}	2.40^{c}	2.37^{c}	0.31	0.30	0.308^{d}
Nutrient management strategies												
Control	0.28^{dc}	0.26^{dc}	0.270^{c}	0.59^{b}	0.64^{b}	0.62b	6.03^{a}	6.03^{a}	6.03^{a}	0.33	0.32	0.322^{b}
100% RDF through fertilizers	0.28^{c}	0.27^{cb}	0.272^{c}	0.88^{a}	0.93^{a}	0.90a	4.67^{c}	4.74^{c}	4.70^{c}	0.49	0.47	0.480^{a}
50% RDF + 25% RDN-LC + Bio	0.30^{b}	0.29^{b}	0.293^{b}	0.88^{a}	0.93^{a}	0.90a	5.25^{b}	5.31^{b}	5.28^{b}	0.32	0.32	0.321^{c}
50% RDF + 25% RDN-VC + Bio	0.33^{a}	0.32^{a}	0.322^{a}	0.90^{a}	0.94^{a}	0.92a	5.76^{a}	5.73^{a}	5.74^{a}	0.31	0.31	0.311^{d}

Data represent mean values (n = 3) within a column followed by means with the same letter are not significantly different ($P < 0.05$) according to Tukey's Studentized Range test

DSBR, Direct-seeded *basmati* rice; RDF, Recommended dose of fertilizers; RDN, Recommended dose of nitrogen; LC, Leaf compost; VC, Vermicompost; Bio, Biofertilizers

100% RDF through fertilizers (0.480 MJ/US$) followed by control (0.322 MJ/US$).

Land use and production efficiency

Production efficiency and land use efficiency were significantly influenced by the different CS and NMS (Table 3). DSBR-cabbage-onion system registered significantly highest average production efficiency in REY (rice yield equivalent) (67.8 kg REY/ha/day) as well as monetary returns (18.9 US$/ha/day) followed by DSBR-cabbage-greengram system (54.4 kg REY/ha/day and 15.1 US$/ha/day). DSBR-wheat-greengram and DSBR-cabbage-onion systems recorded higher land-use efficiency, which was 24.3% and 22.8% greater over the DSBR-wheat-fallow system, respectively.

Among the NMS, the highest production efficiency in terms of REY and monetary returns was registered with application of 50% RDF + 25% RDN-VC + biofertilizer treatment (48.8 kg REY/ha/day and 13.1 US$/ha/day) followed by 50% RDF + 25% RDN-LC + biofertilizer NMS (46.7 kg REY/ha/day and 12.2 US$/ha/day). The lowest production efficiency was recorded in control (25.8 kg REY/ha/day and 6.6 US$/ha/day).

System productivity and protein equivalent yield for adults

The yield of component crops in the system was expressed as rice equivalent yield (REY) under different CS and NMS (Table 4). The highest REY was registered in DSBR-cabbage-onion (20.7 Mg/ha) system, which was 250.8% higher over DSBR-wheat-fallow, 191.5% over DSBR-wheat-greengram, and 58.0% over the DSBR-cabbage-greengram systems. Among the NMS, the application of 50% RDF + 25% RDN-VC + biofertilizer increased the REY by 87.5% over the control.

The DSBR-wheat-greengram CS had 20.4% and 20.2% higher protein yield and protein equivalent yield for adults as compared to the DSBR-wheat-fallow system (Table 4), respectively. Similarly, the DSBR-cabbage-onion system had 18.5% and 18.6% higher total system protein yield and protein equivalent yield for adults than DSBR-wheat-fallow, respectively. Among the NMS, the highest total system protein yield and protein equivalent yield for adults were registered with application of 50% RDF + 25% RDN-VC + biofertilizer (89.7% and 92.6% higher) followed by 100% RDF (82.8% and 83.0% higher) and 50% RDF + 25% RDN-LC + biofertilizer (80.8% and 81.1% higher) over the control. Intensification and diversification of traditional rice–wheat and rice-based CS with greengram and vegetables (cabbage and onion) increased the total protein yield significantly compared to rice–wheat-fallow CS. The rice–wheat system with greengram increased the total protein yield by 0.808 Mg/ha followed by DSBR-cabbage-onion CS by 0.795 Mg/ha compared to rice–wheat-fallow CS, which produced 0.671 Mg protein/ha. Thus, the CS with greengram (DSBR-wheat-greengram) and vegetables (DSBR-cabbage-onion) could meet the adult protein demand of 36.9 and 36.4-persons/year, respectively, compared to 30.7-persons/year (pooled average basis) in the rice–wheat system alone. On a protein demand equivalent basis, integrated nutrient management practices can accommodate 17–18 more persons towards their protein demand in a year than control.

System economics

Production economics of DSBR-based CS under different NMS is presented in Table 5. The highest cost of cultivation was registered under DSBR-cabbage-onion CS (2445 US$/ha) followed by DSBR-cabbage-greengram CS (1597 US$/ha), DSBR-wheat-greengram CS (1480 US$/ha) and least in DSBR-wheat-fallow CS (1237 US$/ha). The maximum system gross returns, net returns, and B:C ratio was recorded under DSBR-cabbage-onion CS (8200, 5755 US$/ha and 2.35) followed by DSBR-cabbage-greengram CS (5176; 3579 US$/ha and 2.24, respectively). Among the NMS, the application of 50% RDF + 25% RDN-VC + biofertilizer resulted in the maximum system gross returns (5630 US$/ha), whereas, the highest system net returns (4009 US$/ha) and net B:C ratio (2.68) was obtained with application of 100% RDF.

Discussion

The results of this study showed the positive effects of including pulse crops in cereals-based cropping systems, along with integrated nutrient management strategies, on energy consumption, net energy, energy output, energy productivity, energy use efficiency, production efficiency, system productivity, and protein equivalent yields (PEY). Despite the best yield and superior performance of the crops, the lowest energy balance, energy output efficiency, energy profitability, and energy intensiveness were recorded in DSBR-cabbage-onion CS, due to its high energy requirement, less energy output, and lower energy equivalent. This can be attributed to the greater energy-intensive manual work for irrigation, intercultural operations, and harvesting of the produce (Mishra et al. 2013; Kumar et al. 2015). Additionally, the inclusion of vegetables in cropping systems, requires higher fertilizer and manures, as compared to cereals and pulses. The greater energy consumption for inorganic fertilizers and manures in many cropping systems has been extensively reported (Salami et al. 2010; Sørensena et al. 2014).

Table 3 Effect of cropping systems and nutrient sources on production and land-use efficiency in direct-seeded *basmati* rice-based cropping systems

Treatment	Production efficiency (kg REY/ha/day)			Production efficiency (US$/ha/day)			Land use efficiency (%)		
	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled
Cropping systems									
DSBR-wheat	23.2^{b}	24.0^{c}	23.6^{c}	6.6^{c}	6.5^{c}	6.6^{c}	68.2	68.0	68.1^{c}
DSBR-wheat-greengram	22.1^{cb}	23.7^{dc}	22.9^{c}	6.0^{dc}	6.3^{dc}	6.2d^{c}	84.9	84.4	84.7^{a}
DSBR-cabbage-greengram	53.6^{a}	55.2^{b}	54.4^{b}	14.6^{b}	15.1^{b}	14.9^{b}	66.0	65.8	65.9^{d}
DSBR-cabbage-onion	69.1^{a}	66.5^{a}	67.8^{a}	18.8^{a}	18.9^{a}	18.9a	83.6	83.6	83.6^{b}
Nutrient management strategies									
Control	25.8^{b}	25.7^{b}	25.8^{b}	6.7^{d}	6.6^{c}	6.6^{d}	75.7	75.4	75.6^{a}
100% RDF through fertilizers	47.5^{a}	47.7^{a}	47.6^{a}	14.4^{a}	14.6^{a}	14.5^{a}	75.7	75.4	75.6^{a}
50% RDF + 25% RDN-LC + Bio	46.2^{a}	47.1^{a}	46.7^{a}	12.0^{cb}	12.5^{b}	12.2^{cb}	75.7	75.4	75.6^{a}
50% RDF + 25% RDN-VC + Bio	48.7^{a}	48.8^{a}	48.8^{a}	13.1^{b}	13.2^{ab}	13.1^{b}	75.7	75.4	75.6^{a}

Data represent mean values (n = 3) within a column followed by means with the same letter are not significantly different ($P < 0.05$) according to Tukey's Studentized Range test

DSBR, Direct-seeded *basmati* rice; RDF, Recommended dose of fertilizers; RDN, Recommended dose of nitrogen; LC, Leaf compost; VC, Vermicompost; Bio, Biofertilizers

Table 4 System productivity, total system protein yield, and protein equivalent yield for adults under different direct-seeded *basmati* rice-based cropping systems and nutrient sources

Treatment	System productivity REY (Mg/ha)			Total system protein yield (Mg/ha)			Protein equivalent yield for adults (ha/year)		
	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled
Cropping systems									
DSBR-wheat	5.8^{dc}	5.9^{d}	5.9^{d}	0.669^{b}	0.674^{dc}	0.672^{cb}	30.5^{b}	30.8^{dc}	30.7^{cb}
DSBR-wheat-greengram	6.9^{c}	7.3^{c}	7.1^{c}	0.780^{a}	0.836^{a}	0.808^{a}	35.6^{a}	38.2^{a}	36.9^{a}
DSBR-cabbage-greengram	12.9^{b}	13.3^{b}	13.1^{b}	0.646^{cb}	0.705^{c}	0.676^{b}	29.5^{cb}	32.2^{c}	30.9^{b}
DSBR-cabbage-onion	21.1^{a}	20.3^{a}	20.7^{a}	0.801^{a}	0.790^{b}	0.796^{a}	36.6^{a}	36.1^{b}	36.4^{a}
Nutrient management strategies									
Control	7.2^{b}	7.1^{b}	7.2^{b}	0.444^{c}	0.459^{d}	0.452^{c}	20.3^{c}	20.9^{b}	20.6^{c}
100% RDF	13.2^{a}	13.2^{a}	13.2^{a}	0.811^{ab}	0.840^{b}	0.826^{ab}	37.0^{ab}	38.3^{a}	37.7^{ab}
50% RDF + 25% RDN-LC + Bio	12.8^{a}	13.0^{a}	12.9^{a}	0.799^{b}	0.834^{c}	0.817^{b}	36.5^{b}	38.1^{a}	37.3^{b}
50% RDF + 25% RDN-VC + Bio	13.5^{a}	13.5^{a}	13.5^{a}	0.841^{a}	0.872^{a}	0.857^{a}	38.4^{a}	39.8^{a}	39.1^{a}

Data represent mean values (n = 3) within a column followed by means with the same letter are not significantly different ($P < 0.05$) according to Tukey's Studentized Range test

DSBR, Direct-seeded *basmati* rice; RDF, Recommended dose of fertilizers; RDN, Recommended dose of nitrogen; LC, Leaf compost; VC, Vermicompost; Bio, Biofertilizers

Interestingly, the inclusion of the greengram in the rice–wheat system resulted in an enhancement in the average energy outputs by 13.2% and net energy by 12.9%, as compared to the DSBR-wheat-fallow system. The intensified and diversified conventional rice–wheat system with greengram had the highest energy production capacity due to higher dry matter yields, as compared to other systems (Congreves et al. 2015; Verma et al. 2020). Moreover, lower total energy requirements for the DSBR-wheat-greengram system were largely reflected in reduced quantities of applied fertilizers and cultural operations. (Fernandez and Zentner 2005; Rautaray et al. 2017). Furthermore, lower total energy requirements for any cropping systems that include fallow, or legume crops were also reported earlier by several researchers (Malhi et al. 2002; Hoeppner et al. 2005). Besides that, the inclusion of summer greengram resulted in an improvement in soil fertility (Sharma and Behera 2009; Verma et al. 2017) which can be attributed to higher productivity. This effect of a diversified and intensified cropping system might be

Table 5 System economics under different direct-seeded *basmati* rice-based cropping systems and nutrient sources

Treatment	System economics											
	System cost of cultivation (US$/ha)			Gross returns (US$/ha)			Net returns (US$/ha)			B:C ratio		
	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled	2014–2015	2015–2016	Pooled
Cropping systems												
DSBR-wheat	1224	1249	1237	2870^{d}	2858^{dc}	2864^{d}	1646^{dc}	1609^{dc}	1628^{dc}	1.34^{b}	1.28^{cb}	1.31^{b}
DSBR-wheat-greengram	1465	1494	1480	3329^{c}	3437^{c}	3383^{c}	1864^{c}	1943^{c}	1904^{c}	1.27^{cb}	1.30^{b}	1.29^{ab}
DSBR-cabbage-greengram	1572	1622	1597	5097^{b}	5255^{b}	5176^{b}	3525^{b}	3633^{b}	3579^{b}	2.24^{a}	2.24^{a}	2.24^{a}
DSBR-cabbage-onion	2381	2509	2445	8116^{a}	8284^{a}	8200^{a}	5735^{a}	5775^{a}	5755^{a}	2.40^{a}	2.30^{a}	2.35^{a}
Nutrient management strategies												
Control	1209	1287	1248	3061^{b}	3117^{b}	3089^{b}	1852^{d}	1830^{c}	1841^{d}	1.53^{dc}	1.42^{d}	1.48^{d}
100% RDF	1468	1526	1497	5451^{a}	5559^{a}	5505^{a}	3983^{a}	4034^{a}	4009^{a}	2.71^{a}	2.64^{a}	2.68^{a}
50% RDF + 25% RDN-LC + Bio	1994	2041	2018	5322^{a}	5476^{a}	5399^{a}	3328^{cb}	3434^{b}	3381^{cb}	1.66^{c}	1.68^{cb}	1.67^{c}
50% RDF + 25% RDN-VC + Bio	1971	2019	1995	5578^{a}	5682^{a}	5630^{a}	3607^{b}	3662^{a}	3635^{b}	1.83^{b}	1.81^{b}	1.82^{b}

DSBR, Direct-seeded *basmati* rice; RDF, Recommended dose of fertilizers; RDN, Recommended dose of nitrogen; LC, Leaf compost; VC, Vermicompost; Bio, Biofertilizers

Data represent mean values (n = 3) within a column followed by means with the same letter are not significantly different ($P < 0.05$) according to Tukey's Studentized Range test due to the increased soil microbial activity (Kaschuk et al. 2010) and enhanced root proliferation (Hobbs et al. 2008) for water and nutrients. Among NMS, the highest energy output, net energy returns, energy productivity, and energy output efficiency were registered with the application of 50% RDF + 25% RDN-VC + biofertilizers treatment, which was due to the higher yield performance of crops and lower use of inorganic fertilizers under this treatment. Judicious integration of the organic nutrient sources with inorganic resulted in reducing the input of non-renewable energy. Similarly, different cropping systems managed with organic nutrient management practices have also been reported for energy savings (Karlen et al. 1995; Pimentel et al. 2005; Zentner, et al. 2011). On the contrary, high-energy efficiency and energy profitability were found with no fertilizer control mainly due to low energy input.

Among the different cropping systems, the DSBR-cabbage-onion system registered the highest production efficiency (PE) based on both REY and monetary returns. The higher system productivity and net returns with a relatively shorter duration of the system increased the PE under the DSBR-cabbage-onion system. A similar trend among different crops based-cropping systems was also observed by several workers (Ramachandra et al. 2007; Rao et al. 2014). The use of these energy efficiency indices provides an overview of the system as a whole, in terms of inputs, the economics of land use, energy-intensive operations, productivity, and crop-wise costs involved. DSBR-wheat-greengram and DSBR-cabbage-onion systems recorded higher land use efficiency. The higher land-use efficiency of these systems as compared to other remaining systems might be due to the longer duration of the systems. The results recorded are in accordance with Banik et al. (1999). DSBR-wheat-fallow had the lowest land use efficiency as no summer crop was grown in this system. Land use efficiency was not affected by NMS. Among NMS, the application of 50% RDF + 25% RDN-VC + biofertilizers registered the highest production efficiency in terms of REY and monetary returns due to the higher system productivity and economic returns under this treatment coupled with higher production efficiency.

System productivity in terms of REY was highest for the DSBR-cabbage-onion system followed by the DSBR-cabbage-greengram system. Such an increase in system productivity was due to the inclusion of vegetable crops in the cropping systems which are highly remunerative (Saha et al. 2012; Singh et al. 2013). Saroch et al. (2005) also reported that higher productivity in the cropping system can be obtained by replacing wheat with vegetables in rice–wheat system. Among the NMS, application of 50% RDF + 25% RDN-VC + biofertilizers registered significantly higher REY. This could be due to the regulated supply of plant nutrients including micronutrients from the vermicompost to the crops throughout the growth period (Verma et al. 2017). This is supported by the build-up of soil fertility status as evidenced by N fractions and available N, P, and K in integrated NMS involving VC and biofertilizers as compared to inorganic fertilizers alone (RDF). Barik and Gulati (2009) and Lungmuana Ghosh and Patra (2013) also reported that the incorporation of organic manure in conjunction with inorganic fertilizer significantly enhances the sustainability, stability, and productivity of the cropping system. The use of the energy, land use-related efficiency indices, and production indices help to identify for the farmer, the cost-effective and energy-efficient cropping system.

A diversified cropping system with vegetables was the most remunerative as compared to other cropping systems. Input cost in DSBR-cabbage-onion was significantly higher than other cropping systems followed by DSBR-cabbage-greengram. Similarly, the highest gross and net returns were also registered under DSBR-cabbage-onion system. These findings are in general agreement with those reported by Yadav et al. (2013), Kumar et al. (2014, 2015). Among the NMS, application of 50% RDF + 25% RDN-VC + biofertilizers recorded the highest gross returns, whereas, the highest system net returns were obtained under 100% RDF. This was due to the higher per unit nutrient costs of vermicompost and leaf compost. Singh and Lal (2011) also reported similar results.

Conclusions

DSBR-cabbage-onion system followed by DSBR-cabbage-greengram system gave higher system productivity, profitability, and production efficiency in terms of rice equivalent yield over DSBR-wheat-greengram and DSBR-wheat-fallow systems. The DSBR-wheat-greengram system produced the highest energy output and net energy returns *vis-à-vis* rice equivalent yield among the various cropping systems studied. The results also illustrated the promise that the inclusion of legumes in rice-based CS, grown with the supply of nutrients partly through organic sources, as having a positive effect on protein equivalent yield for adults; such nutrient management strategies (NMS) can be therefore recommended for widespread cultivation. Furthermore, intensification and diversification of the traditional rice–wheat system with greengram and vegetables (cabbage and onion), would be able to meet the protein demand of the additional malnourished population, as compared to the traditional DSBR-wheat system.

Supplementary Information

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Additional file 1: Table S1. Crop cycle and year, season, varieties, fertilizer application rate, and form in DSBR-based cropping systems. **Table S2.** Energy equivalents of different inputs and outputs in agricultural operations. **Table S3.** ANOVA of the statistical analysis used for energy efficiency ratio, energy input, energy intensiveness and energy output. **Table S4.** ANOVA of the statistical analysis used for energy output efficiency, energy productivity, energy profitability and land use efficiency. **Table S5.** ANOVA of the statistical analysis used for net energy, production efficiency and system productivity.

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Author contributions
RKV led the research work, performed the experiments, collected the samples, performed chemical analysis of plant samples for N estimation and protein calculation, statistically analysed the data, and also wrote the initial draft of the manuscript with significant contributions. YSS planned and supervised the experiment, and read and edited the manuscript. RP provided microbial cultures, and read and edited the manuscript. PCG, CMP, MC, and RM helped in the planning of the experiment. All authors read and approved the final manuscript.

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Author details
[1]Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India. [2]ICAR-Indian Institute of Soybean Research, Indore 452 001, India. [3]Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India. [4]ICAR-Indian Institute of Farming Systems Research, Modipuram 250 110, India. [5]ICAR-Indian Grassland and Fodder Research Institute, Jhansi 284 003, India.

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