Estimation and comparison of energy input–output and efficiency indices for rice–wheat agroecosystems of Doon Valley, India

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Energy use in the rice–wheat crop production system is a major contributor to global greenhouse gas (GHG) emissions. Understanding input-wise energy flows in the production system is vital to optimize input–output and estimating GHG emissions and global warming potential. Doon Valley, India, has energy-intensive agriculture practices and a survey-based assessment was undertaken in this area covering 63 farms. According to the present study, rice and wheat production requires 63,825 and 50,799 MJ ha^{-1} of total energy input respectively. The main contributors were electricity, fertilizers and diesel for both crops; however, irrigation water was also a significant contributor in the case of rice. The yield per unit of energy use was relatively low which warrants better crop management practices to reduce the environmental footprint of the rice–wheat cropping system.

Keywords: Agriculture, energy productivity, efficiency indices, global warming, rice–wheat system.

AGRICULTURE has become increasingly energy-intensive to provide more food and adequate nutrition to the rising world population. Applying chemical fertilizers and burning of fossil fuels in agriculture contribute to greenhouse gas (GHG) emissions, and other pollutants in the air and water. Reduction in GHG emissions to mitigate climate change is the leading objective of global agriculture. Its contribution to the worldwide GHG emissions is 10–12%, while it is 14% for carbon dioxide (CO_2) emissions. In India, agriculture accounts for 18% of the total GHG emissions. Improved knowledge of energy input flows in the crop production system can assist in developing better crop management practices to tackle environmental and human health challenges[1].

The largest agriculture production system globally is the rice–wheat cropping system covering 24 million hectares. The conventional rice–wheat production system is plagued by many sustainability concerns, including unsustainable water use, high energy intensity and high GHG emissions when compared to other food crops. The highest energy intensity and GHG emissions are associated with rice. The largest contributor to CO_2 emissions is energy use for irrigation in rice–wheat cultivation[2]. In the past decades, GHG emissions in the rice–wheat production system have seen an upward trajectory owing to the widespread application of chemical fertilizers, aggressive use of direct energy input in irrigation and increased farm mechanization.

Numerous studies exist on estimating energy consumption and energy indicators for a specific crop, but only a few focus on a particular cropping system. In addition, there is a paucity of literature on the two most significant crops (in terms of share in total gross sown area and total food production), i.e. rice and wheat in India. Thus, the main aim of the present study is to estimate: (a) input-wise energy requirement and (b) energy efficiency indicators in the rice–wheat agroecosystem in Doon Valley, India.

Material and methods

Selection of the study area, data collection and input estimation

The share of agriculture in the state domestic product of Uttarakhand, North India, is around 11%. It is the principal source of livelihood for about 70% of the population. Agriculture is commercialized in the plains and valleys while farming in the mountains is mostly subsistence. Major crops grown in the valleys and plains are rice, wheat and sugarcane. Rice and wheat are the most important strategic crops in the state and are crucial for food security. In 2016–17, the share of rice in the total sown area during the *kharif* season was 54%. Similarly, in the *rabi* season, wheat constituted around 93% share of the major crops.

In this study, high-input and irrigated rice–wheat crop production was assessed in Doon Valley and the plains of Uttarakhand (30.15°–30.25°N, 78.00°–78.10°E). Rainfall per annum was above 800 mm and occurred predominantly during the monsoon season. July and August were the

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wettest months. During the summer months, the temperature varied between 36°C and 16.7°C, while in winter between 23.4°C and 5.2°C.

The production of rice and wheat in 2016–17 was 0.59 and 0.79 million tonnes with average productivity of 2340 and 2310 kg ha^{-1} respectively. The primary source of irrigation was tube wells, with a share of 58%, followed by canals (28%). Data were collected from a random selection of 63 farmers using a questionnaire survey.

Machine usage was captured by tillage, transporting, fertilizer application and spraying. Consumption of diesel was captured by operation. Human labour was assessed for tillage, seeding, weeding, irrigation, fertilizers, pesticides and harvesting (cutting, threshing and picking). Water for irrigation was estimated for rice and wheat in the study area utilizing the CROPWAT simulation software of FAO by considering local climatic parameters and soil data, which influence reference crop evapotranspiration (ET_0)[3]. The Penman–Monteith method was used to estimate ET_0, and adequate rainfall in the model was calculated using the soil conservation method of the United States Department of Agriculture[4].

Estimation of energy indices

Total input and output energy and their energy equivalents were calculated (Table 1)[1,5]. Total energy input is classified into renewable, non-renewable, direct and indirect energy[6]. Water for irrigation, seeds, human labour and manure constitute renewable energy resources. Non-renewable resources constitute diesel, pesticides, electricity, machine use and fertilizers. Direct energy includes diesel, electricity, human labour and water for irrigation. Indirect energy comprises machinery, chemical fertilizers, seeds, pesticides and manure. Output energy was estimated using grain and straw/residual yield.

Input and output energy and grain yield were used to determine various energy indices according to eqs (1)–(5)[1,7]. The agrochemical energy ratio is the proportion of applied energy through chemicals – including pesticides and fertilizers – to the total energy input.

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

$$\text{Energy productivity} = \frac{\text{Grain productivity (kg ha}^{-1}\text{)}}{\text{Total energy input (MJ ha}^{-1}\text{)}}. \quad (2)$$

$$\text{Net energy} = (\text{Total energy output (MJ ha}^{-1}\text{)}) - (\text{Total energy input (MJ ha}^{-1}\text{)}). \quad (3)$$

$$\text{Agrochemical energy ratio} = \frac{\text{Energy input for agrochemical (MJ ha}^{-1}\text{)}}{\text{Total energy input (MJ ha}^{-1}\text{)}}. \quad (4)$$

$$\text{Specific energy ratio} = \frac{\text{Total input energy (MJ ha}^{-1}\text{)}}{\text{Grain productivity (kg ha}^{-1}\text{)}}. \quad (5)$$

Table 1. Energy equivalents of input and output in irrigated rice–wheat production

Input/output	Units	Energy equivalent	Reference
Input			
Human labour	h	1.96	16
Machinery	h	62.70	17
Diesel	l	51.33	17
Chemical fertilizers	kg		
Nitrogen		66.14	18
Phosphate (P_2O_5)		12.44	18
Potassium (K_2O)		11.15	18
Farmyard manure	kg	0.30	1
Pesticides	kg		
Herbicides		101.20	1
Insecticides		199.00	1
Electricity	kWh	3.60	7
Water for irrigation		1.02	17
Seed	kg	17.60	7
Output			
Grain (rice)	kg	17.00	5
Straw (rice)	kg	12.50	5
Grain (wheat)	kg	14.70	11
Straw (wheat)	kg	12.50	1

Results and discussion

Analysis of input energy in rice production

Table 2 gives the quantity of input and output for rice–wheat and their respective energy equivalents. Total energy input in rice cultivation is estimated to be 63,824.68 MJ ha^{-1}, which is in line with a study conducted in Punjab, India (energy input in the range 52,400 ± 13,000 MJ ha^{-1})[8]. Agriculture in Punjab is similar – irrigated, high-input and energy-intensive. Another study estimated energy input for rice in India as ranging from 54,877 to 95,117 MJ ha^{-1} (ref. 9), which is consistent with our findings. According to this study[2], the primary contributors are water for irrigation, electricity and fertilizers, reiterating our conclusions.

Among the components of total energy input shown in Figure 1, the maximum share is of electricity (35%), followed by diesel and irrigation water (16% each) and chemical fertilizers (15%). The study conducted on rice in Punjab reported that significant contributors were irrigation water (40%) and chemical fertilizers (24.7%)[8]. Another study conducted in 1985 estimated the total energy input in irrigated rice to be between 35,000 and 45,000 MJ ha^{-1} for producing 4500 kg ha^{-1} of the crop. The average productivity

Table 2. Estimated input, output and their energy equivalent in the rice–wheat cropping system

	Units	Quantity of input per unit area (ha)		Total energy equivalents (MJ ha^{-1})	
		Rice	Wheat	Rice	Wheat
Input					
Human labour	h	1,120.13	525.22	2,195.45	1,029.44
Machinery	h	68.60	68.22	4,300.95	4,277.32
Diesel	l	193.78	158.33	9,946.66	8,127.25
Chemical fertilizers	kg				
Nitrogen		125.26	116.34	8,284.76	7,694.80
Phosphate (P_2O_5)		62.72	64.69	780.20	804.80
Potassium (K_2O)		18.32	27.86	204.23	310.62
Farmyard manure	kg	12,500.00	11,875.00	3,750.00	3,562.50
Pesticides					
Herbicides	l	5.75	4.57	581.65	462.90
Insecticides	l	5.31	4.72	1,056.06	938.47
Electricity	kWh	6,221.00	4,132.00	22,395.60	14,875.20
Water for irrigation	M^3	9,878.00	5,898.00	10,075.56	6,015.96
Seeds	kg	14.41	153.39	253.56	2,699.66
Total input energy (MJ)				63,824.68	50,798.91
Output					
Grain	kg	5,812.50	3,979.17	98,812.50	58,493.75
Straw	kg	5,000.00	4,062.50	62,500.00	50,781.25
Total output energy (MJ)				161,312.50	109,275.00

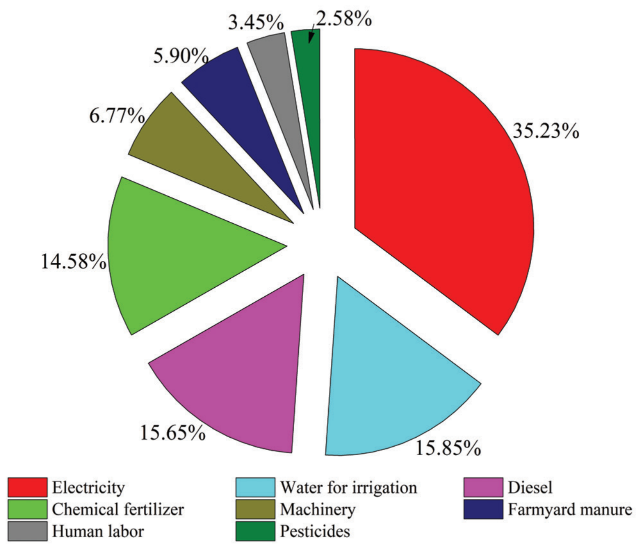

Figure 1. Percentage share of various components in total energy input in rice production.

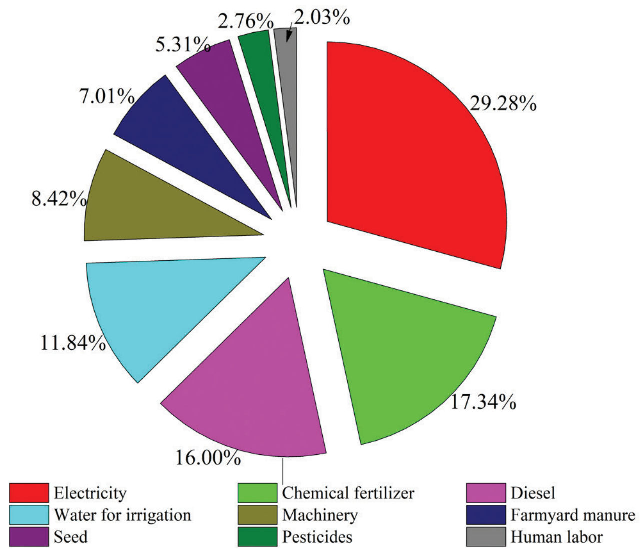

Figure 2. Percentage share of various components in total energy input in wheat production.

recorded in the present study is 5812.50 kg ha^{-1}. The yield and energy input have increased by 1.3 and 1.4 times respectively, reflecting an increase in agriculture's energy intensification and the resultant yield improvement. Hence, our estimates are consistent with other comparable studies.

Analysis of input energy in wheat production

Total input energy in wheat cultivation was 50,798.91 MJ ha^{-1}. A comparative study conducted in Iran on high-input (irrigated) wheat agroecosystem reported the total input as 60,832.52 MJ ha^{-1} (ref. 1). Our estimates are consistent with this study[1]. From Figure 2, it can be observed that the largest contributor is electricity (29%), followed by chemical fertilizers (17%), diesel (16%) and irrigation water (12%).

The study in Iran also reported a maximum share of electricity (36%), followed by chemical fertilizers (21%), diesel (13%) and water for irrigation (10%) for the irrigated high-input wheat production system[1]. A similar study in Turkey on irrigated wheat cultivation reported chemical fertilizers as the major contributor to input energy, followed by diesel and seeds. Interestingly, the present study also found wheat

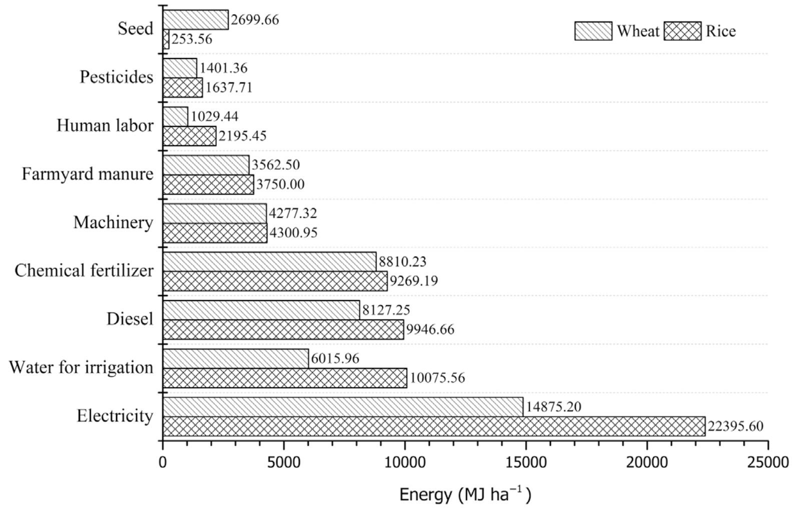

Figure 3. Input-wise energy consumption for rice and wheat.

Table 3. Different forms of energy and their percentage share in total energy input

Forms of energy	Quantity per unit area (MJ ha^{-1})		Percentage of total energy	
	Rice	Wheat	Rice	Wheat
Direct energy	44,613.28	30,047.85	70	59
Indirect energy	19,211.40	20,751.07	30	41
Renewable energy	16,274.57	13,307.56	25	26
Non-renewable energy	47,550.11	37,491.36	75	74
Total energy input	63,824.68	50,798.91	100	100

seeds to contribute 5.50% (Figure 3), which is significant compared to rice seeds (0.50%). The other significant changes between rice and wheat are in electricity and water use for irrigation. A study estimated input and output energy for the rice–wheat agroecosystem in the Middle Indo-Gangetic Plains in India[9]. The energy input for the combined system was calculated as 39,740 ± 17,230 (± SD) MJ ha^{-1} and output as 250,890 ± 40,130 MJ ha^{-1}. Our estimates for the combined system are 114,623.59 and 270,587.50 MJ ha^{-1} respectively, which are well within the permissible range.

It can be seen from Figure 3 that water for irrigation is a key contributor to input energy for rice when compared to wheat. In absolute terms, electricity and water use are significantly higher for rice while the other components are more or less similar for both crops.

Analysis of output energy in rice and wheat production

Average grain and straw productivity for rice were estimated as 5813 and 5000 kg ha^{-1} respectively. This was converted into output energy as 161,313 MJ ha^{-1}. A study reported average grain yield in rice as 6470.80 kg ha^{-1} and output energy as 108,321.75 MJ ha^{-1} (ref. 10). Therefore, our estimates are backed by other comparable studies.

The productivity of wheat was reported as 3979 kg ha^{-1} and straw output as 4063 kg ha^{-1}. This translates into 109,275 MJ ha^{-1}. The study in Iran estimated the average grain yield of high-input and low-input wheat agroecosystem as 7000 and 1967.50 kg ha^{-1} respectively. Our estimates are well within this range.

Analysis of energy forms in the rice–wheat production system

Table 3 shows the different forms of energy. Direct energy constituted 70% of the total input energy in rice, with a share of 44,613.28 MJ ha^{-1}. A study in Malaysia estimated direct energy in high-input rice to be around 30% (ref. 10). However, in this study water and energy for irrigation were not incorporated in the analysis. In the present study, the share of water and electricity was 51% of the total energy input. Therefore, our results are not contradictory to the existing literature. Direct energy made up 59% of the input energy in wheat production, with a share at 30,047.85 MJ ha^{-1}. The residual is indirect energy (30% and 41% for rice and wheat respectively). The study in Iran estimated direct and indirect energy in high-input wheat to be 59% and 41% respectively[1], which agrees with our study.

Studies on wheat and corn in Iran concluded that the percentage of indirect energy was less than direct energy in crop production systems due to the greater importance of irrigation and fuel to drive machines and motor pumps in the modern crop production system[1,7]. Various studies[7,11] have reported similar results that the share of direct energy is evidently more than indirect energy. Our results are consistent with these findings.

Renewable energy had a minor share and non-renewable energy accounted for 75% and 76% share in rice and wheat respectively. The study on wheat showed that renewable energy use was 21% for high-input agriculture[1]. Our results differ due to the greater use of farmyard manure (6%) in the total energy input. According to the study on wheat in Turkey[12], non-renewable energy constituted 77% of the total energy input, and our estimates are well within the permissible range.

Analysis of energy indices

Table 4 shows the key energy indices. Energy use efficiency ratio and specific energy are important indicators to capture the efficiency of a crop production system. Energy use efficiency was estimated at 2.53 for rice and 2.15 for wheat. If energy use efficiency is above 1, the production system generates energy. The study in Iran estimated energy efficiency in high-input wheat production as 3.03 (ref. 1), which is 20% higher than our estimate. Therefore, there is scope for improvement in energy efficiency through modernization, farm mechanization, better nutrient management and energy-efficient irrigation pumps. A balanced scientific application of nitrogen and minimum tillage will reduce energy input by 64.70% and 11.20% respectively[13].

Specific energy measures the input energy per kilogram of production and a lower value is desirable. Specific energy was estimated as 10.98 and 12.77 MJ kg^{-1} for rice and wheat respectively. Other studies on wheat in India have estimated a specific energy ratio between 3.87 and 8.00 MJ kg^{-1} (refs 8, 11), which is significantly better than our estimate. In addition, compared to the study on wheat in Iran[1], our estimate is 75% higher. Hence there is scope to improve productivity per unit of energy input. Another study estimated the ratio of the combined system at 4.4 MJ kg^{-1} (ref. 9; compared to our estimate of 11), owing to the fertile Indo-Gangetic Plains characterized by high yield. The potential productivity of rice and wheat in this region reached 10,700 and 7900 kg ha^{-1} respectively[14], compared to our yield estimates of 5813 and 3979 kg ha^{-1}. Hence energy use efficiency estimated by Soni *et al.*[9] is 6.87.

Table 4. Forms of energy input and critical indices

Indicators	Rice	Wheat	Units
Total input energy	63,824.68	50,798.91	MJ ha^{-1}
Total output energy	161,312.50	109,275.00	MJ ha^{-1}
Grain production	5,812.50	3,979.17	kg ha^{-1}
Straw output	5,000.00	4,062.50	kg ha^{-1}
Energy use efficiency	2.53	2.15	Ratio
Energy productivity	0.09	0.08	kg MJ^{-1}
Net energy	97,487.82	58,476.09	MJ ha^{-1}
Agrochemical energy ratio	0.17	0.20	Ratio
Specific energy	10.98	12.77	MJ kg^{-1}

The net energy gain was estimated as 97,487.82 and 58,476.09 MJ ha^{-1} for rice and wheat respectively. Per kilogram net energy gain for rice was 16.70, which is significantly higher than wheat (14.70), thereby implying that every unit of production of rice leads to higher energy gain. The combined net energy gain of the rice–wheat cropping system was estimated at 155,963.91 MJ ha^{-1}, which is well within the range estimated by Soni *et al.*[9] for the fertile Indo-Gangetic Plains (1,537,900–2,685,100 MJ ha^{-1}). Our estimates are at the lower end of this range owing to a significant lower comparative yield in the study area.

The agrochemical energy ratio for rice was 17% and for wheat it was 20%. A high ratio implies a large agrochemical footprint and negative environmental effects such as nitrogen leaching, air and water pollution and GHG emissions[15]. The higher consumption of nitrogen in the total input energy was the reason for the higher ratio in wheat. However, the ratio for rice and wheat was lower than the comparative studies in Iran[7], which estimated the corn production ratio as 40%, illustrating a chemical-intensive production system. In our study area, there was a significant application of organic manure (6% for rice and 7% for wheat), leading to less application of chemicals per unit area.

Energy productivity for rice and wheat was estimated as 0.09 and 0.08 kg MJ^{-1} respectively, which is low compared to similar studies. A study estimated energy productivity as 0.18 (ref. 7), while the study in Iran estimated the ratio for irrigated and unirrigated wheat as 0.11 and 0.14 respectively[1]. This reiterates the need and potential for improving energy efficiency and increasing productivity in Doon Valley.

Conclusion

The total energy input for rice and wheat was 63,825 and 50,799 MJ ha^{-1} respectively. Taking rice and wheat together the total energy input and output was 114,624 and 270,588 MJ ha^{-1} respectively. The primary contributors to input energy were electricity for water pumps and water for irrigation, followed by nitrogen fertilizer and diesel. The input-wise energy estimates can be used to estimate GHG emissions and the global warming potential (GWP) of the rice–wheat cropping cycle in North India for better policy-relevant interventions. Energy use efficiency in the studied system was low (2.53 for rice and 2.15 for wheat) and the specific energy ratio was high (10.98 MJ kg^{-1} for rice and 12.77 MJ kg^{-1} for wheat) when compared to similar studies. This implies a need to optimize energy use, implement energy efficiency measures and improve productivity per unit of energy consumed in the study system. There is a close association between GHG emissions, GWP and non-renewable energy input. Our estimated share of non-renewable sources was 75% for rice and 74% for wheat. Therefore, we must reduce the use of non-renewable energy resources. There is considerable scope for energy savings through expanding the area under energy efficient irrigation pumps, minimum tillage and harmonizing the sowing season with the monsoon season, etc. Optimizing fertilizer management by reducing synthetic fertilizer input, increasing organic compost and improving water management is vital. The state departments like state agriculture, water and electricity departments should converge to introduce energy-efficient practices that will go a long way in ensuring the sustainability of the production system in Uttarakhand.

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