Energy balance and environmental impacts of rice and wheat production: A case study in Nepal

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Abstract: Energy and environment are the key concerns in todays' agriculture. This study investigated energy balance and environmental impact of rice and wheat production systems in terms of energy ratio, impact of energy inputs to the crop yield and CO_2e (carbon dioxide equivalent) emissions under terai and hill geographical regions of Nepal. Primary data were collected from 139 randomly selected farms by using structured questionnaire. The results revealed that the total energy consumption in rice and wheat production were 9.70 GJ/hm^2 (terai) to 11.78 GJ/hm^2 (hill) and 8.40 GJ/hm^2 (hill) to 10.95 GJ/hm^2 (terai), respectively. The energy balance of rice and wheat production were found 46.33 GJ/hm^2 (hill) to 59.29 GJ/hm^2 (terai) and 27.14 GJ/hm^2 (terai) to 38.52 GJ/hm^2 (hill), respectively, where energy use efficiency in terai and hill were found to be 7.14 and 4.97 in rice, and 3.49 and 5.59 in wheat, respectively. The contribution of fertilizer on impacts was significant among other energy inputs in rice and wheat production in both geographical regions. The CO_2e emissions from rice and wheat were higher by 52% and 78% in hill as compared to respective crop rice (1786 kg CO_2e/hm^2) and wheat (843 kg CO_2e/hm^2) in terai. This study showed that rice production system in terai is more energy and environmentally efficient, whilst wheat production in hill is more energy efficient.

Keywords: energy indices, environmental impact, productivity, profitability, GHG emissions, rice, wheat, sensitivity analysis
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1 Introduction

Rice (*Oryza sativa*) and wheat (*Triticum aestivum*) are not only staple crops at a global scale, but also are the key source of employment and income for rural populations. Rice-wheat is the major cropping system in Nepal covering about 70% of the total cultivated area with contribution of 73% to the national food basket[1]. The productivity of rice and wheat are relatively lower (3.4 t/hm^2 and 2.5 t/hm^2, respectively) as compared to average yield of South Asian countries (3.7 t/hm^2 and 2.7 t/hm^2, respectively), which is the major challenges to meet the demand of feeding the growing population[2]. With a predicted population of 40.6 million by the year 2030, the country needs to produce about 47% more cereals (rice, wheat and maize) as compared to year 2010 in order to meet its domestic demand[3]. The productivity enhancement is the most practical way to increase the production, which demands intensive crop cultivation practices and inputs use. In order to increase the crop production and productivity, todays' agriculture has become an energy intensive sector with many of its activities attributing to the energy inputs. Energy use in crop production systems has been increasing in response to increasing populations, limited agricultural land and economic growth. There is a close nexus among energy, environment and economics; and the productivity and profitability of agriculture greatly depend upon energy consumption[4]. As energy inputs in agriculture are speedily increasing and accruing several benefits to the farmers, but it also adversely affect the environment by deteriorating natural resources and contributing to global warming substantially through increased greenhouse gas (GHG) emissions[5].

The consumption of agricultural inputs in Nepal is increasing, but there is no corresponding proportional growth in agricultural production[1]. Energy consumption and GHG emissions were increased by 19% and 90% in the year 2012 as compared to year 2003[2]. Consumption of different chemical fertilizers has increased by over 50% in the year 2014 as compared to year 2012[2]. Similarly, electricity consumption in agriculture sector is increasing by about 8% annually, whereas diesel oil is increasing by about 11% annually[6]. The agricultural irrigated area as the percentage of total agriculture land has also increased from 24% in the year 2006 to 30% in year 2010[7]. As the energy inputs used in agricultural production systems are growing at increasing rate, it is therefore imperative to investigate the energy and environmental performances of the major crops for their sustainability in food production systems.

The geographical build of Nepal is of extreme diversity, which is divided into three broad geographical regions such as terai, hill and mountain on the basis of topographic elevation with an elevation range of 70 m to 600 m, 600 m to 3600 m and 3600 m to 8848 m, respectively. The terai region is called food basket of Nepal, where the most of staple crops are grown. The production of 70% and 27% of the total rice, and 61% and 33% of the total wheat comes from terai and hill, respectively[1]. A different crop production system under different agro-ecological conditions and climatic conditions requires different agricultural inputs, and produces different energy, economic and environmental outputs; agriculture system is the both energy producer and energy

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consumer in nature[8]. The variation in crop production systems results variation in energy consumption, energy use efficiency and GHG emissions from different agricultural production activities[4].

Efficient use of energy inputs in agriculture is the key to reduce environmental problems, prevent destruction of natural resources and support sustainable agricultural production. Maximization of land productivity and minimization of energy inputs are the main aims of a sustainable cultivation system. An energy input-output analysis is used to determine the performance of crop production systems on efficient use of energy and corresponding GHG emissions[4]. The energy and GHG emissions analyses of different crop production systems can be an approach to assess environmental problems and sustainability issues.

Several researches on energy and environmental analysis have been done worldwide while studying rice and wheat crop production systems. Soni et al.[4] and Mohammadi et al.[9] have studied energy and environmental performances of rice production, while Khakbazan et al.[10], Khoshnevisan et al.[11] and Mohammadi et al.[9] studied wheat production system. Similarly, energy input-output analyses of rice and wheat crops are well documented in the literature such as in: rice production system[12-15] and in wheat production system[12,16,17]. But none of such analysis is known to be reported on these aspects in the context of Nepal.

The objective of this study was to investigate energy input-output performance and GHG emissions of rice and wheat production systems under irrigated condition in terai and hill geographical regions of Nepal to specify the energy use efficiencies, impact of energy inputs to the crop yield and CO_2e emissions.

2 Materials and methods

2.1 Study area and data collection

This study was done in Baijapur, Banke district as the terai geographical region, and in Kunathari, Surkhet district as the hill geographical region, both located in the mid-western development region of Nepal. The study area of Banke and Surkhet districts received 1626 mm and 2060 mm rainfall, respectively, during the study period from May to April, in which more than 75% of the total rainfall occurred during July to September. Monthly maximum and minimum temperatures were recorded in June as 39.7 ℃ and 26.3 ℃, respectively, in Banke, and 36.3 ℃ and 23.9 ℃, respectively, in Surkhet. January was the coolest month in both geographical regions, which had mean maximum and minimum temperatures 17.9 ℃ and 8.9 ℃, respectively, in Banke, and 21.5 ℃ and 6.3 ℃, respectively, in Surkhet.

Primary data were collected from household survey by using a structured questionnaire for stratified random samples. A total of 139 farms were surveyed under this study, including 30 farms for each crop in hill and, 42 and 37 farms for rice and wheat, respectively, in terai. Farmers did not apply any plant protection chemical for pest management in rice and wheat in both geographical regions.

2.2 Energy input-output analysis

All key inputs and output in crop production systems were converted into energy units to perform the energy analyses. The data includes hours or amount of inputs used from different energy sources such as seeds, labor, draft animal, farmyard manure, chemical fertilizers, diesel fuel, farm machinery, farm tools and yield as an output. The energy used and produced by the crop production systems were calculated by appropriate energy conversion factors (Table 1). Total energy input and output were derived in the study as:

$$EI_c = \left(\sum_{n=1}^{N} \sum_{i=1}^{I} e_i^{En} \times E_{c,n,i}^{En} \right) / A_c \tag{1}$$

where, EI_c is the total energy input of the crop type c, GJ/hm^2; e_i^{En} is coefficient of energy equivalent of energy input type I; $E_{c,n,i}^{En}$ is energy recourse input type i for unit farm operation n for crop type c.

$$EO_c = (Y_c^M \times e_c^{En}) / A_c \tag{2}$$

where, EO_c is the total energy output of crop type c, GJ/hm^2; Y_c^M is the yield of crop type c and e_c^{En} is the coefficient of energy equivalent of the yield of crop type c; A_c is the cultivated area in hectare of crop type c.

The energy balance, energy use efficiency, specific energy, energy productivity and energy intensiveness were calculated by using Equations (3)-(7).

$$\text{Energy balance} = \text{Energy output} - \text{Energy input} \tag{3}$$

$$\text{Energy use efficiencny} = \frac{\text{Energy output}}{\text{Energy input}} \tag{4}$$

$$\text{Specific energy} = \frac{\text{Energy input}}{\text{Crop yield}} \tag{5}$$

$$\text{Energy productivity} = \frac{\text{Crop yield}}{\text{Energy input}} \tag{6}$$

$$\text{Energy intensiveness} = \frac{\text{Energy input}}{\text{Total cost of production}} \tag{7}$$

Table 1 Energy equivalent of inputs and outputs

Energy sources	Unit	Energy equivalent/MJ unit^{-1}
Rice – seed, grain	kg	14.7
Wheat – seed, grain[17]	kg	15.7, 14.7
Human labor – man, woman	h	1.96, 1.57
Animal–Bullock – large, medium	Pair h^{-1}	14.05, 10.10
Farmyard manure (FYM)[18]	kg	0.30
Nitrogen (N)[18]	kg	66.14
Phosphorus (P_2O_5)[18]	kg	12.44
Potassium (K_2O)[18]	kg	11.15
Spade	h	0.31
Sickle	h	0.84
Plough	h	0.63
Cart	h	5.20
Cultivator	h	3.14
Thresher	h	7.52
Diesel engine	h	0.58
Tractor 45 hp and above	h	16.42
Diesel[18]	L	56.31

Note: Values are obtained from Nassiri and Singh[13].

2.3 Sensitivity analysis

In order to investigate the relationship between energy inputs and crop yield, a mathematical Cobb-Douglass (CD) production function was chosen[5,19,20]. The CD production function is expressed as:

$$Y = f(x)\exp(u) \tag{8}$$

Equation (8) can be expressed in the following form:

$$InY_i = \alpha_0 + \sum_{j=1}^{n} \alpha_j In(X_{ij}) + e_i \quad i = 1, 2, ..., n \tag{9}$$

where, Y_i denotes the yield of i^{th} farmer; X_{ij} is vector of inputs used in production process; α_0 is a constant term; α_j represents the coefficient of inputs, which are estimated from the model and e_i is the error term. When the energy input is zero, the crop production is also zero and hence Equation (9) can be written as:

$$InY_i = \sum_{j=1}^{n} \alpha_j In(X_{ij}) + e_i \quad i = 1, 2, ..., n \tag{10}$$

As a function of energy inputs, yield can be expressed as:

$$InY_i = \alpha_1 In(X_1) + \alpha_2 In(X_2) + \alpha_3 In(X_3) + \alpha_4 In(X_4) + \alpha_5 In(X_5) + \alpha_6 In(X_6) + \alpha_7 In(X_7) + \alpha_8 In(X_8) + e_i \tag{11}$$

where, Y_i represents the yield of i^{th} farmer and X_j (j = 1, 2, …, 7) designates input energies including seed (X_1), labor (X_2), draft animal (X_3), farmyard manure (X_4), chemical fertilizers (X_5), diesel fuel (X_6), farm machinery (X_7) and farm tools (X_8). In order to analyze the relationship between the forms of energy inputs and crop yield, CD function was utilized to evaluate the effect of direct and indirect, and renewable and non-renewable energy sources as in following forms:

$$InY_i = \beta_1 In(DE) + \beta_2 In(IDE) + e_i \tag{12}$$

$$InY_i = \gamma_1 In(RE) + \gamma_2 In(NRE) + e_i \tag{13}$$

where, Y_i denotes the yield of i^{th} farmer, DE, IDE, RE and NRE are the direct, indirect, renewable and non-renewable energy, respectively, that are used for crop production systems; β_1 and γ_1 are the coefficients of variables and e_i is the error term.

2.4 Environmental analysis

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were considered as key GHGs, where all these gases are conveniently expressed as equivalent to CO_2. For calculating emissions from FYM used, we converted it into its nutrients (N, P_2O_5 and K_2O) and multiplied with its corresponding emissions coefficients[4]. We found 1.87:0.52:0.9 and 0.99:0.6:1.5 N:P:K percent in FYM by laboratory analysis of samples collected from farms of terai and hill, respectively. For calculation of GHG, CO_2 emissions coefficients of various inputs used in the crop production systems were considered (Table 2).

CH_4 emissions from rice field was calculated by using the default seasonal integrated emission factor of 10 g CH_4/m^2 under continuously flooded condition without organic amendments. Due to the unavailability of emission factor of Nepal, we considered CH_4 emission factor of India because of similarity in rice cultivation practices. The scaling factors in relation to emission factors for continuously flooded condition, 0.5 and 0.2 for intermittently flooded single and multiple aeration condition, respectively, and 2 for the organic amendments condition were used to calculate CH_4 emission under specific condition[22]. Total GHG production was derived in the study as:

$$GHGe_c = \left(\sum_{n=1}^{N} \sum_{i=1}^{I} e_i^c \times G_{c,n,i}^c \right) / A_c \tag{14}$$

where, $GHGe_c$ is the total GHG emissions from the crop type c (kg CO_2e/hm^2); e_i^c is CO_2 emissions coefficient of input type I; $G_{c,n,i}^c$ is GHGs recourse input type i for unit farm operation n for crop type c; A_c is the cultivated area in hectare of crop type c.

Table 2 GHG emissions coefficients of various inputs used in crop production systems

	Emission sources	Gas	Emission coefficients /kg CO_2e unit^{-1}	Unit
1	Fertilizers			
	Nitrogen (N)	CO_2	1.3	kg CO_2e (kg N)$^{-1}$
	Phosphorus (P_2O_5)	CO_2	0.2	kg CO_2e (kg P_2O_5)$^{-1}$
	Potassium (K_2O)	CO_2	0.15	kg CO_2e (kg K_2O)$^{-1}$
2	Diesel oil	CO_2	74.1×10^{-3}	kg CO_2e MJ^{-1}
		CH_4	21×10^{-5}	kg CO_2e MJ^{-1}
		NO_2	19×10^{-5}	kg CO_2e MJ^{-1}
3	Direct N_2O from N inputs (synthetic and organic fertilizers, manure)	NO_2	4.87	kg CO_2e (kg N)$^{-1}$
4	Direct N_2O from N leaching or runoff	NO_2	1.096	kg CO_2e (kg N)$^{-1}$
5	Indirect N_2O from atmospheric decomposition of N volatirised as NH_3 and NO_2			
	Synthetic fertilizer	NO_2	0.487	kg CO_2e (kg N)$^{-1}$
	Organic fertilizer and manure	NO_2	0.974	kg CO_2e (kg N)$^{-1}$
6	Machinery[21]	CO_2	0.071	kg CO_2e MJ^{-1}

Note: Values are obtained from Soni et al.[4]

3 Results and discussion

3.1 Energy sources in rice and wheat production systems

The sources of energy inputs used in rice and wheat production systems are presented in Table 3. In rice, contribution of chemical fertilizers energy (2.99 GJ/hm^2) to the total energy input was higher than other energy inputs in terai, which was 139% higher than that of chemical fertilizers energy used in hill. The contribution of draft animal (3.40 GJ/hm^2), farmyard manure (3.21 GJ/hm^2) and labor (2.59 GJ/hm^2) energy inputs were higher than other energy inputs in the hill, which were found 204%, 194% and 86% of that of terai, respectively. Similarly, in wheat, chemical fertilizers (3.81 GJ/hm^2), seeds (2.46 GJ/hm^2) and diesel fuel (2.13 GJ/hm^2) were the major energy inputs in terai, whereas farmyard manure (2.87 GJ/hm^2) and draft animal (2.02 GJ/hm^2) energy inputs were the major energy inputs for the same crop in hill. Farmers in hill have high preference for using farmyard manure.

Rice and wheat production in hill are more labor intensive as compared to terai, mainly due to lack of farms machinery use in crop production process. The level of farm mechanization is increasing in terai, where the most of farmers use farm machinery for land preparation, irrigation and threshing purposes.

3.2 Forms of energy used in rice and wheat production systems

Direct and indirect energy are the two classification on the basis of source, popularly considered in agricultural production systems. Direct energy comes from labor, draft animal and diesel fuel, while indirect energy is the energy that comes from seeds, chemical fertilizers, farmyard manure, farm machineries and farm tools. Energy inputs were also classified as renewable such as labor, draft animal, seeds and farmyard manure and non-renewable such as diesel fuel, chemical fertilizers, farm machineries and farm tools[14].

Table 3 Energy inputs for rice and wheat production systems

GJ/hm^2

Energy inputs	Rice			Wheat		
	Terai	Hill	*p* value	Terai	Hill	*p* value
Seeds	1.56±0.036	0.85±0.017	**	2.46±0.052	1.15±0.019	**
Labor	1.39±0.027	2.59±0.113	**	1.04±0.028	1.25±0.028	**
Draftanimal	1.12±0.111	3.40±0.097	**	0.51±0.093	2.02±0.041	**
Chemical fertilizers	2.99±0.124	1.25±0.096	**	3.81±0.135	0.78±0.099	**
Farmyard manure	1.09±0.130	3.21±0.128	**	0.57±0.078	2.87±0.162	**
Diesel fuel	1.19±0.136	–	–	2.13±0.114	–	–
Farm machinery	0.076±0.009	–	–	0.13±0.007	–	–
Farm tools	0.28±0.008	0.48±0.015	**	0.29±0.008	0.33±0.008	**

Note: ** indicates significance at $p < 0.01$ in *t*-test carried out between terai and hill.

In rice, contribution of direct and renewable forms of energy inputs to the total energy input were calculated at 38% and 53% in terai, and 51% and 85% in hill, respectively (Figure 1). The forms of energy used in this study are different from other systems reported in literature. A significantly higher share of direct energy as compared to indirect form of energy in the total energy input was reported in rice production system[4], while Pishgar-Komleh et al.[14] observed the portion of non-renewable form of energy was higher as compared to renewable energy in the same crop, where the use of diesel fuel and farms machinery were quite high.

The proportion of indirect form of energy to the total energy input was found higher in wheat, which was calculated at 66% and 61% for terai and hill, respectively. Similarly, the contribution of non-renewable form of energy recorded higher in terai (58%), in contrast, the proportion of renewable energy to the total energy input was observed higher in the hill (87%) (Figure 1). Ghahderijani et al.[20] also reported higher share of non-renewable form of energy than that of renewable energy in wheat production due to higher use of diesel fuel and chemical fertilizers in Iran.

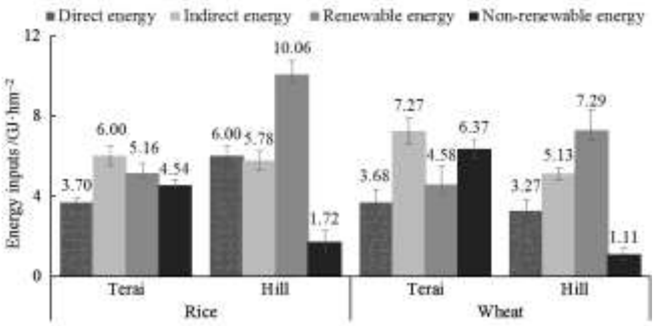

Figure 1 Different forms of energy inputs used in rice and wheat production systems

3.3 Energy indices of rice and wheat production systems

All the energy indices in rice and wheat production systems were differed significantly (p<0.01) under terai and hill geographical regions (Table 4). In rice, requirement of total energy input in hill was higher by 21% as compared to terai (9.70 GJ/hm^2), which used a high amount of farmyard manure, labor and draft animal energy of inputs. In contrast, energy output and energy balance in terai were found higher by 19% and 28%, respectively, as compared to hill (58.11 GJ/hm^2 and 46.33 GJ/hm^2, respectively). This was mainly due to higher crop yield and lower use of energy inputs in terai as compared to hill. The energy use efficiency was calculated at 7.14 in terai and 4.97 in hill.

The results on energy input and output in rice production system of the current study are consistent with other Southeast Asian countries like Thailand[4] and Myanmar[23]. In contrast, Mushtaq et al.[23] reported a high energy input and output in the Philippines and Indonesia due to higher use of chemical fertilizers and diesel fuel. Similarly, the energy requirement for rice production was reported higher in the South Asian country like India[12,13] and Pakistan[23] as compared to the current study, where the use of agrochemicals and farms machinery in crop production process were very high.

Wheat production in terai required higher total energy input, which was 30% higher than that of hill (8.40 GJ/hm^2). This was due to higher use of chemical fertilizers, diesel fuel and seeds energy of inputs in terai as compared to hill. In contrast, energy output and energy balance in hill were higher by 23% and 42%, respectively, as compared to terai (38.09 GJ/hm^2 and 27.14 GJ/hm^2, respectively). These results were achieved due to higher economic yield and lower requirement of energy for wheat production in hill compared with terai. The energy use efficiency in wheat production system was calculated at 3.49 in terai and 5.59 in hill. The levels of energy input and output in wheat production of the current study are in line with other South Asian countries like Bangladesh[16,24], whilst Chaudhary et al.[12] and Kumar et al.[25] reported higher energy input and output for the same crop production system in India, due to a high level of farm mechanization in wheat production.

The specific energy in rice was found higher in hill (2.99 MJ/kg) as compared to terai (2.07 MJ/kg), in contrast, it was recorded higher in terai (4.24 MJ/kg) as compared to hill (2.68 MJ/kg) in wheat production. In contrast to the specific energy, the energy productivity of rice was found higher in terai (485.70 kg/GJ) than hill, whereas it was higher in hill (379.48 kg/GJ) than terai in wheat. Studies on specific energy and energy productivity are well documented in the literature. Pishgar-Komleh et al.[14] reported specific energy and energy productivity in rice were 10.0-11.76 MJ/kg and 0.08-0.1 kg/MJ, respectively, under different farm categories in Iran, whereas Nassiri and Singh[13] reported specific energy in the same crop was 10.7-14.8 MJ/kg under different farm categories in India. In an another study in wheat, Ghahderijani et al.[20] reported specific energy and energy productivity were 0.07-0.17 MJ/kg and 5.96-15.17 kg/MJ, respectively, under different farm categories, whereas Taghavifar and Mardani[17] reported these were 0.12 MJ/kg and 8.41 kg/MJ, respectively. The energy intensiveness in rice and wheat were found to be 15.75-20.64 MJ/USD and 19.88-24.37 MJ/USD, respectively.

Table 4 Energy indices of rice and wheat production systems

Energy indices	Rice			Wheat		
	Terai	Hill	*p* value	Terai	Hill	*p* value
Total energy input/GJ·hm^{-2}	9.70 ±0.165	11.78 ±0.286	**	10.95 ±0.148	8.40 ±0.220	**
Energy output/GJ·hm^{-2}	68.99 ±1.629	58.11 ±1.408	**	38.09 ±0.471	46.92 ±1.611	**
Energy balance/GJ·hm^{-2}	59.29 ±1.555	46.33 ±1.219	**	27.14 ±0.420	38.52 ±1.434	**
Energy use efficiency	7.14 ±0.154	4.97 ±0.106	**	3.49 ±0.046	5.59 ±0.127	**
Specific energy/MJ·kg^{-1}	2.07 ±0.045	2.99 ±0.059	**	4.24 ±0.053	2.68 ±0.069	**
Energy productivity/kg·GJ^{-1}	485.70 ±10.495	338.09 ±7.182	**	237.50 ±3.120	379.48 ±8.693	**
Energy intensiveness/MJ·USD^{-1}	20.64 ±0.249	15.75 ±0.295	**	24.37 ±0.223	19.88 ±0.260	**

Note: ** indicates significance at $p < 0.01$ in *t*-test carried out between terai and hill.

3.4 Effects of energy inputs to the yield of rice and wheat

CD production function was used to explore the relationship between the energy inputs as exogenous variables and crop yield as an endogenous variable to determine the efficient allocation of farm resources in crop production systems. The relationship between energy inputs and yield in rice and wheat production are presented in Table 5. Results revealed that impacts of farmyard manure and chemical fertilizers energies were positive and significant at p<0.05 in rice, where 10% additional use of farmyard manure and chemical fertilizers, the yield of rice will increase by 3.1% and 3.0%, respectively, in terai, and 2.8% and 3.4%, respectively, in hill. In wheat production system, the impact of farmyard manure energy was positive and significant at p<0.01, while the impact of chemical fertilizers energy was significant at p<0.05 under both geographical regions. The contribution of draft animal energy in wheat was the highest in hill with α of 0.55 (p<0.05).

The results of CD production function are well documented in the literature. Ghahderijani et al.[20] reported that machinery and seed have a significant effect on wheat yield at p<0.01 and p<0.05, respectively. Pishgar-Komleh et al.[19] reported the contribution of chemical fertilizers and diesel fuel energies were significant at p<0.01 in potato (*Solanum tuberosum*) production system. Kuswardhani et al.[5] concluded that labor energy has the greater impact than other energy inputs to the yield of vegetable crops.

The R^2 values in rice and wheat were calculated at 0.21-0.55 and 0.42-0.84, respectively, which implied that variation in total energy inputs for rice (55%) and wheat (84%) in hill had major influence on the yield. The lower values of R^2 between energy inputs and crop yield implied that the yield variation might be due to some others factors like irrigation, crop variety, seed quality and time of planting. The R^2 values of wheat in the study are compatible with the finding of Ghahderijani et al.[20], where they noted it as 0.84 in wheat. In order to examine the autocorrelation, Durbin-Watson test was done and the values were found 1.82 to 2.20 and 2.05 to 2.62 in rice and wheat, respectively. These values indicated that error deviation was uncorrelated.

The results of regression analysis for different forms of energy inputs in rice and wheat are presented in Table 6. In rice, indirect, renewable and non-renewable energies significantly contributed to the yield (p<0.01) with α of 0.33, 0.33 and 0.32 in terai, respectively, whereas in hill, the contribution of indirect and non-renewable energies (p<0.05) were higher with α of 0.31 and 0.37, respectively. Similarly, results revealed that significant contribution of renewable (p<0.01) and indirect (p<0.05) energy inputs to the yield of wheat were higher with α of 0.15 and 0.10, respectively, in terai, whilst direct (p<0.05), indirect (p<0.01) and renewable (p<0.01) energies significantly contributed to the yield of wheat in hill with α of 0.57, 0.39 and 0.48, respectively. Ghahderijani et al.[20] also reported the significant impact (p<0.01) of direct, indirect, renewable and non-renewable form of energy inputs on wheat yield, where they calculated impacts of these forms of energy inputs to the yield of wheat with α of 0.56, 0.33, 0.51 and 0.47, respectively.

Table 5 Impact of energy inputs to the yield of rice and wheat

Independent variables	Rice				Wheat			
	Teari		Hill		Teari		Hill	
	α_i	*t*-ratio	α_i	*t*-ratio	α_i	*t*-ratio	α_i	*t*-ratio
Seeds	0.34	0.69	0.38	0.45	0.01	0.03	0.46	0.93
Labor	0.11	0.15	0.25	1.51	0.31	1.20	0.64	1.56
Draft animal	0.02	0.10	0.06	0.34	0.11	1.21	0.55	2.29*
Farmyard manure	0.31	2.26*	0.28	2.47*	0.24	3.22**	0.53	8.07**
Chemical fertilizers	0.30	2.03*	0.34	2.23*	0.07	1.71*	0.21	2.29*
Diesel fuel	-		-	-	0.09	1.50	-	-
Farm machinery	-		-	-	-	-	-	-
Farm tools	-		0.35	0.25	-	-	–4.57	–3.54
Durbin-Watson	2.20		1.82		2.05		2.62	
R^2	0.21		0.55		0.42		0.84	
Return to scale	1.08		1.66		0.83		-2.18	

Note: * and ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively.

Table 6 Econometric estimation of energy forms

Independent variables	Rice				Wheat			
	Terai		Hill		Terai		Hill	
	α_i	t-ratio	α_i	t-ratio	α_i	t-ratio	α_i	t-ratio
Direct	0.35	1.40	0.16	2.18^{*}	0.12	1.95	0.57	2.63^{*}
Indirect	0.33	3.32^{**}	0.31	4.24^{*}	0.10	2.19^{*}	0.39	6.67^{**}
Durbin-Watson	2.07		1.81		2.26		1.70	
R^2	0.24		0.54		0.23		0.69	
Return to scale	0.68		0.47		0.22		0.96	
Renewable	0.33	3.42^{**}	0.21	3.77^{**}	0.15	3.80^{**}	0.48	8.05^{**}
Non-renewable	0.32	2.75^{**}	0.37	2.65^{*}	0.09	2.74^{**}	0.20	1.83
Durbin-Watson	2.07		1.70		2.21		1.88	
R^2	0.24		0.53		0.30		0.73	
Return to scale	0.65		0.58		0.24		0.68	

Note: * and ** indicate significance at p<0.05 and p<0.01, respectively.

The Durbin-Watson values were calculated with 1.81-2.07 and 1.70-2.26 in rice and wheat, respectively, under relationship between direct and indirect forms of energy inputs, and crop yields. The values were 1.70-2.07 and 1.88-2.21 in rice and wheat, respectively, under relationship between renewable and non-renewable forms of energy inputs, and crop yields. As it can be concluded that error deviation were uncorrelated, and similar results were also reported by Kuswardhani et al.[5] and Ghahderijani et al.[20] in the study of econometric estimation in vegetables and wheat production systems, respectively.

3.5 Environmental impacts of rice and wheat production systems

The results of environmental impacts in terms of CO_2e emissions from rice and wheat production systems are shown in Figure 2. The value of CO_2e emissions was estimated at 1786-2708 kg CO_2e/hm^2 and 843-1496 kg CO_2e/hm^2 from rice and wheat production systems, respectively. The CO_2e emissions from rice and wheat in hill were found higher by 52% and 78% as compared to respective crops in terai. This results were achieved due to higher amount of farmyard manure used in hill as compared to terai; farmyard manure was identified as the major environmental detrimental input used in rice and wheat production systems in both geographical regions. The CO_2e emissions in hill can be reduced by increasing chemical fertilizers and reducing the use of farmyard manure.

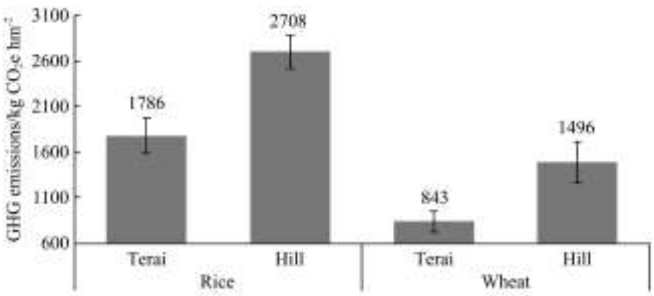

Figure 2 GHG emissions (kg CO_2e/hm^2) from rice and wheat

The CO_2e emissions from rice production in the current study are slightly different from other Southeast Asian countries like Thailand[4], where the emissions from rice production was recorded at 1052-1112 kg CO_2e/hm^2 depending upon the cultivation practices. The results on CO_2e emissions from rice and wheat production systems are compatible with South Asian country like India[26,27]. Similarly, the variation in GHG emissions from different agricultural crop production systems was reported by many researchers, where they reported CO_2 emissions ranged from 845-1672 kg CO_2e/hm^2 in rice[27,28] and 410-1624 kg CO_2e/hm^2 in wheat production system[9,10,20,29], due to differences in management practices and locations.

4 Conclusions

Energy balance and GHG emissions are the key indicators of sustainable crop production systems. The average energy requirement for rice and wheat production under irrigated condition were 10.74 GJ/hm^2 and 9.68 GJ/hm^2 with energy efficiency value of 6.06 and 4.54, respectively. The lower energy requirement and higher energy balance in rice production recorded in terai as compared to hill. However, wheat production in hill has positive energy balance with lower energy consumption compared with terai. The CO_2e emissions were estimated at 1786-2708 kg CO_2e/hm^2 and 843-1496 kg CO_2e/hm^2 from rice and wheat production systems, respectively, where the emissions in hill were higher as compared to terai under both crop production systems.

Further validation of the current results along with policy implementation from the relevant agencies in the context of energy use and environmental impacts are recommended. Adaptation of modern crop production technologies could help in improving energy use efficiency with minimum burden in environment.

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