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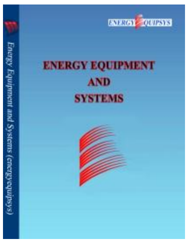

Energy use efficiency, GHG emissions, and carbon efficiency of paddy rice production in Iran

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ABSTRACT

The energy efficiency, greenhouse gas (GHG) emissions, and carbon efficiency of paddy rice production were analysed in Sari in the Mazandaran province of Iran during 2011–2012. Data was collected through questionnaires and interviews with paddy producers. The results showed that the net energy gain was 27,932 MJ ha^{-1} *and energy efficiency was 1.83 during production. The results of the Cobb-Douglas (CD) model showed that the energy inputs of machinery, diesel fuel, chemical fertilizers, and biocides had positive impacts on yield, while the impacts of seed and human labour were negative. For every 1 MJ increase in energy input, the inputs of seed, labour, machinery, diesel fuel, chemical fertilizers and biocides, changed the yield as -0.058, -0.992, 0.078, 0.004, 0.027, and 0.089 kg, respectively. The energy input of machinery with a high beta coefficient (0.64) had the most impact on crop yield* ($p \leq 0.01$)*. The total GHG emission for paddy production was determined to be 1,936* $kgCO_2eq\ ha^{-1}$*, with diesel fuel and machinery having the greatest contributions. Carbon efficiency was estimated to be 4.01.*

Keywords: Diesel Fuel, Environmental Management, Sensitivity Analysis, Cobb-Douglas Model.

1. Introduction

In Iran, rice (Oryza sativa L) is the second-most important food crop after wheat, with an area of cultivation estimated to be 564,000 hectare (FAO, 2013). Approximately 430,000 ha are in the Mazandaran province [8], making this the most important rice-producing region in the country [35] Management of energy resources is a challenge and there is considerable potential for use of renewable energy resources. To optimize food production efficiency, research is needed to investigate energy use and flow of agricultural production in order to achieve sustainable development. Moreover, investigating inputs and outputs from an environmental management point of view is also important. Increasing agricultural mechanization and the use of fossil fuel-derived inputs causes greenhouse gas (GHG) emissions and managing these is a serious challenge [7].

There have been many studies on energy use and GHG emissions from crop production. For example, Pishgar-Komleh et al. (2011a) showed that rice production in the Guilan province of Iran used a total energy input of 39,333 MJ ha^{-1} and the energy ratio was 1.53. The greatest share of energy consumption

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was from diesel fuel (46%), followed by chemical fertilizers (36%). Nassiri and Singh (2009) showed that small farmers had a high energy ratio and a low specific energy requirement compared to large farmers producing paddy rice. Soltani et al. (2013) studied energy use and GHG emissions from wheat production in the Gorgan province of Iran and reported a total energy input of 15.58 GJ ha^{-1}. They suggested that the conservation tillage and improved nitrogen management would reduce energy use and GHG emissions. Khoshnevisan et al. (2013) found that electricity and chemical fertilizers contributed to the most energy consumption for wheat production in the Isfahan Province of Iran. Pishgar-Komleh et al. (2012) analysed the energy consumption and GHG emissions of cotton production in Iran. They found that the total GHG emission was 1,195 kgCO$_2$eq ha^{-1} with machinery input and diesel being the most important inputs.

The review of literature showed little research on GHG emissions and carbon efficiency of paddy rice production, and no studies on the relationship between energy inputs and yield for the Mazandaran province of Iran, which is the most important region for this crop. The objective of this research was to quantify mass and energy inputs and outputs of paddy rice production to gain a better understanding of the relationship between energy inputs and yield, GHG emissions, and carbon efficiency for paddy production in the Mazandaran province of Iran.

2.MATERIALS and METHOD

2.1.Study area and data collection

The study was conducted in the Sari region of the Mazandaran province in Northern Iran, centred on a longitude of 53° North and latitude of 36° East. The sample size was calculated using the Cochran method [29]:

$$n = \frac{N(s \times t)^2}{(N-1)d^2 + (s \times t)^2} \quad (1)$$

$$d = \frac{t \times s}{\sqrt{n}} \quad (2)$$

where n = sample size, N = number of holdings in the target population, t = the reliability coefficient (1.96), s = the variance, and d = precision. As a result of this calculation, data was collected from 42 rice farmers using a questionnaire administered face-to-face in 2011–2012. Each farmer was asked to detail activity as inputs to rice production recorded as seed used (kg), human labour (hr), machinery use (hr), diesel fuel (lit), chemical fertilizer (kg), and biocides (kg), and as the output yield (kg).

2.2.Calculation of energy from inputs and yield

The energy associated with each input was estimated by multiplying the activity data for each farm by a characterization factor (Table 1).

Table 1. Energy equivalent of inputs and outputs

	Energy equivalent (MJ unit^{-1})	**Reference**
Inputs		
Seed (kg)	14.7	(Singh and Mittal, 1992; Ozkan et al., 2004)
Human labour	1.96	(Singh et al., 1994)
Machinery(h)	62.7	(Singh and Mittal, 1992)
Diesel (L)	56.31	(Mobtaker et al., 2010)
Chemical fertilizer		
- N (kg)	66.14	(Ozkan et al., 2011)
- P$_2$O$_5$ (kg)	12.44	(Ozkan et al., 2011)
- K$_2$O (kg)	11.15	(Ozkan et al., 2011)
Biocide	120	(Khoshnevisan et al., 2013)
Output		
Paddy of rice	14.7	(Singh and Mittal, 1992; Ozkan et al., 2004)

A number of energy indices were then calculated for each farm:

$$\text{Energy ratio} = \frac{\text{Output energy (MJ ha}^{-1}\text{)}}{\text{Input energy (MJ ha}^{-1}\text{)}} \tag{3}$$

$$\text{Energy productivity} = \frac{\text{Paddy rice output (kg ha}^{-1}\text{)}}{\text{Input energy (MJ ha}^{-1}\text{)}} \tag{4}$$

$$\text{Specific Energy} = \frac{\text{Input energy (MJ ha}^{-1}\text{)}}{\text{Paddy rice output (kg ha}^{-1}\text{)}} \tag{5}$$

$$\text{Net energy} = \text{Output energy (MJ ha}^{-1}\text{)} - \text{Input energy (MJ ha}^{-1}\text{)} \tag{6}$$

The Cobb-Douglas function was then used to find the relationship between energy inputs and yield for the region using data compiled from all the farms [24]:

$$Lny_i = a_0 + \sum_{j=1}^{n} \alpha_j \ln(x_{ij}) + e_i = 1,2,\dots,n \tag{7}$$

where y_i denotes the yield of the i^{th} farmer and x_{ij} each of the inputs used in the production process (units as noted above). The constant α_j represents the coefficients of inputs that are estimated from the model and e_i is an error term. With this assumption, the yield function of energy inputs, Eq. (7), can be expanded to Eq. (8):

$$Lny_i = a_0 + \alpha_1 lnx_1 + \alpha_2 lnx_2 + \alpha_3 lnx_3 + \alpha_4 \ln x_4 + \alpha_5 lnx_5 + \alpha_6 lnx_6 + e_i \tag{8}$$

where x_1 is seed energy, x_2 human labour, x_3 machinery, x_4 diesel fuel, x_5 chemical fertilizer, and x_6 biocide. The impact of the energy inputs on the output was quantified by using standard beta. Finally, the sensitivity of yield in the region to energy input was investigated using the marginal physical productivity (MPP) method, which shows the change in the output for one unit change in a given input, keeping all other factors constant [21,26]. The MPP of the various inputs was calculated as [22]:

$$\text{MPP}_{xj} = \frac{\text{GM(Y)}}{\text{GM}(\text{X}_{ij})} \times \alpha_{ij} \tag{9}$$

where MPP_{ij} is the marginal physical productivity of the jth input, α_j is the regression coefficient of the jth input, GM (Y) is the geometric mean of the yield, and GM (X_j) denotes the geometric mean of the jth input energy on a per hectare basis [10].

2.3.GHG emissions

The GHG emissions from paddy rice production were determined by multiplying the input activity data by an emission factor (Table 2). The CO_2 emission of machinery contributes to the emissions in manufacturing and using these inputs in the farm.

Table2. Greenhouse gas emission coefficients

Inputs	Unit	(kg CO_2eq unit^{-1})	Reference
Machinery	MJ	0.071	Dyer and) (Desjardins, 2006
Diesel fuel	lit	2.76	Dyer and) (Desjardins, 2003
Chemical fertilizer			
(N)	kg	1.3	(Lal, 2004)
(P_2O_5)	kg	0.2	(Lal, 2004)
(K_2O)	kg	0.2	(Lal, 2004)
Biocide			
Fungicides	kg	3.9	(Lal, 2004)
Insecticides	kg	5.1	(Lal, 2004)
Herbicides	kg	6.3	(Lal, 2004)

2.4.Carbon efficiency ratio

In the previous step, we obtained GHG emissions based on carbon dioxide equivalent (CO_2eq), to estimate the carbon content this amount should be multiplied on ratio of carbon to carbon dioxide that it is 0.27 [34]. Bolinder et al. (2007) estimated that carbon content is 45% of the total yield. Finally, carbon efficiency was calculated as [34]:

$$Carbon\ efficiency\ ratio = \frac{Yield's\ carbon\ content\ \ (kg\ C\ ha^{-1}}{Carbon\ emissions\ (kg\ C\ ha^{-1})} \quad (10)$$

All calculations were conducted using Microsoft Excel 2007 and JMP8.

3.RESULTS AND DISCUSSION

3.1. Analysis of input–output energy

The energy consumption of paddy cultivation is shown in Table 3. Diesel fuel was the greatest contributor at 48% of all inputs. This is similar to the results of Taheri-Rad et al. (2014) with respect to cotton production in the Golestan province of Iran. They showed that diesel fuel with the highest energy use and GHG emission in cotton production accounted for only about 2.7% of the variable costs. The greater amount of the energy equivalent of this input in Iran contributes to the use of old and inefficient machinery [14].

Fuel energy was followed by the machinery with a contribution of 26.5% of the total energy input (Fig.1). This input for kiwifruit production was 10,760.2 MJ ha^{-1}. The energy of chemical fertilizer input was determined to be 6,217.56 $MJha^{-1}$. Chemical fertilizer energy accounted for 15.30% of total energy inputs. The amounts of biocide and seed energy input used for paddy production were 2,476.14 and 1,170.65 MJ ha^{-1}. Labour had the minimum amount of energy consumption among the other inputs.

The total energy requirements and total energy output for producing the rice paddy crop were 40,623.68 and 68,555.45 $MJha^{-1}$. The total energy inputs of rice paddy production in the Sari region were higher than the energy consumption for the production of rice in Guilan [18]. The reason for the relatively higher energy input for paddy production in the Sari region can be attributed to the higher energy share of diesel fuel in the paddy production in the region.

The energy ratio for paddy production was found to be 1.8 (Table 4). In studies performed previously for other crops, the energy ratios were calculated as 1.53 for rice, 0.22 for tea, 1.24 for olive, 3.92 for peanut, 1.54 for kiwifruit, and 4.62 for soybean [14,15,4,23,18,11]. The energy ratio in all cases except for the production of peanut in Guilan province and soybean in Golestan province of Iran were higher.

Energy productivity for paddy production in the Sari region, Iran was determined as 0.12. The specific energy and net energy gain were also 8.71 $MJkg^{-1}$ and 27,931.8 $MJha^{-1}$. These values for paddy production in the Sari region of Iran was higher than the corresponding values in rice, olive, and cotton production, and less than the values for soybean, kiwifruit, peanut, and tea production [11,23,18,21,4,14,15].

Table3. Energy inputs and output for rice paddy production in Sari, Iran

Inputs and output	Average ($MJha^{-1}$)	Percentage
Seed	1,171	3
Labour	638	2
Machinery	10,760	26
Diesel fuel	19,360	48
Chemical fertilizer	6,218	15
-N	4,799	
-P2O5	970	
-K2O	449	
Biocide	2,476	6
Total energy input	40,624	
Rice paddy	68,555.45	
Total energy output	68,555.45	

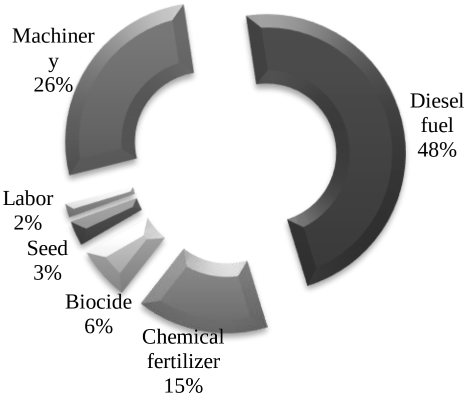

Fig.1. The percentage of energy inputs for rice paddy production in Sari, Iran

Table 4. Energy indicators and forms for rice paddy production in Sari, Iran

Form of energy		Average	Percentage
Energy ratio	-	1.83	
Energy productivity	kg MJ^{-1}	0.12	
Specific energy	MJ kg^{-1}	8.71	
Net energy	MJ ha^{-1}	27,931.77	
Direct energy[a]	MJ ha^{-1}	19,999.15	49.2
Indirect energy[b]	MJ ha^{-1}	20,624.53	50.8
Renewable energy[c]	MJ ha^{-1}	1,809.45	4.4
Non-renewable energy[d]	MJ ha^{-1}	38,814.23	95.5

[a] Includes diesel fuel and human labour
[b] Includes biocide, chemical fertilizer, seed, and agriculture machinery
[c] Includes human labour and seed
[d] Includes agriculture machinery, diesel fuel, chemical fertilizer, and biocide

The amounts of direct and indirect energy formed in rice paddy production were calculated as 19,999.5 and 20,624.5 MJha^{-1}, respectively. The amounts of renewable and non-renewable energy were also 1,809.4 and 38,814.2 MJha^{-1}, respectively. The share of renewable energy of paddy production was low. Hence, the amount of renewable energy contribution for paddy production was less than those reported in a lot of crops [14,23,18].

The results of the Cobb-Douglas model showed that the impacts of the energy inputs of machinery, diesel fuel, chemical fertilizers, and biocides on yield were positive, while the impact of energy inputs of the seed and human labour were negative (Table 5). Increasing one MJ of energy input of seed, labour, machinery, diesel fuel, chemical fertilizers, and biocides changed the yield as -0.058, -0.992, 0.078, 0.004, 0.027, and 0.089 kg, respectively. The energy input of the machinery had a high beta coefficient (0.64, $p \leq 0.01$), which was the maximum value among all of the production inputs, followed by the energy input of labour.

3.2.GHG emissions

As can be seen in Table 6, the GHG emission of diesel fuel was 948.9 kgCO_2eq ha^{-1}. Diesel fuel had the highest share (49%) of the total GHG emission for paddy production in the Sari region. The emission of machinery accounted for 39.5% of total emissions. The amount of GHG emissions resulting from this input for paddy production was 736.97 kgCO_2eq ha^{-1} (Table 6). In similar studies on wheat, potato, and canola production, fuel and chemical fertilizer were reported as the inputs with the highest GHG emissions[30,19]. The input of chemical fertilizer GHG emissions was 118 kgCO_2eq ha^{-1}. Biocide had the lowest share, 5.4%, in the total GHG emissions of rice paddy production in Sari, Iran (Table 6).

Total GHG emission of paddy production was 1,936.11 kgCO_2eq ha^{-1} (Table 6). Other researchers reported the total GHG emissions, such as 2,712 kgCO_2eq ha^{-1} for wheat, 1,195 kgCO_2eq $ha^{-1}$for cotton, and 993 kgCO_2eq ha^{-1} for potato [19,20,5]. Comparing the results showed a relatively high GHG emission for paddy production due to old machinery. High usage of this input is the main reason for high

Table 5. Estimation of relationship between energy inputs and yield of rice paddy production in Sari, Iran

	Coefficient	t-ratio	P-Value	MPP	Standard Beta
$Model: Lny_i = a_0 + \alpha_1 lnx_1 + \alpha_2 lnx_2 + \alpha_3 lnx_3 + \alpha_4 \mathrm{ln}x_4 + \alpha_5 lnx_5 + \alpha_6 lnx_6 + e_i$					
Seed	-0.014	-0.27	0.788	-0.058	-0.027
Human labour	-0.125	-2.72	0.016	-0.992	0.369-
Machinery	0.161	5.55	0.0001	0.078	0.639
Diesel fuel	0.012	0.68	0.506	0.004	0.069
Chemical fertilizers	0.036	0.35	0.732	0.027	0.047
Chemicals	0.047	0.69	0.499	0.089	0.069
R^2	0.88				
R^2_{Adj}	0.82				
Durbin-Watson	2.28				
Return to scale	0.12				

Table 6. GHG emissions of paddy production in Sari region, Mazandaran province, Iran

Sources	Average (kgCO2eq. ha_1)	Percentage (%)
Chemical fertilizers	117.97	6.1
Nitrogen	94.32	
(P2O5) Phosphorus	15.91	
(K2O) Potassium	8.05	
Chemicals	105.24	5.4
Machinery	753.97	39.5
Diesel fuel	948.94	49.0
Total GHG emissions	1936.11	

GHG emission in paddy production in the Sari region.

3.3.Input-output carbon rate

The carbon content of inputs for the rice production system in the Mazandaran province of Iran was calculated as 522.75 kg C ha^{-1}. Meanwhile, output yield was computed as 4,663.64 kg ha^{-1}. Therefore, carbon content of the rice yield was estimated at 2,098.64 kg C ha^{-1} and then carbon efficiency was determined to be as 4.0.1 Lal et al. (2004) showed that the amount of carbon efficiency ratio was 5.3 for corn production in the USA [6]. In a similar study, the carbon efficiency ratio was reported to be 10.95, which had a high ratio due to the high yield of sugar beet tuber [34]. In this case, the carbon efficiency ratio of the rice production system was less than the carbon efficiency ratio for corn and sugar beet cultivation. Khorramdel et al., (2013) showed that carbon sequestration could be an effective way to decrease atmospheric carbon dioxide.

4.Conclusions

Based on the results, the following conclusions are drawn:

- Energy ratio and total GHG emissions of paddy production were obtained at 1.83 and 1,936.1 $kgCO_2eq$ ha^{-1}, respectively. GHG emissions of paddy production were high.
- The diesel fuel had the highest share of energy use and GHG emission for paddy production in Sari, Iran.
- The results of the Cobb-Douglas model showed that the impact of the energy inputs of machinery, diesel fuel, chemical fertilizers, and biocides on yield were positive, while the impact of the energy inputs of seed and human labour were negative ($p \leq 0.01$).
- The input carbon, carbon content of yield, and carbon efficiency for rice paddy production in the Mazandaran province of Iran were estimated at 522.75 kg C ha^{-1}, 2,098.64 kg C ha^{-1}, and 4.01, respectively.

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