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Research Paper

Toward Environmentally Sustainable Wheat Harvesting Operation in Rainfed and Irrigated Systems

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Abstract

This study aimed to assess the environmental sustainability of wheat harvesting operation in rainfed and irrigated farming systems in three different locations in Iran, including Sari, Mashhad and Parsabad Moghan counties. Four sustainability indices of energy, emergy, exergy, and greenhouse gas emissions were investigated in this research. Results revealed that the energy efficiency of harvesting operation in irrigated systems was higher than that in rainfed systems. The emergy analysis results highlighted that the environmental sustainability indices for rainfed systems in Mashhad, Parsabad Moghan, and Sari were 0.047, 0.035 and 0.034, respectively. The values for the irrigated systems were 0.036, 0.035 and 0.034, respectively. The results of exergy analysis also indicated that the exergy efficiency of harvesting operation in rainfed and irrigated systems in Sari and Parsabad Moghan was higher than that in other areas by 56.07 and 128.72, respectively. Total GHG emissions of harvesting operation in Sari, Parsabad Moghan, and Mashhad in rainfed systems were determined to be lower than that in the irrigated systems (54.88, 47.64 and 36.03 kg CO2eq ha^{-1} versus 67.52, 66.56 and 59.22 kg CO2eq ha^{-1}, respectively). In conclusion, the wheat harvesting system was environmentally more sustainable in Sari and Parsabad Moghan counties in rainfed and irrigated farming systems, respectively.

Keywords:
Emergy; energy; environmental impacts; exergy; wheat

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INTRODUCTION

Sustainable agriculture is a holistic concept introduced to fulfill the needs of increasing consumption of inputs in the agricultural sector and to face several challenges such as climate change, depletion and pollution of water resources, and rising production costs (Velten et al., 2015). Interests in moving towards sustainable agriculture have called for the development of technologies and practices that do not have negative impacts on the environment, are effective and accessible to farmers, and increase productivity (Pretty, 2007). Therefore, sustainability should be quantifiable across regions and countries to allow the comparison of strengths and potentials as well as deficiencies and bottlenecks of different production systems (Häni, 2006). In developing countries such as Iran, this concern is of much higher importance due to the inappropriate manner of using resources and inputs and lower production rate than developed countries (Ohadi et al., 2015). Beheshti Tabar et al., (2010) reported that the total energy consumption in Iran's agricultural sector has had an increasing trend from 32.40 GJ ha^{-1} in 1990 to 37.20 GJ ha^{-1} in 2006 and the non-renewable energy has had the greatest share in the sector. This significant increase in input use in the crop production systems has increased greenhouse gas (GHG) emissions and the resulting environmental impacts. Thus, managing the environmental sustainability of the sector could contribute to optimizing input usage in the sector and alleviating its environmental impacts. To assess the environmental sustainability of agricultural systems, several indices have been suggested such as energy, emergy, exergy analysis, and GHG emissions, which were considered for environmental sustainability assessment of wheat production systems in this study.

Wheat is one of the most important agricultural crops in the world by global acreage of 222.11 million hectares in 2016-2017 and the total global production of about 753 million tons in 2017-2018 (United States Department of Agriculture (USDA), 2017). Iran was the 12th main wheat producer in the world by approximately 5.44 million hectares of wheat farms (USDA, 2017; Ministry of Agriculture of Iran, 2018) and around 15 million tons of wheat production in 2017-2018 (Boersch et al., 2017). This crop was the main cereal produced in Iran by around 49% in 2016-2017 (Ministry of Agriculture of Iran, 2018).

Given the significant role of wheat in the agricultural sector in the world, several studies have focused on assessing different farming systems of this crop especially from the perspective of environmental aspects. In a study on the energy flow in rainfed and irrigated wheat production systems in Iran from 1980 to 2008, it was stated that the total energy input and output of the crop had increased in this period. Moreover, the mean energy efficiency of the rainfed system was found to be 1.16 versus 1.22 for the irrigated system (Kardoni et al., 2015). Most studied that have investigated the energy audit of different wheat farming systems have considered all operations from tillage to harvesting operations (Ajabshirchi et al., 2012; Khoshnevisan et al., 2013; Molaeei & Afzalinia, 2012; Rajabi et al., 2012). Furthermore, comparisons of different wheat farming systems, i.e. rainfed against irrigated systems, have also been reported by several researchers (Asgharipour & Salehi, 2015; Ghorbani et al., 2011; Mondani et al., 2017; Safa et al., 2011; Taki et al., 2018a). Some other studies have compared different types of one or more operations such as tillage operation (Arvidsson, 2010; Kiani & Houshyar, 2012; Tabatabaeefar et al., 2009) or tillage and sowing operations (Kumar et al., 2013 and Tajik et al., 2013).

The environmental impacts of wheat production systems have been another method used by various researchers. Tahmasebi et al. (2018) reported that the environmental impact of the irrigated wheat farming system was 110 percent higher in GHG emissions and 62 percent higher in producing carbon footprint than that of the rainfed system.

However, the comparison of the life cycle assessment of rainfed and irrigated wheat farming systems in other research studies have illustrated that rainfed systems produce more pollutants due to their lower yield per hectare (Taki et al., 2018b). In another research, it was reported that the total GHG emissions from irrigated and rainfed wheat production systems were 637.8 and 65.12 $kgCO_{2eq}$, respectively and the diesel fuel input had the highest share by 33 percent and 77 percent in these systems, respectively (Motamedolshariati et al., 2017). Analyzing the environmental sustainability of Mediterranean wheat production systems, Strano et al. (2019) also stated that the fertilizers had the most environmental impacts. Moreover, planting and harvesting operations were the first and fourth most influential operations of wheat production among five studied operations. Ilahi et al., (2019) reported that the total energy input and output for wheat production in Punjab, Pakistan were around 34500 and 48300 MJ ha^{-1}, respectively. The total GHG emissions from wheat production in this area were also estimated at 866.43 kg CO_{2eq} ha^{-1}. In addition, the emergy analysis of wheat production systems showed that the sustainability index (ESI) of wheat production was 0.03 and 0.11 in Denmark (Ghaley & porter, 2013) and China (Wang et al., 2014), respectively. Houshyar et al. (2017) also reported that the environmental loading ration of wheat production in Iran was 115 and it would be improved by 20-55 percent via using appropriate input management measures. Moreover, the ESI for fallow-durum wheat-pea rotation in Canada (Fan et al., 2018) and for fodder maize production in Denmark (Ghaley et al., 2018) was also reported to be 1.94 and 0.24, respectively. Finally, there have been a few studies on the exergy analysis of wheat production. In a study in Sweden, the total exergy for wheat production was determined to be 14800 MJ ha^{-1}, and the fuel was the third significant input by a share of 18 percent (Hovelius & Wall, 1998). Yildizhan and Taki (2019) also estimated the total exergy consumption (CE_xC) for one ton of wheat in irrigated and rainfed systems to be 7700.78 and 3451.21 MJ, respectively, whereas the total exergy per ton of fresh tea leaf was estimated to be 273.43 and 821.86 MJ ton^{-1} for black sea tea (Pelvan & Özilgen, 2017) and Gamboeng tea (Bardant et al., 2018), respectively.

Optimizing the flow of inputs in agricultural operations for crop production can have significant effects on energy use efficiency and decreasing the environmental impacts of a system. Harvesting operation is one of the main operations in different production systems so that it needs significant energy use by agricultural machines. Therefore, the assessment of environmental impacts of the harvesting operation in different systems has been studied in different research (Abbas & Handler, 2018; Bacenetti et al., 2016; Bernardi et al., 2018). This operation accounts for one of the main contributors to the total energy usage in different wheat production systems in Iran. Therefore, environmental sustainability assessment of wheat harvesting operation in different farming systems can help to make decisions more appropriately based on the flow of energy and inputs in the farms.

Although extensive research has addressed different aspects of environmental sustainability in wheat production systems, it seems that data on the share of each operation in this issue are insufficient. Thus, the purpose of this study was to compare the environmental sustainability of wheat harvesting operation by four different sustainability indices of energy, emergy, exergy, and GHG emissions in two farming systems, i.e. rainfed and irrigated systems, in three counties of Iran with different climatic patterns including Mashhad, Sari, and Parsabad Moghan as three most important areas of wheat production in Iran. These three counties are hosts to three large Iranian agro-industry companies.

METHODOLOGY

Study site

The study was carried out in three counties of Iran, including Mashhad, Sari, and Parsabad Moghan. These regions are located in the east, north, and northwest of Iran, respectively (Figure 1). The geographical characteristics, climatic conditions, mean annual air temperature and mean annual rainfall of the studied areas are presented in Table 1. Data required for the study were collected from farmers, combine drivers, and experts of the large agricultural companies by a face to face questionnaire during 2017 and 2018.

System boundary and functional unit

For the sustainability assessment of a system, it is necessary to determine the spatial and temporal boundaries and draw a diagram to categorize and illustrate the inputs and outputs of the system. Since the study aimed to compare the environmental impacts of the harvesting operation in rainfed and irrigated wheat farming systems, the system boundary included the inputs and outputs of the wheat harvesting operation in both systems (Figure 2). In this research, two functional units were considered including land-based (one hectare of harvested wheat) and biomass-based (1000 kg harvested wheat).

Figure 1. Location of the Studied Areas

Table 1. *Geographic Characteristics and Climatic Conditions of Mashhad, Parsabad Moghan, and Sari Regions*

	Coordinates	Elevation from sea (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)
Mashhad	36°18′N59°36′E	982	13.5	251
Parsabad Moghan	39°38′N47°55′E	32	12.1	382
Sari	36°33′N53°03′E	43	16.7	690

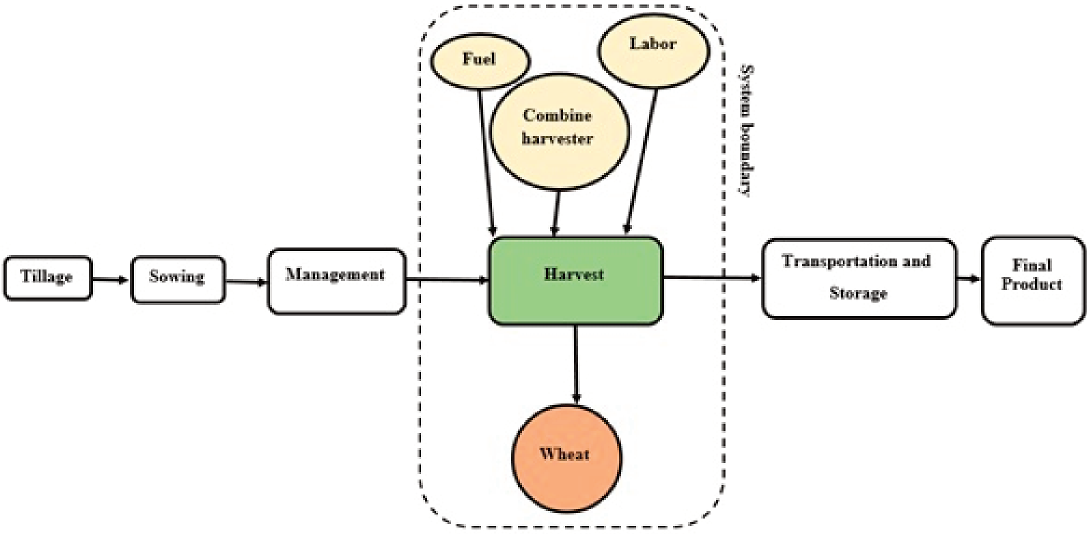

Figure 2. System boundary for the wheat harvesting operation

Table 2. *Inputs and Output Values of Matters/Energy for Rainfed and Irrigated Wheat Farming Systems in studied area*

Inputs/Outputs	Rainfed			Irrigated		
	Sari	Parsabad Moghan	Mashhad	Sari	Parsabad Moghan	Mashhad
Quantity per ha						
Diesel fuel (L)	12.10	10.48	8.04	15.18	15.50	13.67
Machinery (h)	1.04	0.91	0.67	1.24	1.15	1.04
Human labor (h)	2.78	2.53	2.85	3.45	3.53	3.30
Total output (kg)	1722.50	849.68	560.50	4037.00	5067.05	3425.50
Quantity per 1000 kg						
Diesel fuel (L)	7.02	12.33	14.34	3.76	3.06	3.99
Machinery (h)	0.60	1.07	1.20	0.31	0.23	0.30
labor (h)	1.61	2.98	5.08	0.85	0.70	0.96
Total output (kg)	1000	1000	1000	1000	1000	1000

Energy analysis

To assess the energy flow of the wheat harvesting operation, labor, combine harvester and fuel were considered to be the inputs and the harvested wheat was taken as the output. Table 2 represents the amount of inputs consumed per hectare and per 1000 kg of wheat during harvesting operation in rainfed and irrigated farming systems in Mashhad, Sari, and Parsabad Moghan. The values of energy inputs and outputs in each system were determined by multiplying the consumed input and its energy equivalent (Table 3). It is necessary to estimate energy indices to help comparing and decision making; thus, the energy indices including energy efficiency (EF), energy productivity (EP), and energy intensity (EI) were calculated (Asgharipour et al., 2016; Gokdogan et al., 2016; Khanali et al., 2016; Mardani and Taghavifar, 2016; Mohammadi-Barsari et al., 2016). Moreover, two new indices were introduced to compare the field

Table 3. *Energy Equivalents of Inputs and Outputs of Wheat*

Items	Unit	Energy equivalent (MJ)	References
Inputs			
Human labor	h	1.96	Taki et al., (2018a)
Machinery	kg yr^{-1}	87.3	Taki et al., (2018a)
Diesel fuel	L	56.31	Hatirli et al., (2005)
Outputs			
Wheat	kg	14.7	Ozkan et al., (2004)

capacity of the combine harvesters in different counties, including the amount of wheat harvested per hour (C_{PH}) and amount of energy consumed per hour (C_{EH}) which were estimated based on the effective field capacity (EFC) and material capacity (MC) of a combine harvester (Hancock et al., 1991).

$$EF=\frac{\text{Energy output }\left(\text{MJ ha}^{-1}\right)}{\text{Energy input of harvest operation }\left(\text{MJ ha}^{-1}\right)} \quad (1)$$

$$EP=\frac{\text{Wheat yield }\left(\text{kg ha}^{-1}\right)}{\text{Energy output of harvest operation }\left(\text{MJ ha}^{-1}\right)} \quad (2)$$

$$EP=\frac{\text{Energy output of harvest operation }\left(\text{MJ ha}^{-1}\right)}{\text{Wheat yield }\left(\text{kg ha}^{-1}\right)} \quad (3)$$

$$C_{PH}=\frac{\text{Wheat yield }\left(\text{kg ha}^{-1}\right)}{\text{Number of working hours }\left(\text{hr ha}^{-1}\right)} \quad (4)$$

$$C_{EH}=\frac{\text{Energy input }\left(\text{MJ ha}^{-1}\right)}{\text{Number of working hours }\left(\text{hr ha}^{-1}\right)} \quad (5)$$

Emergy analysis

Emergy is the available energy that is directly or indirectly required to produce a product or provide a service (Odum et al., 2000). It was originally developed by Odum (1996) as a methodology to combine energy use and ecology of a system (Wang et al., 2014). In this research, the emergy analysis of wheat harvesting systems was conducted by the methodology proposed by Odum et al., (2000) and Ghaley et al., (2018). The system boundary and inputs were considered as has been mentioned in Figure 2. These inputs were categorized into three groups of local renewable inputs (R), local non-renewable inputs (N), and purchased inputs (P) (Ghaley et al., 2018; Wang et al., 2014) whose sum presents the net emergy of a harvesting system. By definition, combine harvester and fuel were grouped within the purchased inputs and labor was considered to be a combination of local renewable input (88%) and purchased input (12%) based on the research conducted by Wang et al., (2014). Thus, the amount of local non-renewable input was zero in this study. The total emergy required to harvest wheat in different farming systems was calculated by multiplying the energy input and its relevant transformity. These coefficients were mostly derived from previous studies, which have focused on wheat production in Iran (Table 4). All transformities were related to the 15.83E24 seJ $year^{-1}$ standard (Odum et al., 2000; Wang et al., 2014).

Emergy indices calculated in this research were solar transformity (ST), emergy yield

Table 4. *Emergy Transformity Coefficients for Different Inputs in Wheat Harvesting Operation*

Items	Unit	Transformity (seJ unit^{-1})	References
Human labor	h	7.56E+06	Houshyar et al., (2017)
Machinery (combine harvester)	gr	1.13E+10	Houshyar et al., (2017)
Diesel fuel	kg	1.11E+05	Houshyar et al., (2017)

ratio (EYR), fraction of local renewables (PLR), environmental loading ration (ELR), and emergy sustainability index (ESI) for wheat harvesting operation in rainfed and irrigated farming systems (Ghaley & Porter, 2013; Ghaley et al., 2018; Jafari et al., 2018; Wang et al., 2014).

$$\text{Solar transformity } (\text{seJ J}^{-1}) = \frac{\text{Total emergy used in harvest operation(seJ)}}{\text{Energy output(J)}} \quad (6)$$

$$\text{EYR} = \frac{\text{Total emergy used in harvest operation (seJ)}}{\text{The emergy of purchased inputs (seJ)}} \quad (7)$$

$$\text{PLR} = \frac{\text{The emergy of renewables(seJ)}}{\text{Total emergy used in harvest operation(seJ)}} \quad (8)$$

$$\text{ELR} = \frac{\text{The emergy of phurchased and local non-renewables(seJ)}}{\text{The emergy of local renewables(seJ)}} \quad (9)$$

$$\text{ESI} = \frac{\text{EYR}}{\text{ELR}} \quad (10)$$

Exergy analysis

Exergy can be estimated by systems' inputs based on the thermodynamic chemical properties of a crop and it can be used as a powerful tool to understand the loss mechanisms of a production process (Yildizhan, 2018). Therefore, the application of this method to assess the sustainability of different farming systems has been increased in recent years (Jokandan et al., 2015). Accordingly, mass, energy, exergy, and entropy balance equations were employed to calculate the cumulative exergy of a product (CExC) (Özilgen & Sorgüven, 2011; Sorgüven & Özilgen, 2012; Yildizhan & Taki, 2018):

Mass balance:

$$\sum m_{in} = \sum m_{out} \quad (11)$$

Energy balance:

$$\sum (mh)_{in} - \sum (mh)_{out} = W - Q \quad (12)$$

Exergy balance:

$$\sum (mb)_{in} - \sum (mb)_{out} + \sum \left(1 - \frac{T_o}{T_k}\right) Q_k - W = I \quad (13)$$

Entropy balance:

$$\sum S_{generation} = \sum (ms)_{out} + \sum (ms)_{in} - \sum \frac{Q_k}{T_k} \quad (14)$$

where Q_k, W and b are the heat amount transferred across the border, work and the flow availability of a stream (Yildizhan, 2018).

In this study, to determine the produced and consumed exergy of the wheat harvesting operation in rainfed and irrigated farming systems, fuel and wheat were considered to be the input and output, respectively. Accordingly, the specific exergy of fuel and chemical exergy of wheat were derived from previous studies by 57.5 MJ kg^{-1} (Özilgen, 2018) and 17.6 MJ kg^{-1} (Hovelius &Wall, 1998), respectively. Moreover, the index of exergy efficiency of the harvesting operation (EX_d) was introduced as a measure for comparing the sustainability of different wheat harvesting operations in studied areas and was defined as the ratio of chemical exergy of the harvested wheat per hectare to the total consumed exergy by fuel (Eq. 15). The higher values of the index indicate that more fraction of fuel exergy was used in the harvesting operation and as a result, the sustainability of the system was higher.

$$EX_d = \frac{\text{Total chemical exergy of harvest wheat (MJ)}}{\text{Total consumed exergy of fuel (MJ)}} \quad (15)$$

GHG emission

Each agricultural operation can emit CO_2 and other GHGs. The emission of GHGs of wheat harvesting operation in irrigated and rainfed farming systems was calculated by multiplying the input rate of agricultural machinery (combine harvester) and diesel fuel by their CO_2 emission coefficients (Nikkhah et al., 2015) as presented in Table 5 (expressed in kilograms of carbon equivalent (kg CO_{2eq})).

Table 5. *GHG Coefficients of Different Inputs*

Items	Unit	GHG coefficient (kg CO_{2eq} $unit^{-1}$)	References
Machinery (combine harvester)	MJ	0.071	Dyer and Desjardins (2006)
Diesel fuel	L	2.76	Dyer and Desjardins (2003)

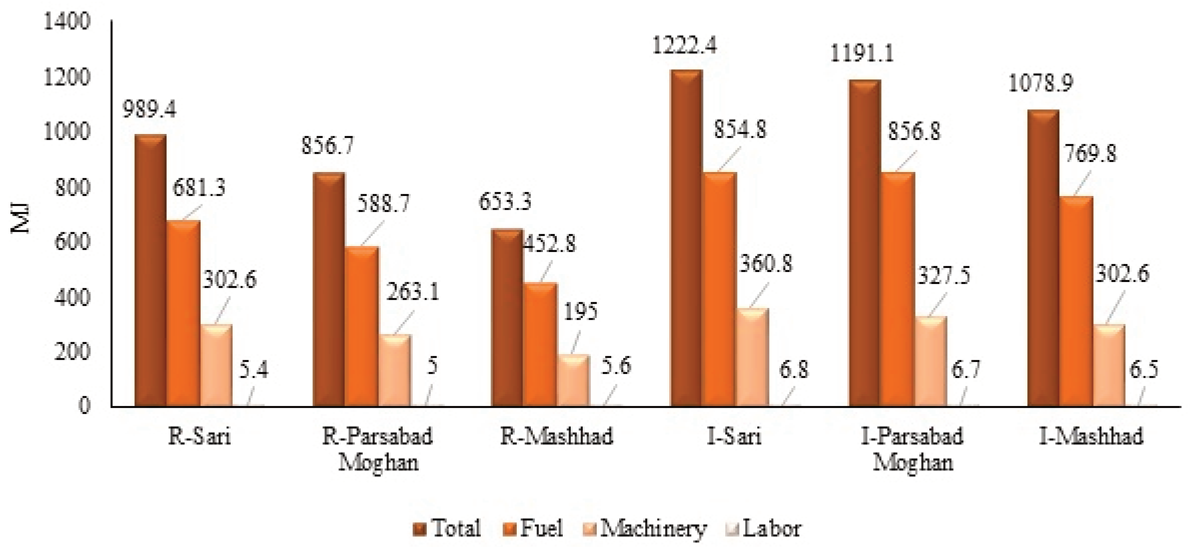

Figure 3. The share of each energy input total energy consumption per hectare for wheat harvesting operation in rainfed (R) and irrigated (I) systems in Mashhad, Parsabad Moghan and Sari Counties

RESULTS AND DISCUSSION

Energy analysis

Figure 3 indicates the total consumed energy per hectare during harvesting operation in rainfed and irrigated systems. The total energy input of harvesting operation in rainfed systems in Mashhad, Parsabad Moghan and Sari was determined to be 653.3, 856.7, and 989.4 MJ ha^{-1}, respectively. This index was also calculated for irrigated systems as to be 1078.9, 1191.1, and 1222.4 MJ ha^{-1}, respectively. The results showed that the total input energy for harvesting wheat in the irrigated systems was more than that in the rainfed systems because the combine harvester works slower in irrigated farms and takes more time to harvest due to higher wheat yield in these fields. Safa et al. (2011) stated that the energy consumption of wheat harvesting operation in irrigated systems (862 MJ ha^{-1}) was more than that in rainfed systems (861 MJ ha^{-1}) in Canterbury, New Zealand. Moreover, the total energy consumption of wheat harvesting and threshing operations in different regions of India was reported to be 1809.05, on average (Singh et al., 2007). It can also be observed that Sari County had the highest energy consumption in both rainfed and irrigated systems. In this county, due to the higher rates of rainfall and soil moisture during wheat harvesting operation, combine harvesters work at lower speeds and with more breakdowns. Therefore, whereas the wheat yield in Sari was lower than that in Parsabad Moghan, the energy consumption was higher in this county.

According to Figure 3 in both rainfed and irrigated systems, diesel fuel was the most consumed input in all three regions and the consumption of this input was 681.3 MJ ha^{-1} and 854.8 MJ ha^{-1} higher in Sari County than in other counties in the rainfed and irrigated systems, respectively. According to Figure 4, in the rainfed systems, the share of this input was approximately equal in all counties by around 69 percent . In the irrigated systems, the contribution of diesel fuel input was the highest (71.94%) in Parsabad Moghan County and the lowest (69.93%) in Sari County. In a study, it was reported that the total diesel fuel consumption for the irrigated wheat production systems in Dire County, Iran was 15.13 L ha^{-1} equal to 851.97 MJ ha^{-1} (Afsharzade et al., 2016). The agricultural machinery (combine harvester) was the second most intensively used input in both rainfed and irrigated systems in all three areas. The contribution of this input in Sari (302.6 MJ ha^{-1} in rainfed systems and 360.8 MJ ha^{-1} in irrigated systems) was more than in other areas. The energy consumed by machinery to harvest irrigated wheat and rapeseed farms in Eghlid County, Iran was determined to be 399 and 460 MJ ha^{-1}, respectively (Molaeei & Afzalinia, 2012). Accounting for less than 1 percent of total energy use, human labor had the lowest share in energy consumption in both rainfed and irrigated systems in all three areas. In a study on energy analysis of three different systems of giant reed harvesting, it was reported that in all scenarios, diesel fuel had the highest share in energy consumption by around 60 percent and it was followed by agricultural machinery and labor inputs (Pari et al., 2016).

Figure 5 depicts the total energy input per 1000 kg of wheat harvested in both rainfed and irrigated systems. This value was determined to be 1165.5, 1008.3 and 574.4 MJ ton^{-1} for the rainfed systems in Mashhad, Parsabad Moghan, and Sari, respectively versus 314.9, 235.1 and 302.8 MJ ton^{-1} for the irrigated systems in these three counties, respectively. The results highlighted that the total input energy used to harvest 1000 kg of wheat was approximately four times higher in the rainfed systems than in the irrigated systems in Mashhad and Parsabad Moghan as well as about 1.5 times higher in Sari. It can be associated with the lower yield of wheat, which caused the combine harvester to spend more time to harvest 1000 kg of wheat in the rainfed systems. The results also indicate that Mashhad County had the highest energy consumption per 1000 kg of harvested wheat in both rainfed and irrigated systems, due to the lower wheat yield in this region, which caused the combine to harvest 1000 kg of wheat in a larger area and spend more time.

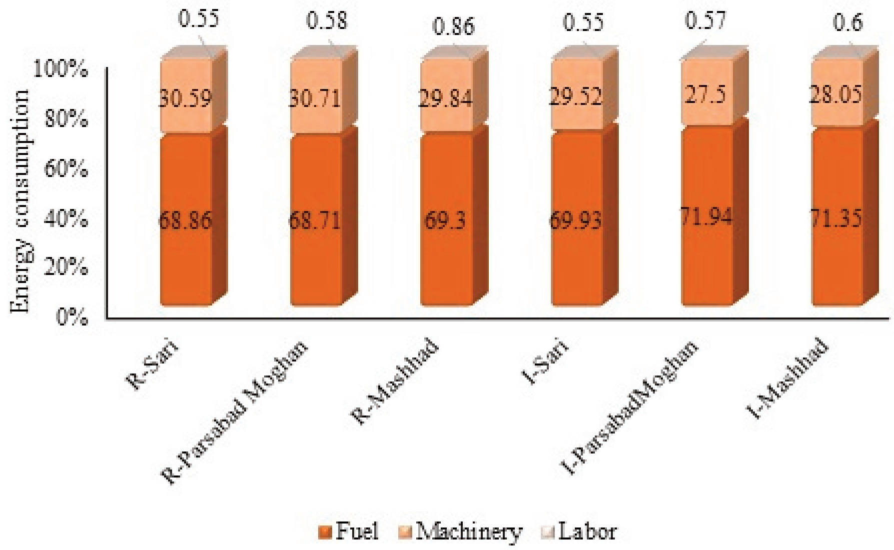

Figure 4. The contribution of energy inputs for wheat harvesting operation in rainfed (R) and irrigated (I) systems in Mashhad, Parsabad Moghan and Sari Counties

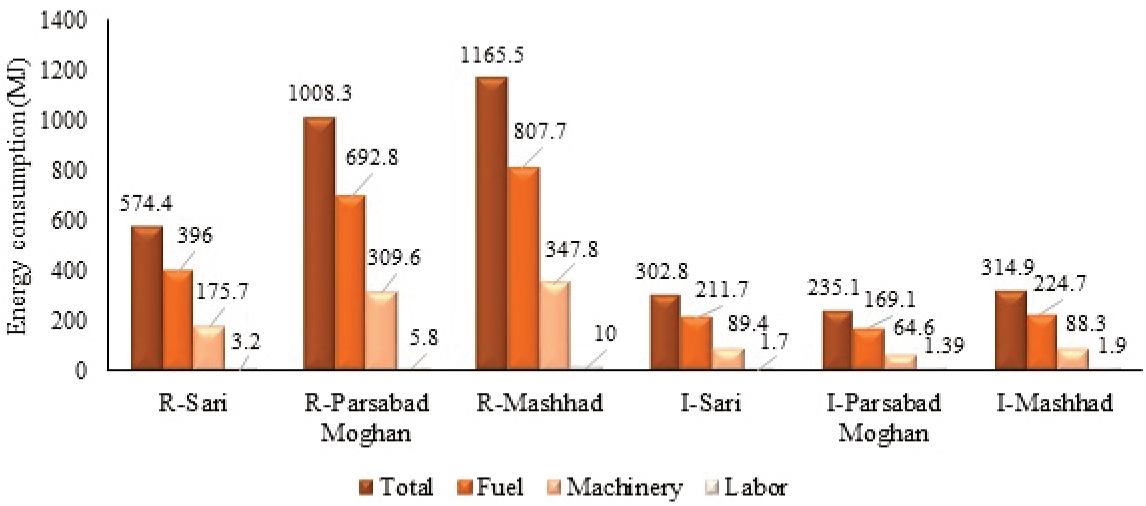

Figure 5. The share of each energy input and total energy consumption per 1000 Kg for harvested wheat in rainfed (R) and irrigated (I) systems in Mashhad, Parsabad Moghan and Sari Counties

Energy indices

Table 6 depicts the energy indices of wheat harvesting operation in the rainfed and irrigated systems for the studied areas. The energy efficiency of wheat harvesting operation in the rainfed systems was determined to be 12.61, 14.58 and 25.59 in Mashhad, Parsabad Moghan, and Sari, respectively. This index was also calculated to be 46.76, 62.53 and 48.55 in the irrigated systems, respectively. The results highlighted that from the perspective of energy use in wheat harvesting operation, the irrigated systems were more efficient than the rainfed systems, indicating that in a given time, the combine harvested more wheat in the irrigated systems. Moreover, the highest values of energy efficiency of wheat harvesting operation in the rainfed and irrigated systems belonged to Sari and Parsabad Moghan, respectively, due to the higher yields and, consequently, higher energy output in these areas.

In the study of energy productivity of the rainfed system, the highest and lowest values of this index were related to Sari and Mashhad counties by 1.74 kg MJ^{-1} and 0.86 kg MJ^{-1}, respectively and in the irrigated system, the highest and lowest values of this index were related to Parsabad Moghan and Mashhad counties by 4.25 kg MJ^{-1} and 3.77 kg MJ^{-1}, respectively. This points to the lower value of energy productivity in wheat harvesting operation in Mashhad. Moreover, energy productivity of the harvesting operation was higher in the irrigated systems than in the rainfed systems, indicating that more wheat was harvested in the irrigated systems for each mega Joule energy consumed during harvesting operation.

Moreover, the lowest values of energy intensity in the rainfed and irrigated systems were related to Sari and Parsabad Moghan Counties by 0.57 and 1.74 kg MJ^{-1}, respectively (Table 6). The index showed that harvesting one kilogram of wheat had the least energy consumption in Sari and Parsabad Moghan in the rainfed and irrigated systems, respectively. In conclusion, the results of energy indices highlighted that energy management of harvesting operations was better in the irrigated systems than in the rainfed systems. Sari and Parsabad Moghan counties also had higher energy efficiency in rainfed and irrigated systems, respectively.

Figure 6 presents the results of determining the indices of the field capacity of combine harvester. The results of calculating C_{PH} showed that for each hour of combine harvesting operation, the rainfed systems in Sari County and the irrigated systems in Mashhad County had the highest amounts of harvested crops. This indicates the high field capacity of harvesting operation in these areas. Moreover, C_{EH} showed that for each hour of combine harvester work, the highest amount of harvested wheat was obtained in Sari and Mashhad region in the rainfed and irrigated systems, respectively. Comparing two rainfed and irrigated systems highlighted that the value of both indices was higher in the irrigated systems than in the rainfed systems.

Emergy analysis

Figure 7 depicts the amount of input emergy per hectare of harvesting operation in the rainfed and irrigated farming systems in the studied areas. The total input emergy of wheat harvesting operation in the rainfed systems was determined to be 15.6, 13.71 and 11.77 (1E + 10^{13}seJ ha^{-1}) in Sari, Parsabad Moghan, and Mashhad, respectively. This index was also calculated to be 19.27, 19.25 and 17.35 (1E + 10^{13}seJ ha^{-1}) in these regions, respectively. The results revealed that this index in all regions – except for the rainfed systems in Mashhad - was higher than that of China which was reported to be 12.23 (1E + 10^{13}seJ ha^{-1}) (Wang et al., 2014). The results revealed that the total input emergy of harvesting operation was higher in the irrigated systems than in the rainfed systems, and Sari County had the highest input emergy per hectare in both systems.

Table 6. *Energy Indices of Wheat Harvesting Operation in Rainfed and Irrigated Systems in Studied Area*

Energy indices	**Unit**	**Rainfed**			**Irrigated**		
		Sari	**Parsabad Moghan**	**Mashhad**	**Sari**	**Parsabad Moghan**	**Mashhad**
Energy efficiency (Harvest)	-	25.59	14.58	12.61	48.55	62.53	46.67
Energy Productivity (Harvest)	kg MJ^{-1}	1.74	0.99	0.86	3.30	4.25	3.17
Specific Energy (Harvest)	MJ kg^{-1}	0.57	1.01	1.17	0.30	0.24	0.31

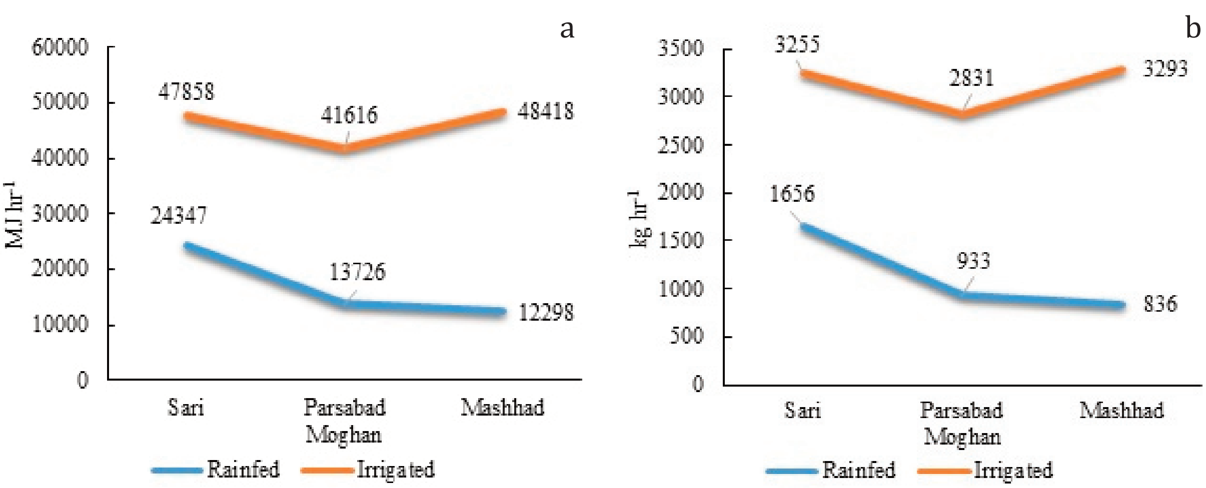

Figure 6. Combine field capacity indices a) C_{PH}, b) C_{EH} for wheat harvesting operation in Mashhad, Parsabad Moghan and Sari Counties

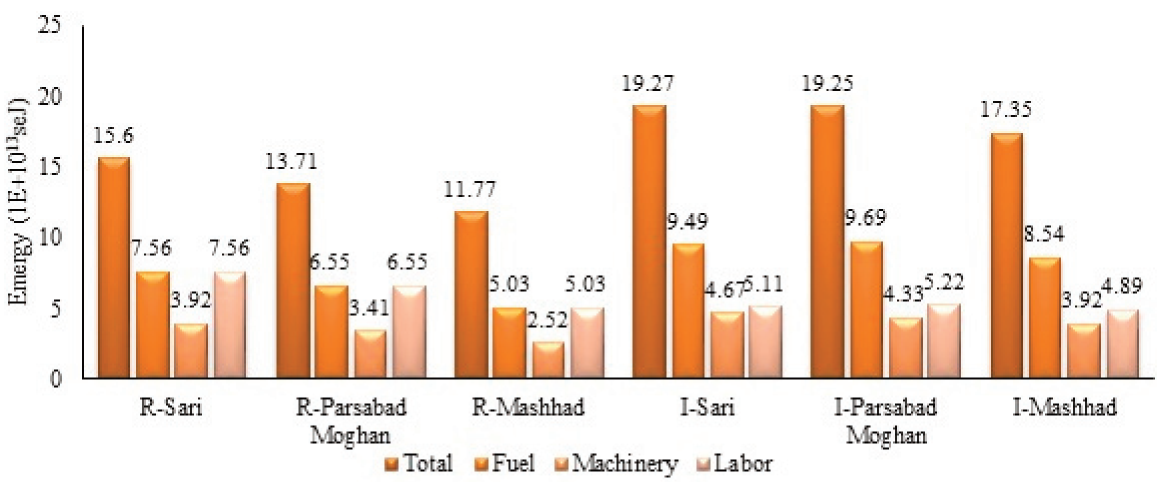

Figure 7. Total energy inputs per hectare of wheat harvesting operation in rainfed (R) and irrigated (I) farming systems in Mashhad, Parsabad Moghan and Sari Counties

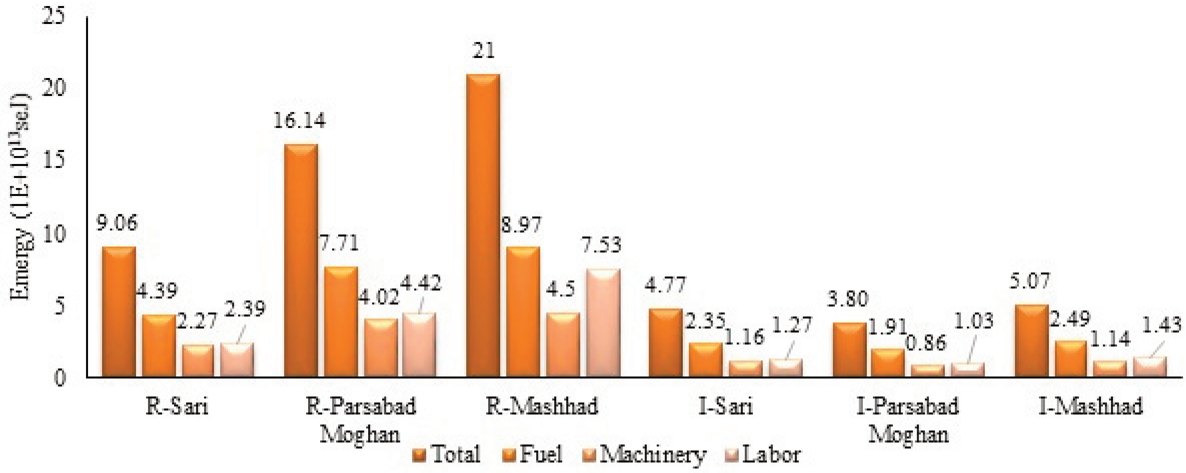

Figure 8. Total input energy per 1000 kg of wheat for harvesting operation in rainfed (R) and irrigated (I) farming systems in Mashhad, Parsabad Moghan and Sari Counties

The total input emergy for harvesting 1000 kg of wheat in the rainfed systems in Mashhad, Parsabad Moghan and Sari was calculated to be 21.00, 16.14 and 9.06 (1E + 10^{13}seJ ton^{-1}), respectively versus 5.06, 3.80, and 4.77 (1E + 10^{13}seJ ton^{-1}) for the irrigated systems, respectively (Figure 8). The results revealed that the total input emergy required to harvest 1000 kg of wheat was higher in the rainfed systems than in the irrigated systems. Findings also indicated that Mashhad County had the highest emergy consumption in both rainfed and irrigated systems by 21.00 and 5.07 (1E + 10^{13}seJ ton^{-1}), respectively.

Emergy indices

Different emergy indices used to evaluate harvesting operation in the rainfed and irrigated systems in the three regions of Mashhad, Sari, and Parsabad Moghan are presented in Table 7. The results revealed that the solar transformity was higher in the rainfed systems than in the irrigated systems. Moreover, the share of local renewable energy resources in both rainfed and irrigated systems was calculated to be about 0.03 in all the three areas, except for the rainfed systems in Mashhad, which was determined to be 0.04. Additionally, the EYR index was nearly equal for all regions in both systems. This index refers to the efficiency of the economic investment for using local resources, and the higher value shows that the efficiency of input consumption is higher (Ghaley et al., 2018). Therefore, it can be mentioned that the economic efficiency of harvesting operation in both systems and in all three studied counties was equal. The results of determining the ELR index also reported that Sari County had the highest values of 30.56 and 30.41 in the rainfed and irrigated systems, respectively. This index reflects the environmental stress load that a product can apply to the environment (Ghaley et al., 2018). Therefore, it has been shown that wheat harvesting operation in Sari had more environmental stress than in the other areas. Finally, the ESI index indicated that the sustainability of the harvesting operation in both rainfed and irrigated systems in Mashhad was higher by 0.047 and 0.036 than other areas, respectively although the difference between the values obtained was slight. Wang et al. (2014) reported that the index of agronomic sustainability in a wheat production system was 0.023, indicating a lower wheat harvesting sustainability in irrigated wheat production systems in the north of China.

Table 7. *Emergy indices of wheat harvesting operation in rainfed and irrigated farming systems in Studied Area*

Emergy indices	Rainfed			Irrigated		
	Mashhad	Parsabad Moghan	Sari	Mashhad	Parsabad Moghan	Sari
ST (seJ J^{-1})	1.43E+4	1.10E+4	6.16E+3	3.44E+3	2.58E+3	3.25E+3
PLR	0.043	0.033	0.032	0.034	0.033	0.032
EYR	1.045	1.034	1.033	1.035	1.034	1.033
ELR	22.23	29.45	30.56	28.57	29.70	30.41
ESI	0.047	0.035	0.034	0.036	0.035	0.034

ST: Solar transformity; PLR: Percentage of local renewable resource use; EYR: Emergy yield ratio; ELR: Environmental loading ratio; and ESI: Emergy sustainability index

Table 8. *Total exergy output per hectare in rainfed and irrigated farming systems in Studied Area*

Total output Exergy (MJ ha^{-1})	Rainfed	Irrigated
Mashhad	9865	60289
Parsabad Moghan	14954	89180
Sari	30316	71051

Exergy analysis

The total output exergy per hectare was determined to be higher in the irrigated systems than the rainfed systems (Table 8). Sari and Parsabad Moghan regions also had the highest total output exergy of 30316 and 89180 MJ ha^{-1} in the rainfed and irrigated systems, respectively.

The results of the input exergy (diesel fuel) per hectare in the rainfed and irrigated farming systems for the studied areas are shown in Figure 9. The input exergy in the rainfed systems for Mashhad, Parsabad Moghan and Sari counties was determined to be 359.30, 468.23 and 540.72 MJ ha^{-1}, respectively. It was 610.88, 692.84 and 678.36 MJ ha^{-1} for the irrigated system, respectively. Accordingly, the amount of exergy consumed by the fuel was higher in the irrigated systems than in the rainfed systems, and this value was the highest in Sari and Parsabad Moghan in these systems, respectively. Yildizhan (2019) also reported the total consumed exergy by agricultural machinery (diesel fuel) in wheat production systems for wheat production in Turkey to be 2321.92 MJ ha^{-1}.

The results concerning the amount of fuel exergy consumed for harvesting 1000 kg of wheat in the rainfed and irrigated systems in the studied areas are illustrated in Figure 10. The total input exergy in the rainfed systems were determined to be 641.02, 551.07 and 313.92 MJ ha^{-1} for Mashhad, Parsabad Moghan and Sari counties, respectively. This index for the irrigated systems was also calculated to be 178.33, 136.73 and 168.04 MJ ha^{-1} in the studied counties, respectively. Accordingly, the amount of exergy input for harvesting 1000 kg of wheat was higher in the rainfed systems than in the irrigated systems, and Mashhad had the highest input exergy in both systems.

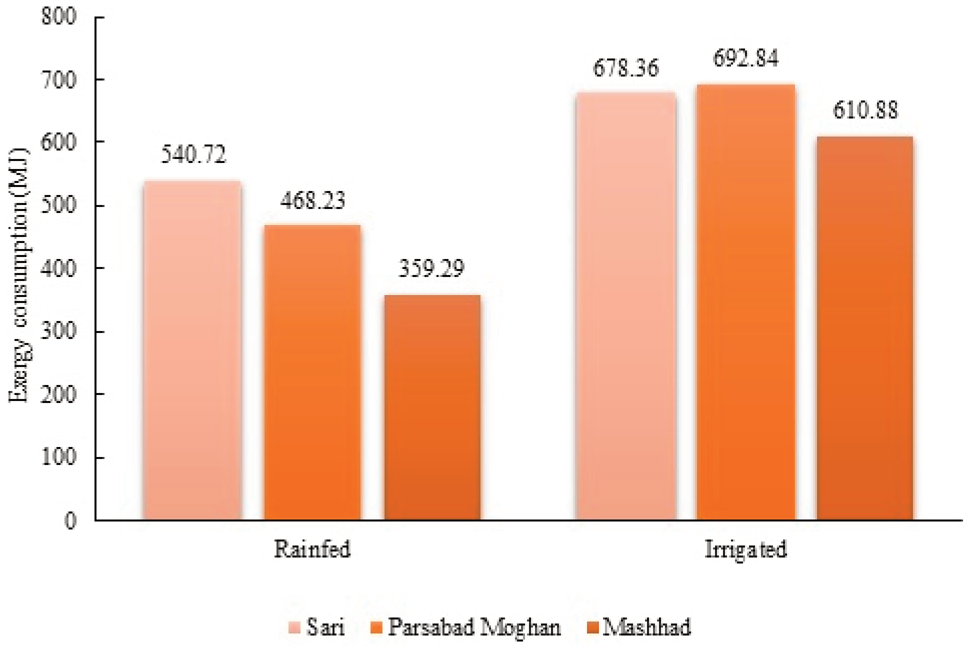

Figure 9. Cumulative exergy consumption per hectare for wheat harvesting operation in Mashhad, Parsabad Moghan and Sari Counties

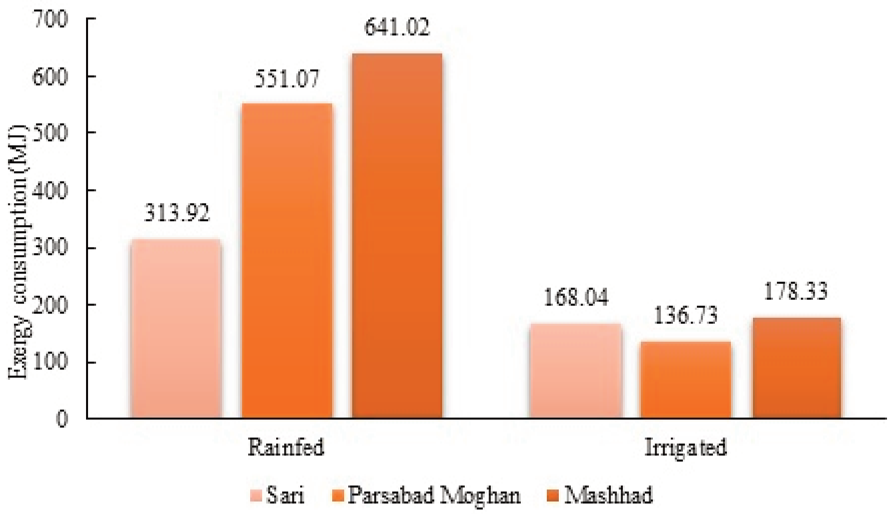

Figure 10. Total input exergy per 1000 kg of wheat for harvesting operation in Mashhad, Parsabad Moghan and Sari Counties

Exergy index

The results of determining the value of the exergy efficiency index indicated that this index was 27.46, 31.94 and 56.07 for Mashhad, Parsabad Moghan and Sari in the rainfed systems, respectively and 98.69, 128.72 and 104.74 in the irrigated systems, respectively (Figure 11). Therefore, it can be concluded that the sustainability of harvesting operation was higher in the irrigated systems than in the rainfed systems. Moreover, Sari and Parsabad Moghan regions had the highest exergy efficiency indices in the rainfed and irrigated systems, respectively.

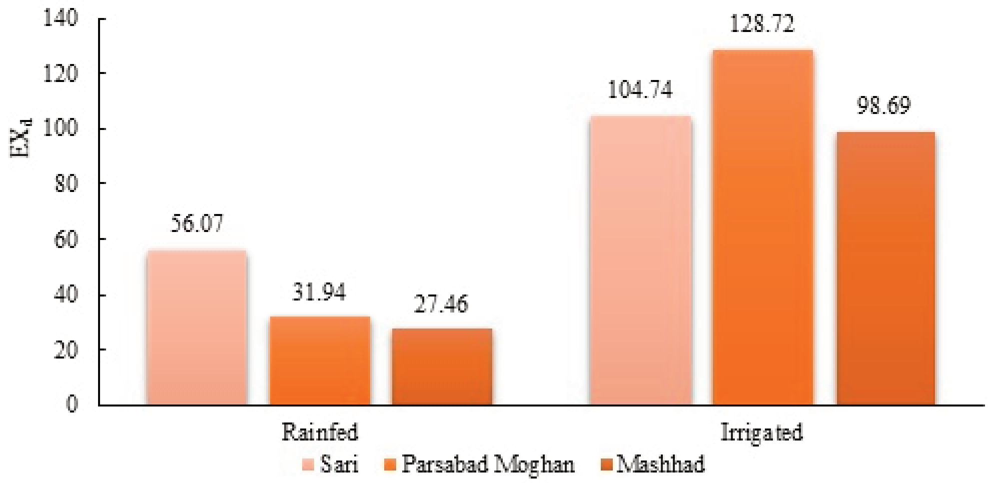

Figure 11. The exergy efficiency of harvesting operation for rainfed and irrigated wheat production systems in Mashhad, Parsabad Moghan and Sari Counties

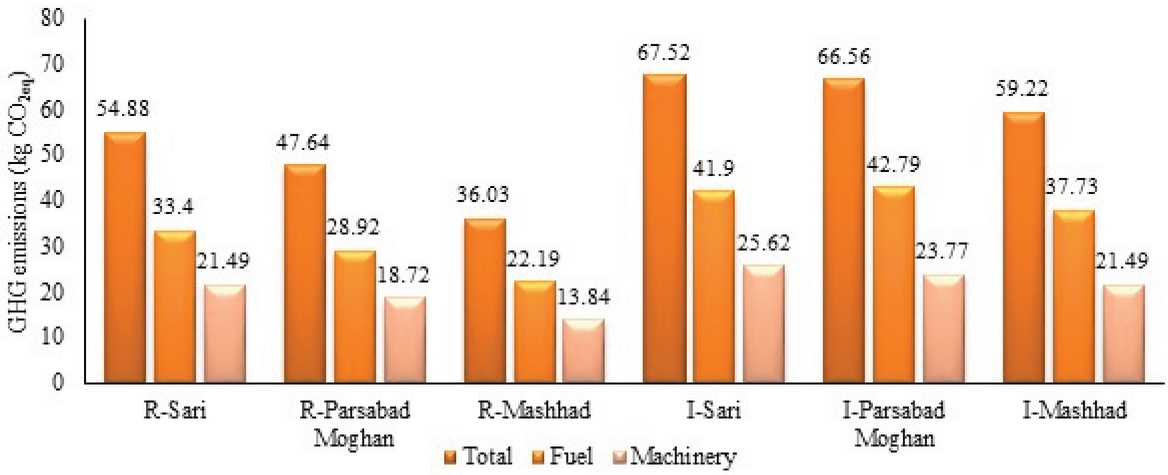

Figure 12. GHG emissions per hectare of wheat harvesting operation in rainfed (R) and irrigated (I) systems in Mashhad, Parsabad Moghan and Sari Counties

GHG emission

Total GHG emissions of wheat harvesting operation in rainfed systems in Sari, Parsabad Moghan and Mashhad were calculated to be 54.88, 47.64 and 36.03 kg CO_{2eq} ha^{-1}, respectively (Figure 12). The values were determined to be 67.52, 66.56 and 59.22 kg CO_{2eq} ha^{-1} in the irrigated systems, respectively. According to the results, the amount of GHG emissions of wheat harvesting operation was higher in the irrigated systems than in the rainfed systems, because combine harvester took more time in these farms due to their higher yields. Moreover, Sari County had the highest GHG emissions among the other two counties in both farming systems that can be attributed to more required working hours in both systems in this region. Figure 12 also depicts that diesel fuel had more share than machinery in both farming systems and in all counties. Afsharzade et al. (2016) also reported that total GHG emissions from wheat harvesting operation in the irrigated systems in Dire County were 41.76 kg CO_{2eq} ha^{-1}. It shows that a lower amount of diesel fuel input was used in the irrigated systems in all studied areas than Dire County, which can be due to the differences in farm management policies and working conditions in these areas.

The amount of GHG emissions per 1000 kg harvested wheat was determined to be significantly higher in the rainfed systems than in the irrigated systems in Sari, Parsabad Moghan and Mashhad by 31.86, 56.07 and 64.29 kg CO_{2eq} ton^{-1} versus 16.72, 13.14 and 17.29 kg CO_{2eq} ton^{-1}, respectively (Figure 13). It was due to the greater usage of inputs for harvesting 1000 kg of wheat in the rainfed systems than in the irrigated systems. Furthermore, harvesting operating in Mashhad emitted more GHG in both farming systems as compared to the other two counties. GHG emission rates in Mashhad County were 64.29 and 17.29 kg CO_{2eq} ton^{-1} in rainfed and irrigated systems, respectively.

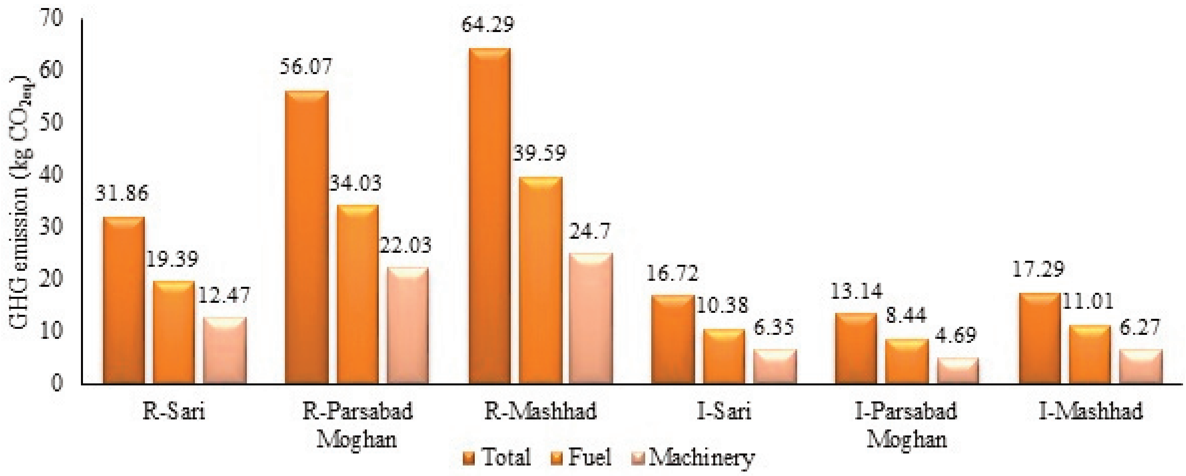

Figure 13. GHG emissions per 1000 kg of harvested wheat in rainfed (R) and irrigated (I) systems in Mashhad, Parsabad Moghan and Sari Counties

CONCLUSION

In this study, the environmental sustainability of wheat harvesting operation in rainfed and irrigated farming systems in three counties of Mashhad, Parsabad Moghan, and Sari was assessed from four perspectives of energy, emergy, exergy audit, and GHG emissions. The inputs used in this study included agricultural machinery (combine harvester), diesel fuel, and human labor. The results of the sustainability assessment of systems based on energy indices of wheat harvesting operation highlighted that Sari and Parsabad Moghan had the highest environmental sustainability in the rainfed and irrigated farming systems, respectively. The comparison of the sustainability from the perspective of emergy indicated that, in both production systems, Mashhad was more sustainable with a slight difference. Comparing the exergy efficiency of harvesting operation in the two rainfed and irrigated farming systems also illustrated that in the rainfed systems, Sari and in the irrigated systems, Parsabad Moghan were the most sustainable systems. Finally, comparing the GHG emissions of harvesting operation showed that Sari and Parsabad Moghan counties had the lowest emitted GHG per 1000 kg of harvested wheat and therefore the highest environmental sustainability in the rainfed and irrigated farming systems, respectively. Therefore, it can be stated that, in the rainfed and irrigated wheat production systems, Sari and Parsabad Moghan counties had the highest environmental sustainability in harvesting operation, respectively.

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