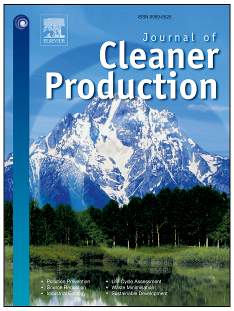

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Morteza Taki, Farshad Soheili-Fard, Abbas Rohani, Guangnan Chen, Hasan Yildizhan

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# Title

## Life Cycle Assessment to compare the environmental impacts of different wheat production systems

# Authors

**Morteza Taki[1*], Farshad Soheili-Fard[1], Abbas Rohani[2], Guangnan Chen[3], Hasan Yildizhan[4]**

1. Department of Agricultural Machinery and Mechanization, Khuzestan Agricultural Sciences and Natural Resources University, Mollasani, Iran
2. Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran
3. Faculty of Health, Engineering and Sciences, University of Southern Queensland, Australia
4. Dortyol/Hatay, 31200, Turkey

# *Corresponding author

**Morteza Taki**

# Complete Postal Address

Department of Agricultural Machinery and Mechanization, Khuzestan Agricultural Sciences and Natural Resources University, Mollasani, Iran

# E-mail

**mortezataaki@gmail.com**
**mtaki@ramin.ac.ir**

# Life Cycle Assessment to compare the environmental impacts of different wheat production systems

## Abstract

The share of fossil-based resources in the implementation of agricultural activities in Iran is very high. In this context, it is important to determine the environmental impacts of energy use in agricultural activities. The purpose of this study was to evaluate and compare the energy consumption and total environmental impacts of irrigated and rainfed wheat production in central Iran, Mahyar plain. For this purpose, data were collected from 120 irrigated and 90 rainfed wheat farms in three different farm size (<2 ha, 2-4 ha and more than 4 ha), through questionnaires and site visits. In this study, standard ISO life cycle assessment methodology was used to evaluate the total impact of all consuming inputs on environmental pollution and show the main hotspot in the production chain. Results of energy analyses showed that large farms used more energy per unit of farm land than that of small farms. Farmers also used higher input energy for irrigated wheat in comparison with rainfed system. The overall energy use efficiency for per unit farm of irrigated wheat production was only half of rainfed wheat production. Results of Life Cycle Assessment (LCA) models show that rainfed wheat actually produced more pollutions than irrigated wheat production because of lower yield in ha. In this study, the rate of Abiotic Depletion (AD) and Acidification (AC) impact were 0.002-0.003 kg Sb eq and 8.991-11.863 kg $SO_2$ eq for wheat production (irrigated and reainfed), respectively. Also the Ozone Layer Depletion (OLD) and Photochemical Oxidation (PO) were calculated 0.00002-0.00004 kg CFC11 eq and 0.145-0.174 kg $C_2H_4$ eq for wheat production (irrigated and reainfed), respectively. The results showed that the main hotspots for irrigated and rainfed wheat production were chemical fertilizers and diesel fuel. Based on the results, it is suggested to use more intensive cropping systems (such as solar greenhouse) to decrease the intensity of input energy and increase the output level of productions with minimum environmental pollutions.

**Keywords**

Sustainable agriculture, wheat production, energy consumption, environmental analysis

**Nomenclature**

| | | | |
|---|---|---|---|
| $E_O$ | Energy output (GJ/ha) | $E_f$ | Fertilizer energy (MJ/ha) |
| $E_I$ | Energy input (GJ/ha) | $W_f$ | Weight of fertilizer (kg/ha) |
| $E_P$ | Energy productivity (kg/GJ) | $E_k$ | Existing energy in fertilizer (MJ/kg) |
| $O_P$ | Output production (kg/ha) | $F_c$ | Fuel consumption required for agricultural practice (L/ha) |
| $E_e$ | Electricity energy (MJ/ha) | $F_{hr}$ | Fuel required (L/hr) |
| $N_E$ | Net energy (GJ/ha) | T | working time of machinery (hr/ha) |
| $M_E$ | Machinery energy (GJ/ha) | $E_m$ | Energy provided by a machine (coefficient equal to 62.7 MJ $kg^{-1}$) |
| W | weight of machine (kg) | $E_t$ | Effective lifetime of tractor (hr) |
| $Q_h$ | Total machine working hours during an agricultural season | ρ | Water density ($kg/m^3$) |
| Φ | Water flow rate ($m^3$/ha) | g | gravitational acceleration ($m/s^2$) |
| $E_R$ | Energy Ration (-) | H | Total dynamic well head (m) |
| $\varepsilon_2$ | Efficiency of energy and power (0.18 -0.22 for electro pump and 0.25-0.30 for diesel) | $\varepsilon_1$ | Pumping efficiency varying between 0.7 and 0.9 |
| TE | Terrestrial Ecotoxicity (g 1,4-DB eq) | AD | Abiotic Depletion (g Sb eq) |
| LCA | Life Cycle Assessment | AC | Acidification (g $SO_2$ eq) |
| LCI | Life Cycle Inventory | EP | Eutrophication (g $SO_2$ eq) |
| LCIA | Life Cycle Impact Assessment | G | Global Warming (kg $CO_2$ eq) |
| FU | Functional Unit | HT | Human Toxicity (g 1,4-DB eq) |
| OLD | Ozone Layer Depletion (g CFC-11 eq) | ME | Marine aquatic Ecotoxicity (g 1,4-DB eq) |
| FE | Fresh water aquatic Ecotoxicity (g 1,4-DB eq) | PO | Photochemical Oxidation (g $C_2H_4$ eq) |

## 1.Introduction

Wheat is one of the important cereals in the world and has a major rank among low-income household in the world (Taki et al, 2016). Planted area of wheat was 4.09 million ha in 2015-2016 in the world. Total harvested cereals in 2015-2016 were 18 million tons which the share of wheat was about 63.16%, followed by barely (17.55%), paddy (12.87%) and corn (6.40%) (Taki et al, 2016).

One of the key criteria for choosing strategic approaches to achieving sustainable agriculture is to increasing the efficiency of production (Bundschuh, and Chen, 2014). Efficiency can be increased in agricultural production by more sustainable use of resources, such as labor, chemical fertilizers, water and fuel. Also application of new technologies and attention to life cycles of byproduct processing can increase the agricultural efficiency (Maraseni, et al., 2015).

Currently, in most developing countries, a lot of fossil energy sources are using to produce agricultural productions, which often lead to air, soil and water pollution (Nemecek et al, 2011). This high energy consumption can loss the valuable fossil fuels and create great energy challenges for future generations (Khoshnevisan et al, 2013a).

LCA as a powerful method was used to investigate the environmental impacts of energy sources in many researches (Taki et al, 2016). This method can determine the total air, water and soil pollution during production a particular product (Chen at al., 2010). A lot of researchers used this method for analyzing the energy consumption of agricultural products. Some of them were focused on cereal production. For example, Taghavifare et al (2015) and Khoshnevisan et al (2015) focused on Iran wheat production. Brentrup et al (2004a and b) analyzed the effect of chemical fertilizers on crop yield in the UK. Achten and Van Acker (2016) reviewed the wheat production systems in Europe. Kim et al (2009) evaluated LCA of corn grain and corn stover in the United States. Biswas et al (2008) presented a LCA analysis of wheat production in south-western Australia.

Iran is dependent on excessive fossil-based energy resources within agricultural activities and $CO_2$ emissions because of agricultural activities are high. This study will indicate the environmental impacts of fossil based energy sources in the wheat production process in specific region of Iran. However, the results of environmental impacts of fossil based energy sources in wheat production will be compared to those of previous LCA studies.

In this study, ISO LCA method (ISO, 2006) was applied for production of irrigated and rainfed wheat in an Iranian farmer cooperative, located in the center of Iran, based on the first phases of life cycle (i.e. from tillage to harvest), with the aim to evaluate their energy flow, environmental performance and the hotspots in the production chains. This area is very important for wheat production in Isfahan province. Considering the mechanization development plans and the necessity of integrating the farms in Iran and also growing concerns about environmental and economic issues, the present study aimed to investigate the relation between farm size and environmental impacts, identify hotspots in the production chains and evaluate energy flow. Actually, it is worthy to be known that, how farm size affects the environmental impacts. So, in the present study, farm size was investigated from environmental point of view in three categories. Also considering the lack of freshwater resources and efforts to find the deeper wells, present study makes an accurate assessment of energy amount for wheat production in this plain and provide solutions to this problem. Some recent researches evaluated the energy consumption in Isfahan province (Khoshnevisan et al, 2013a,b,c) but in this study only Mahyar plain, located in Shahreza city will be evaluated. So the purpose of this study is to accurately assess the amount of energy and its pollution effects for wheat production in this plain and finally provide some solutions for this problem.

## 2.Methodology

### 2.1. Case study region

Shahreza is located 508 km south to Tehran and about 80 km south west of Isfahan. Zard Kooh mountain range runs from northwest to southeast of this city, enjoying a cold climate (Fig.1). In this study, two types of wheat farms were evaluated: irrigated and rainfed. For each category, three samples were selected, i.e small (<2 ha), medium (2-4 ha) and large farms (> 4 ha). The data were collected from 120 irrigated and 90 rainfed wheat farms in Shahreza city in Isfahan province using face to face questionnaire method.

In this research, experimental database was randomly selected from the rural communities in the research region. For calculating the sample size, Neyman technique was used (Taki et al, 2013):

$$n=\frac{\sum N_s P_s}{N^2 D^2+\sum N_s P_s^2} \tag{1}$$

where n is the sample size of total data; N is the number of whole population; $N_s$ is the number of the population in the s stratification; $P_s$ is the standard deviation in the s stratification $p_s^2$, is the variance in the s stratification, $D^2$ is equal to $\frac{d^2}{z^2}$; d is the precision and z is the reliability coefficient (1.96, which represents 95% reliability). Thus the total sample number was 120 irrigated and 90 rainfed wheat farms. Table 1 shows the summary of the sampling wheat farms, according to the size and type of them.

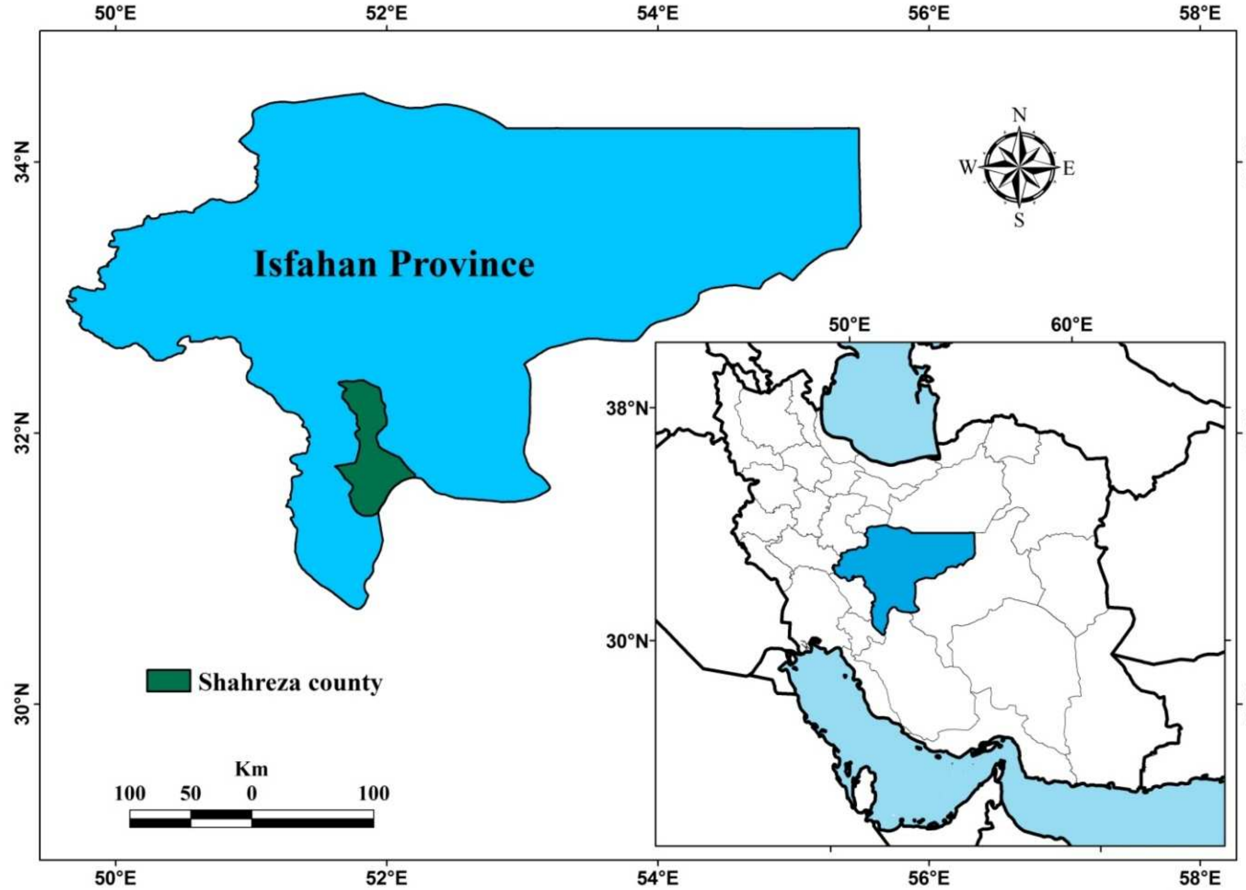


**Fig.1.** Location of the studied area.

**Table.1.** Summery of wheat farm types and number of sampling for each one

| Type of wheat farms | (< 2 ha) | (2-4 ha) | (> 4 ha) |
|---|---|---|---|
| Irrigated wheat farms | 50 | 40 | 30 |
| Rainfed wheat farms | 20 | 40 | 30 |
| Total | 70 | 80 | 60 |

## 2.2.Energy analysis method

In this research, total energy using in wheat production was analyzed (Natural sources of energy such as solar radiation, are not considered). In this study, energy consumption in total process of wheat production (human, diesel fuel, chemical and farmyard fertilizers, electricity, machinery, pesticides and seed) was calculated based interviews and oral questions (Chen at al., 2010). Also, the output energy was calculated only for grain production because it is the main commodity produced. For converting all the materials into the energy equivalents, Table 2 was used.

**Table.2.** Energy coefficients of different materials for wheat production.

| Inputs | | Unit | Energy equivalent (MJ unit$^{-1}$) | Reference |
|---|---|---|---|---|
| 1.Human labor | Man | h | 1.96 | Ranjbar et al, 2013 |
| | Woman | h | 1.57 | |
| 2.Chemical fertilizer and farmyard manure | N | kg | 47.10 | Taki et al, 2012c |
| | $P_2O_5$ | kg | 15.80 | |
| | $K_2O$ | kg | 9.28 | |
| | farmyard manure | kg | 0.30 | |
| 3.Chemical poison | Pesticides | kg | 101.20 | Ranjbar et al, 2013 |
| | Herbicide | kg | 238.00 | |
| 4.Agricultural machinery | Tractor | kg year | 93.61 | Abdi et al, 2012 |
| | Implement and machinery | kg year | 62.70 | |
| | Combine harvester and mower | kg year | 87.63 | |
| 5. Seed | Improved seed or hybrid | kg | 25.00 | Abdi et al, 2013 |
| | General seed | kg | 15.70 | |
| 6.Diesel fuel | | L | 47.80 | Ranjbar et al, 2013 |
| 7.Electricity | | kWh | 3.60 | Taki et al, 2012b |

It is clear that energy conversion factors may be different for different regions, but for a particular area, these factors can be used to let the researchers to have a good comparison between using of energy for production a specific product. In this study, total energy using for wheat production can calculate to below categories:

### 2.2.1. Fuel consumption

Time duration for each section of planting was counted from starting of each agricultural action and also applying the information from the expert farmers. In this study, diesel fuel consumption was calculated using (Taghavifar and Mardani, 2015):

$$F_c = F_{hr} \times T \tag{2}$$

### 2.2.2. Electricity

In wheat production, electricity is consumed for irrigation. Water for irrigation in this region was mostly pumped from deep well by huge electric pumps. One of the serious problems in this region is the lack of adequate water because of excessive consumption and using old irrigation systems. So, one of the largest energy consuming sources in wheat production in this region is the energy needed for water pumping by electric pumps. (Taki et al, 2016):

$$E_e = \frac{\rho \times g \times H \times \Phi}{\varepsilon_1 \times \varepsilon_2} \tag{3}$$

### 2.2.3. Human Labor

Generally, human power is considered as the muscular strength of a working man (Nawi et al., 2012). Multiplying the number of workers with the energy equivalent of 1 hour of man labor and the total working time by the workers can calculate the human power for all agricultural activities. (Nabavi-Pelesaraei et al, 2013).

### 2.2.4. Embodied energy of machinery

For calculating the energy consumption and share of each machine in wheat production, machinery effective lifetime, average area and weight are important factors. The following equation was used to calculate the share and energy of each machine and implement (Ramedani et al, 2011):

$$M_E = E_m \times \frac{W}{E_t} \times Q_h \tag{4}$$

### 2.2.5. Fertilizer

Energy for fertilizer was calculated based on N, $P_2O_5$ and $K_2O$ energy equivalent by the following equation (Taghavifar and Mardani, 2015):

$$E_f = W_f \times E_k \tag{5}$$

### 2.2.6. Spraying

For calculating the energy equivalent of pesticides used in agricultural production, it is possible to use the multiplication of the amount of active ingredient of each poison (kg/L) in the equivalent energy used (Table 2) for its production (Taghavifar and Mardani, 2015).

### 2.2.7. Energy indicates

Some energy indicators can be used to calculate the energy efficiency of agricultural production. (Yuan and Peng; 2017; Taki et al, 2018). Based on the energy equivalents (Table 2), energy use efficiency (energy ratio), energy productivity and net energy gain were computed as (Taki et al, 2012c):

$$\mathrm{E}_R = \mathrm{E}_O / \mathrm{E}_\mathrm{I} \tag{6}$$

$$\mathrm{E}_P = \mathrm{O}_\mathrm{P} / \mathrm{E}_\mathrm{I} \tag{7}$$

$$\mathrm{N}_E = \mathrm{E}_\mathrm{O} - \mathrm{E}_\mathrm{I} \tag{8}$$

## 2.3. LCA methodology

LCA is a widely used method for assessing and studying the performance of crop production (Liamsanguan and Gheewala, 2008). LCA was defined as an assessment and evaluation of the outputs, inputs and the total environmental impacts of a product system during its life cycle (ISO 14040, 2006) (Nabavi-Pelesaraei et al, 2017). The amicability of LCA in numerous previous studies was evaluated (Cleary, 2009). Based on the ISO 14040, the structure of LCA includes four separate stages that contribute to a unified approach (ISO, 2006): 1. Goal and area definition. 2. Life cycle inventory (LCI). 3. Life cycle impact assessment (LCIA). 4. Interpretation (Nabavi-Pelesaraei et al, 2017).

### 2.3.1. Structure of LCA

To define the aim and scope of the study, the suggestions based on the International Reference Life Cycle Data System (IRLCDS) Handbook (European Commission, 2010) was applied. This research is a cradle to gate study and accordingly, the objective of this study is to assess the environmental performance of irrigated and rainfed wheat production. LCA present and analysis total environmental impact of energy consumption based on the system boundaries and Functional Unit (FU) (Rebitzer et al., 2004). FU is usually defined as the system's output. System boundary of this study covers all farm operations for wheat production. Fig.2 shows the system boundary for irrigated wheat production (Rainfed system boundary is very similar to irrigated but has not water for irrigation). As it can be seen, for irrigated wheat, electricity is used for pumping water and therefore the only difference between rainfed and irrigated wheat processing is electricity (Pahlavan et al, 2011). Direct emissions are the result of the operations but the source of indirect emissions is the process of procuring diesel fuels, electricity (produced and consumed) and other products. The FU adopted was the production of 1 ton of wheat during a production period.

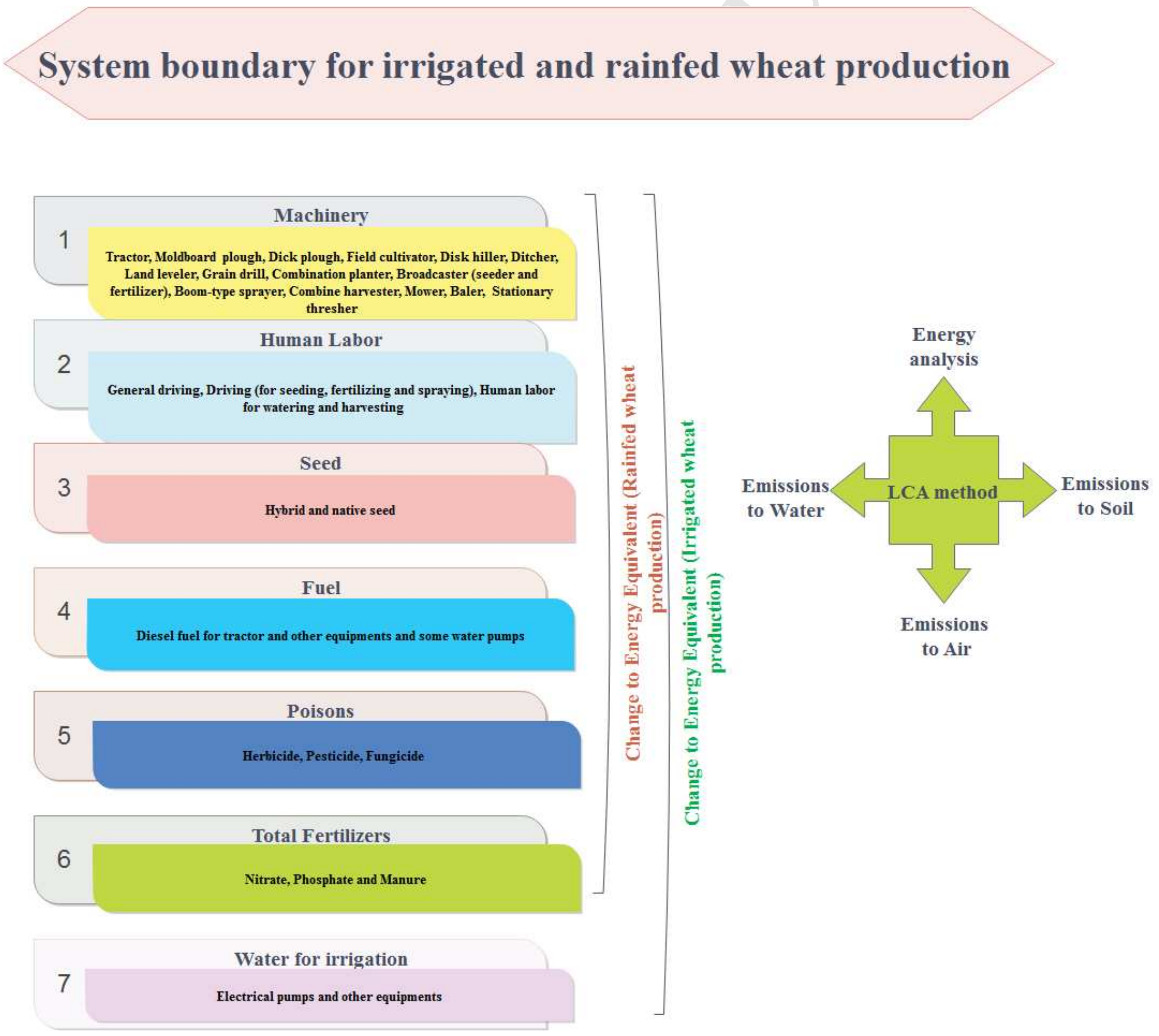


**Fig.2.** System boundary of LCA process for irrigated and rainfed wheat production.

### 2.3.2. Life Cycle Inventory (LCI) Analysis

In the second phase of LCA method, the product system is defined (Blanco et al, 2015). In this stage, total inputs and outputs can change to quantify situation (Kouchaki-Penchah et al, 2017). In this section, LCI data for were acquired (1 ton of wheat). Inventory data in the foreground system (actual crop production) consisted of actual farm practices obtained through face-to-face questionnaire method with wheat farmers (Table 1) (Rivela et al, 2006). Other inventory data such as machinery, nitrogen, phosphate, farmyard manure and biocides were obtained from literature and systematic software databases (Ecoinvent 3.0 and Agri-footprint) (Wernet et al., 2016). Emission of diesel fuel was added from Nemecek and Kagi (2007) and Nielsen et al (2005) (Table 3).

**Table.3.** Life cycle inventory data for a MJ traction in Ecoinvent database.

| Emissions | Amount (g/MJ diesel) |
|---|---|
| $CO_2$ | 74.5 |
| $SO_2$ | 2.41E-02 |
| $CH_4$ | 3.08E-03 |
| Benzene | 2.39E-07 |
| Cd | 1.19E-06 |
| Cr | 1.19E-06 |
| (Cu | 4.06E-05 |
| $N_2O$ | 2.86E-03 |
| Ni | 1.67E-06 |
| Zn | 2.39E-05 |
| Benzo (a) pyrene | 7.16E-07 |
| $NH_3$ | 4.77E-04 |
| Se | 2.39E-07 |
| PAH (polycyclic hydrocarbons) | 7.85E-05 |
| Hydro carbons (HC, as NMVOC) | 6.80E-02 |
| $NO_x$ | 1.06 |
| CO | 1.50E-01 |
| Particulates (b2.5 μm) | 1.07E-01 |

### 2.3.3. Life Cycle Impact Assessment (LCIA)

The aim of the LCIA, is to evaluate the amount and effect of the potential environmental impacts of a product system (Nabavi-Pelesaraei et al, 2014). The impact categories were analyzed based on CML-IA baseline V3.01/EU25 (Guinee, 2002) method and include: human toxicity (HT), acidification (AC), eutrophication (EP), ozone layer depletion (OLD), fresh water aquatic ecotoxicity (FE), abiotic depletion (AD), global warming (GW), terrestrial ecotoxicity (TE), marine aquatic ecotoxicity (ME) and photochemical oxidation (PO) (Durlinger et al., 2014). All these impact categories can affect ecosystem quality, human health, climate change and resources as damage categories. Fig.3 shows the links between impact and damage categories. For energy analysis and evaluate the potential environmental impact, Excel 2013 spreadsheets and SimaPro V8.0 software were used.

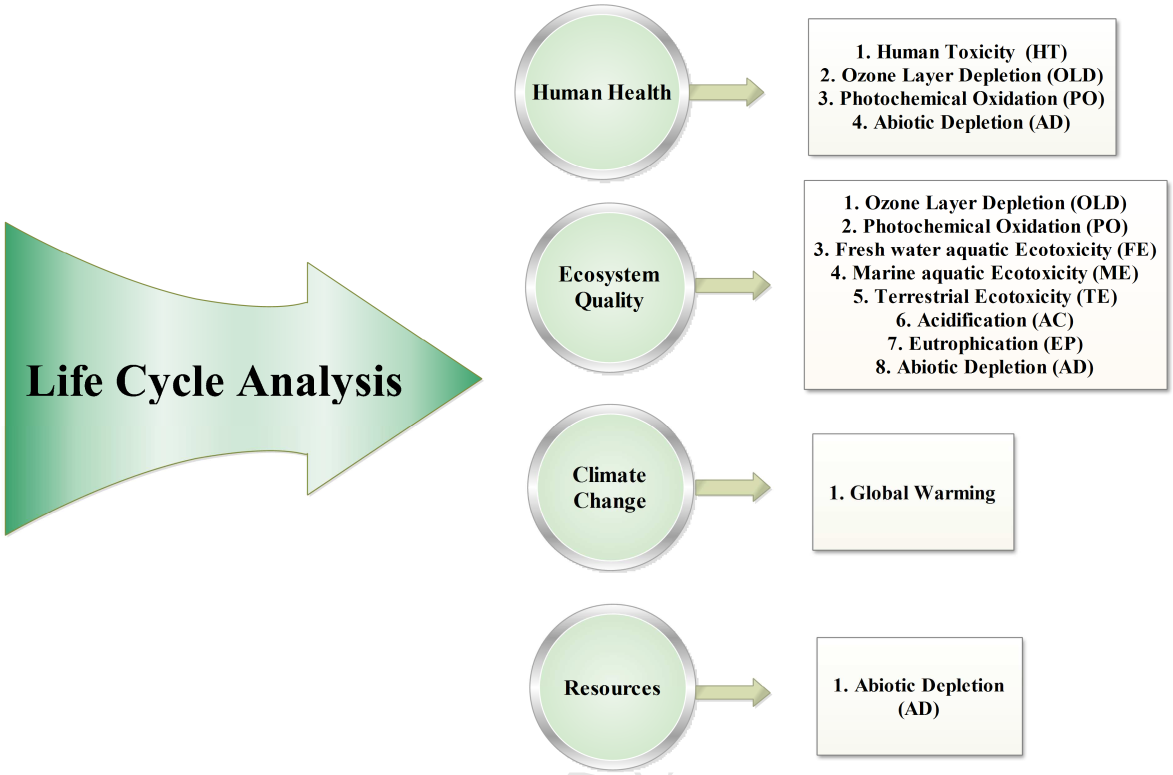


**Fig.3.** Links between impact categories and damage categories

## 3. Results and discussion

### 3.1. Energy consumption

Table 4 shows a summary of energy consumption (GJ $ha^{-1}$) for wheat production in different farm sizes. Total energy consumption in wheat production (irrigated and rainfed) and output energy were 23.41, 9.35 and 64.84, 35.22 GJ/ha, respectively. As it can be seen, in all farm types, diesel fuel had the highest impact on energy output except for small rainfed farms (<2 ha-rainfed). In small farms, total chemical fertilizer and poisons had the highest impact on output energy (The farmers used to spread the fertilizer with hand and this method can increase the fertilizer consumption). Khoshnevisan et al (2013a) reported that total input energy for wheat production in Isfahan province were 80.40, 79.29 and 81.11 GJ/ha for small (<1 ha), medium (1-3 ha) and large (>3 ha) farms, respectively. The results in this research are significantly higher than present results. In that research, electricity and chemical fertilizer had the most important effects on output energy (49% and 29%, respectively).

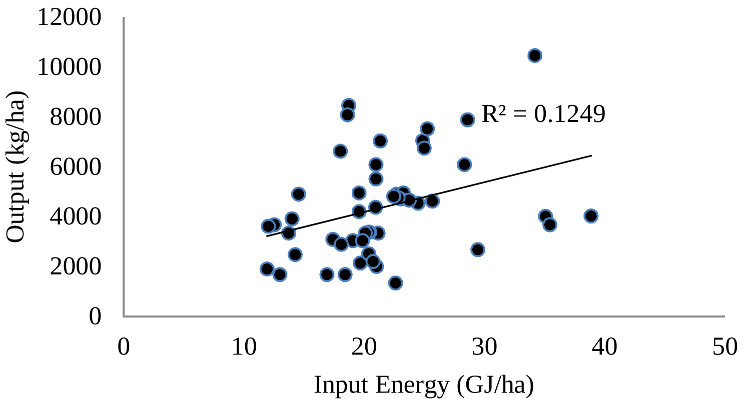
In a similar study, Safa et al (1999) reported that total input energy for irrigated and rainfed (dryland) wheat production in New Zealand were 25.6 and 17.45 GJ/ha, respectively. In that research, chemical fertilizer and electricity had the highest share in irrigated farms. In the present research, some of farmers used diesel fuel engines for water pumping. This type of energy was calculated for diesel fuels. In this region, because of increasing of drought period and also existing of deep wells, farmers had to use much energy for water extraction. Similar results were reported by Abdollahpour and Zaree et al (2009). The authors showed that total input and output energy for irrigated wheat production was 25.67 and 21.01 GJ/ha at west of Iran (Kermanshah province).

The results of present study showed that in large farms (irrigated), the total input energy used per hectare was higher than small farms, but the total output energy per hectare in small farms was actually higher than large farms. This results showed that using of technology was not effective in irrigated wheat farms and will be worse by increasing in farm sizing. Actually, after the White Revolution in 1963-1978, farm lands were divided between farmers and so their sizes became smaller than in the past. The results of Table 4 showed that, total input of machinery will increase by changing the farm sizing (small to large).

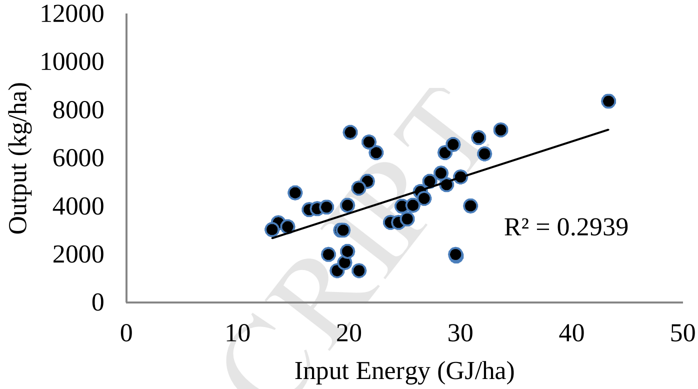
**Table.4.** Energy inputs and output for wheat production (GJ/ha).

| | Item | Irrigated wheat farms | | | | | | Rainfed wheat farms | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (< 2 ha) | | Medium (2-4 ha) | | Large (> 4 ha) | | Small (< 2 ha) | | Medium (2-4 ha) | | Large (> 4 ha) | |
| Inputs | | Mean | Std | Mean | Std | Mean | Std | Mean | Std | Mean | Std | Mean | Std |
| | Machinery | 0.66 | 0.20 | 0.84 | 0.24 | 0.83 | 0.20 | 0.31 | 0.08 | 0.41 | 0.16 | 0.49 | 0.17 |
| | Water for irrigation | 3.19 | 3.51 | 4.54 | 4.53 | 5.46 | 4.68 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Human labor | 0.20 | 0.11 | 0.19 | 0.09 | 0.13 | 0.08 | 0.14 | 0.08 | 0.10 | 0.07 | 0.05 | 0.05 |
| | Diesel fuel | 6.52 | 1.53 | 7.64 | 2.09 | 7.22 | 1.74 | 3.69 | 0.56 | 4.30 | 1.11 | 4.44 | 1.02 |
| | Total chemical Fertilizer | 5.54 | 0.87 | 5.21 | 0.96 | 6.34 | 0.92 | 3.77 | 0.84 | 3.18 | 0.83 | 2.85 | 0.67 |
| | Pesticides | 0.10 | 0.10 | 0.44 | 0.13 | 0.46 | 0.09 | 0.08 | 0.10 | 0.09 | 0.10 | 0.09 | 0.06 |
| | Herbicides | 0.37 | 0.12 | 0.16 | 0.08 | 0.15 | 0.09 | 0.21 | 0.24 | 0.25 | 0.24 | 0.27 | 0.24 |
| | Fungicides | 0.04 | 0.05 | 0.08 | 0.05 | 0.06 | 0.05 | 0.06 | 0.03 | 0.05 | 0.04 | 0.05 | 0.04 |
| | Seed | 4.86 | 3.02 | 4.68 | 3.16 | 4.33 | 2.66 | 1.08 | 0.84 | 1.10 | 0.32 | 1.00 | 0.56 |
| | Total input energy | 21.48 | - | 23.78 | - | 24.98 | - | 9.34 | - | 9.47 | - | 9.24 | - |
| | Average of input energy (irrigated and rainfed) | 23.41 | | | | | | 9.35 | | | | | |
| Output | Output energy (Grain) | 59.80 | - | 62.60 | - | 72.11 | - | 38.48 | - | 35.20 | - | 32.00 | - |
| | Average of output energy (for irrigated and rainfed) | 64.84 | | | | | | 35.22 | | | | | |

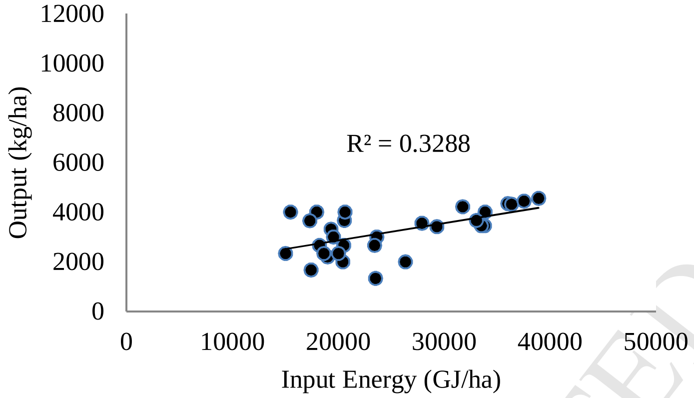
Fig.4 shows the correlation between input energy and yield for irrigated and rainfed wheat production. In this research, for irrigated wheat, diesel fuel has the highest share in total inputs (29%) followed by chemical fertilizers (25%). Diesel fuel consumed the most energy of total energy inputs in rainfed farms (48%), followed by total fertilizers and poisons (35%). The share of total fertilizers in small rainfed farms was higher than diesel fuel, because in these farms, humans usually spread the fertilizers and the farmers did not use machinery for this operation. Ghorbani et al. (2011) reported that total energy input for irrigated and rainfed wheat production systems in Northern Khorasan province of Iran were 45.37 and 9.35 GJ/ha, respectively.



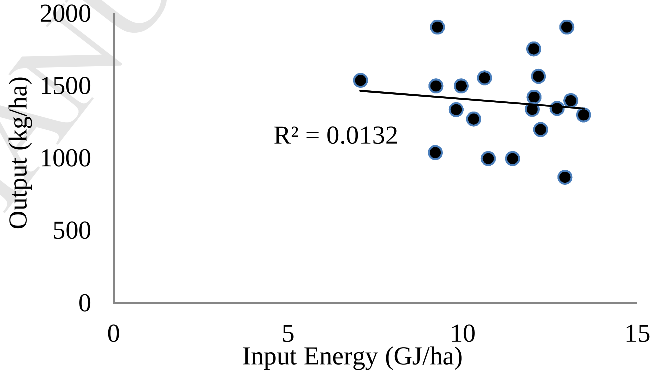
< 2 ha-Irrigated



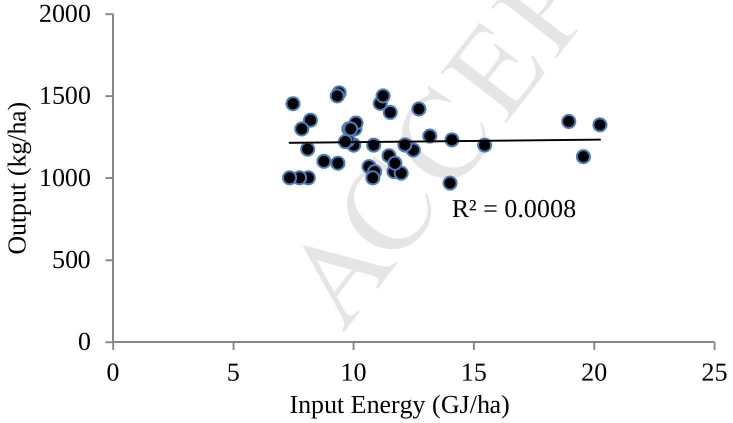
2-4 ha-Irrigated



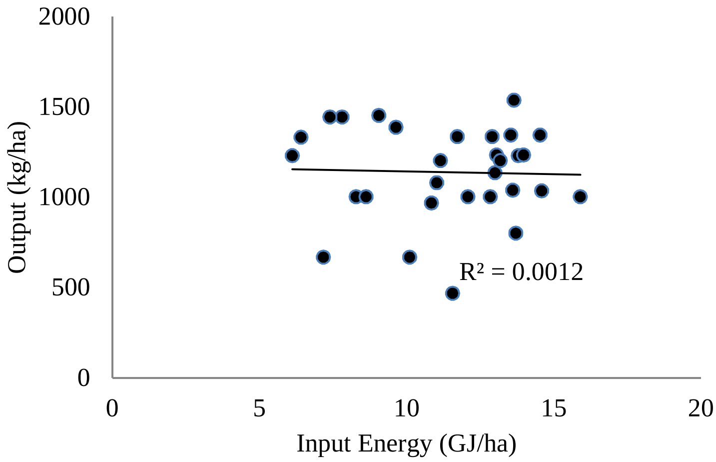
> 4 ha-Irrigated



< 2 ha-Rainfed



2-4 ha- Rainfed



> 4 ha- Rainfed

**Fig.4.** Correlation between energy consumption (GJ/ha) and yield (kg/ha) in irrigated and rainfed wheat production

The results indicated that chemical fertilizers, electricity and diesel fuel inputs were 10.95, 16.84 and 4.32 GJ/ha respectively in irrigated wheat farms. Similar results were reported in other studies for different crops such as irrigated and dryland chickpea production systems (Koocheki et al., 2011) and sugar beet (Asgharipour et al., 2012).

Positive correlation between yield and energy consumption for irrigated and negative correlation for rainfed wheat production farms was the most attractive finding of this research. This indicate can able the farmers to increase energy input and receive more yield at irrigated farms. The reason of this fact is mostly because of irrigation and fertilizer, that prepares better situation for crop growing. However, finding a balanced solution that could optimize the constraints on production, environmental and financial benefits simultaneously is one of the most important purposes in sustainable farming (Safa et al, 2011). As it can be seen, for irrigated farms (especially for large lands), the correlation between input energy and output yield was higher than other (0.32). The energy ratio, energy productivity and net energy of irrigated and rainfed wheat production are tabulated in Table 5.

**Table.5.** The share of each category on total energy inputs for irrigated and rainfed wheat production.

| Item | Irrigated wheat farms | | | | Rainfed wheat farms | | | |
|---|---|---|---|---|---|---|---|---|
| | Unit | (< 2 ha) | (2-4 ha) | (> 4 ha) | Unit | (< 2 ha) | (2-4 ha) | (> 4 ha) |
| Energy ratio | - | 2.78 | 2.63 | 2.89 | - | 4.11 | 3.71 | 3.46 |
| Net energy | GJ/ha | 38.32 | 38.83 | 47.14 | GJ/ha | 29.14 | 25.73 | 22.76 |
| Energy productivity | kg/GJ | 145.49 | 122.50 | 129.90 | kg/GJ | 149.60 | 127.45 | 123.45 |
| [a] Direct energy | GJ/ha | 9.91 (46%) | 12.37 (52%) | 12.81 (51%) | GJ/ha | 3.83 (41%) | 4.41 (46%) | 4.49 (48%) |
| [b] Indirect energy | GJ/ha | 11.57 | 11.40 | 12.17 | GJ/ha | 5.51 | 5.07 | 4.74 |
| [c] Renewable energy | GJ/ha | 5.06 | 4.87 | 4.46 | GJ/ha | 1.22 | 1.20 | 1.05 |
| [d] Non-renewable energy | GJ/ha | 16.42 | 18.90 | 20.51 | GJ/ha | 5.51 | 8.25 | 8.19 |
| Total energy | GJ/ha | 21.48 | 23.77 | 24.97 | GJ/ha | 9.34 | 9.47 | 9.24 |

[a] Includes diesel fuel, human labor and water for irrigation
[b] Includes machinery, farmyard manure, biocide, seed and chemical fertilizer
[c] Includes farmyard manure, seed and human labor
[d] Includes chemical fertilizer, diesel fuel, machinery and water for irrigation

In total energy researches, energy ratio is a general index to evaluate the efficiency of sources. (Kuesters and Lammel, 1999). In this research, this index for different land sizes of irrigated and rainfed wheat production was 2.60-2.90 and 3.10-4.10, respectively. The average of energy use efficiency in rainfed wheat production was nearly more than twice higher than irrigated wheat production, which showed better efficiency in rainfed wheat production based on 1 ha wheat crop. the researches, evaluated the energy ratio for different crops. For example, it was found this indicate was 3.40 for rainfed and 1.4 for irrigated wheat production system (Ghorbani et al., 2011), 1.20 for irrigated and 2.90 for dryland chickpea production system (Koocheki et al., 2011), 13.40 for sugar beet (Asgharipour et al., 2012) and also 3 and 3.85 for irrigated and rainfed wheat production (Mondany et al, 2017). The results indicated that in irrigated wheat production, the highest and the lowest energy use efficiency were 2.63 and 2.89 for medium and large farms, respectively. It shows that larger irrigated farms can produce wheat more effective than smaller irrigated farms.

The results of this study showed that average energy productivity in irrigated and rainfed wheat production were 132.63 and 133.50 kg $GJ^{-1}$, respectively. Energy productivity is a very important indicator for evaluation the crop production systems and energy output. Energy productivity, indicates sustainability and security in agricultural production systems. Several researchers were evaluated this index for agricultural crops production (Rezvani-Moghaddam et al., 2011; Koocheki et al., 2011; Ghorbani et al., 2011). In this study, net energy index shows consuming lots of extra energy in rainfed wheat. It demonstrated that in this region, the farmers have a very significant potential in saving energy. For increasing the energy efficiency systems, the farmers would often need governmental assistance and low-interest loans.

Fig.5 shows the share of two main types of chemical fertilizers in irrigated and rainfed wheat production. As it can be seen, in irrigated farms, chemical fertilizers were consumed more than rainfed. The high final price of production, environmental pollutions and some human hazard risks are the consequences of this excessive consumption.

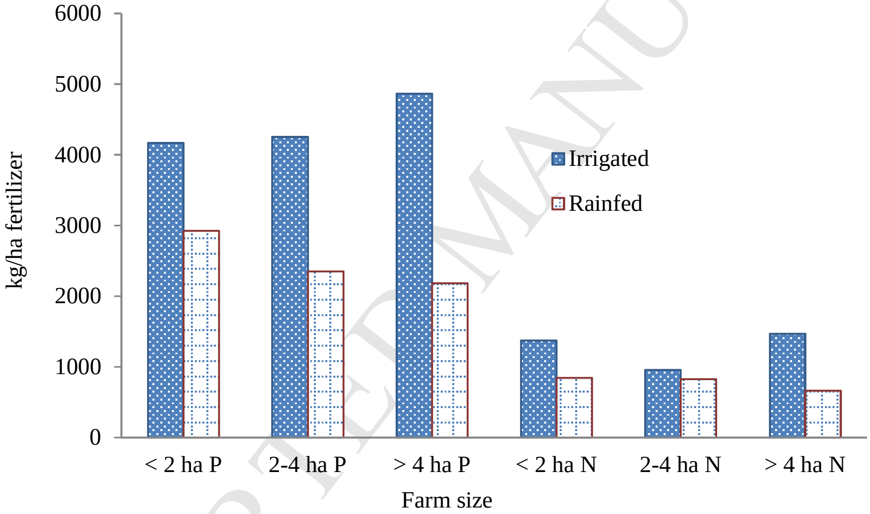


**Fig.5.** The share of two types of chemical fertilizer (N and $P_2O_5$) for irrigated and rainfed wheat production.

The share of direct, indirect, renewable, and non-renewable forms of energy is shown in Table 5. As it can be seen, the share of indirect energy in small and medium farms is higher than in large farms. In large farms, the application of machinery was higher than others. In this region, most of the farmers used hybrid seeds, so the equivalent energy of seed was higher than other researches. The share of direct energy in irrigated wheat production was higher than similar results for rainfed wheat production in all categories (small, medium and large farms) (Table 5). So, it seems that rainfed wheat production was more sustainable production system compared to irrigated wheat system. The results in Table 5 indicates that the share of renewable energy including seed, human labor and farmyard manure in irrigated was higher than rainfed wheat production. In all categories, the average of renewable energy for irrigated and rainfed wheat production is 4.80 and 1.16 GJ/ha, respectively. Fig. 6 shows the share of non-renewable and renewable energy in all categories for irrigated and rainfed wheat production. The excessive consumption of diesel fuel and electricity was the main reason for higher levels of non-renewable energy in all agricultural productions. Mohammadi et al. (2014) reported that total input energy in wheat farms of Golestan province was 26.20 GJ/ha, which the share of direct and indirect energies was 58.8% and 41.2%, respectively. The share of renewable and non-renewable energies was 17.9% and 82.1%, respectively.

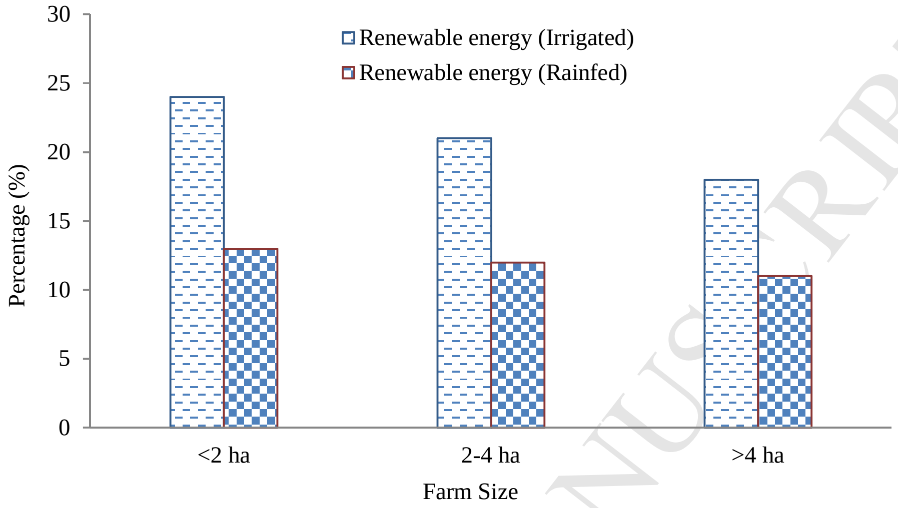


**Fig.6.** The share of renewable energy for irrigated and rained wheat production in different farm sizes.

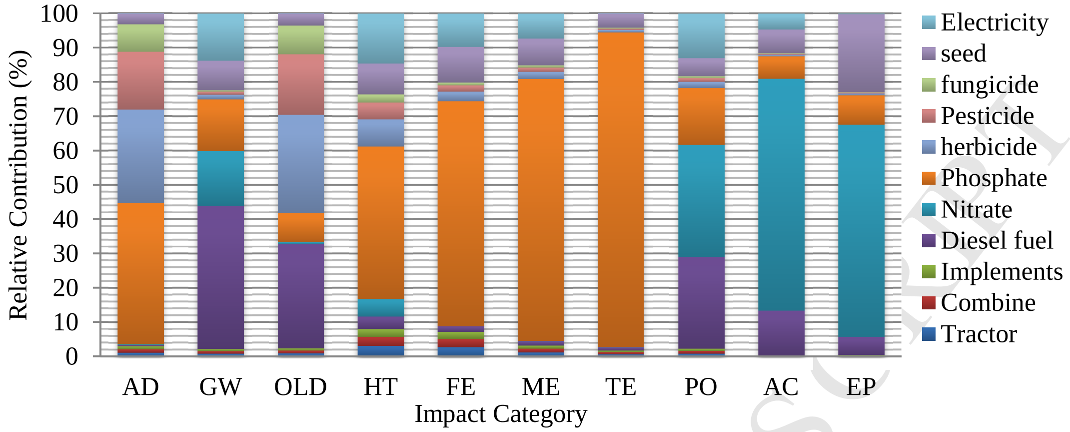
### 3.2.LCA results

A brief summary of environmental impacts based on wheat production (per ton wheat in all periods of cultivation) for irrigated and rainfed wheat production is shown in Table 6.

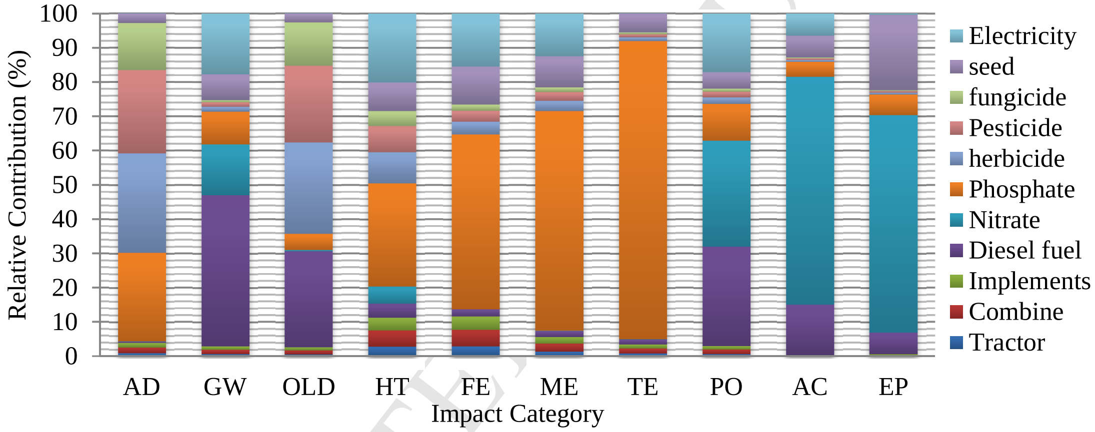
**Table.6.** Values of the potential environmental impact of irrigated and rainfed wheat production per ton of wheat produced.

| Impact Category | Unit | Irrigated Wheat | Rainfed Wheat |
|---|---|---|---|
| AD | kg Sb eq | 0.002 | 0.003 |
| GW | kg $CO_2$ eq | 317.81 | 380.16 |
| OLD | kg CFC-11 eq | 0.00002 | 0.00004 |
| HT | kg 1,4-DCB eq | 81.45 | 99.96 |
| FE | kg 1,4-DCB eq | 40.95 | 53.42 |
| ME | kg 1,4-DCB eq | 203,362.64 | 275,721.25 |
| TE | kg 1,4-DCB eq | 0.46 | 0.69 |
| PO | kg $C_2H_4$ eq | 0.15 | 0.17 |
| AC | kg $SO_2$ eq | 8.99 | 11.86 |
| EP | kg $PO_4^{3-}$ eq | 2.23 | 3.18 |

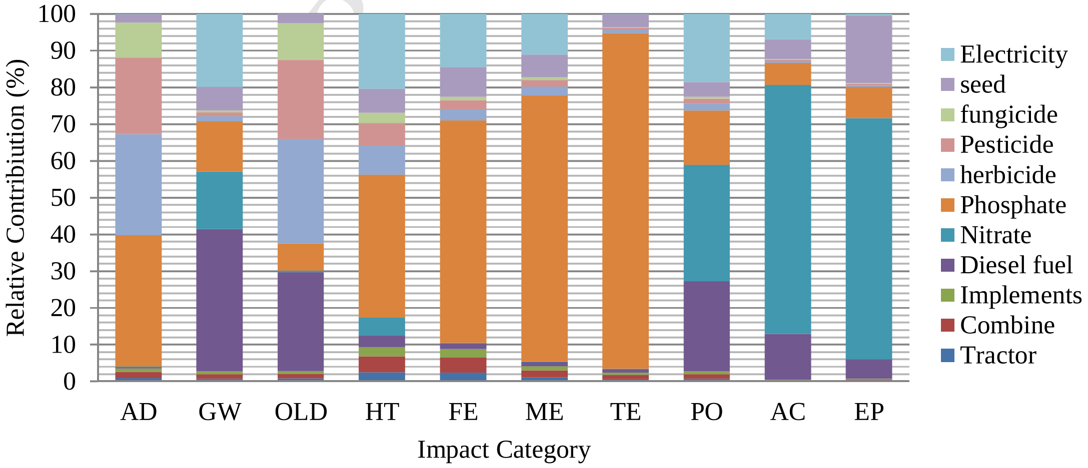
Primary LCA models show that rainfed wheat produced more pollutions than irrigated wheat system because of significantly lower yield. The reason of this fact is more energy consumption per ton of wheat production in rainfed than irrigated system (the results of Table 4 showed this fact). By dividing the amount of each input into wheat production in each hectare (4.8 for irrigated and 1.8 for rainfed farms), it can be seen that more energy has been consumed for production of one ton rainfed than irrigated wheat. The share of each input on final environmental pollution based on different farm sizing and the hotspots in each category are shown in Figs 7-8 and Table 7.



**A: <2 ha farms**

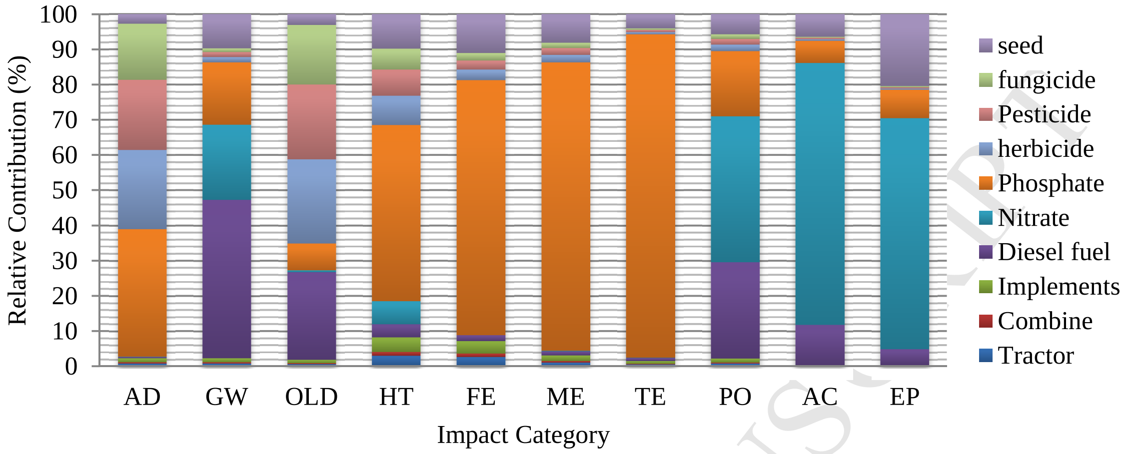


**B: 2-4 ha Farms**

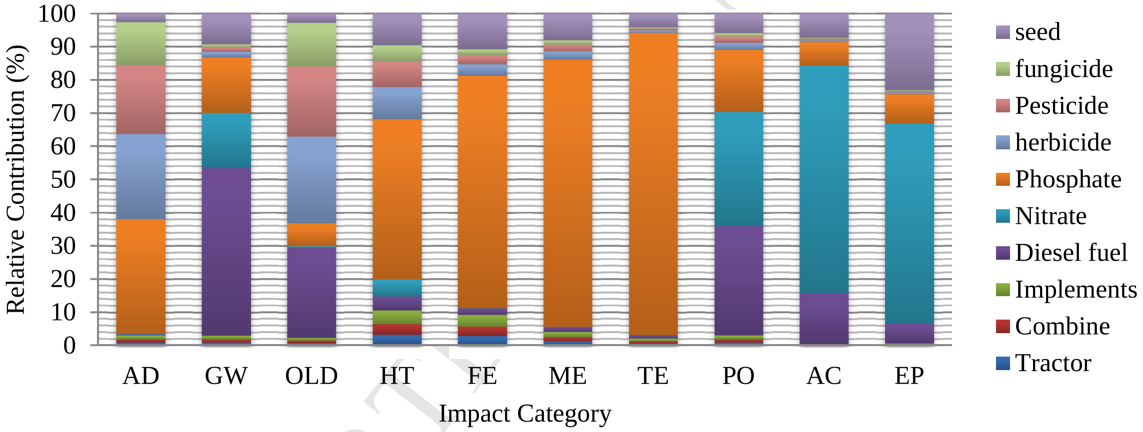


**C: >4 ha Farms**

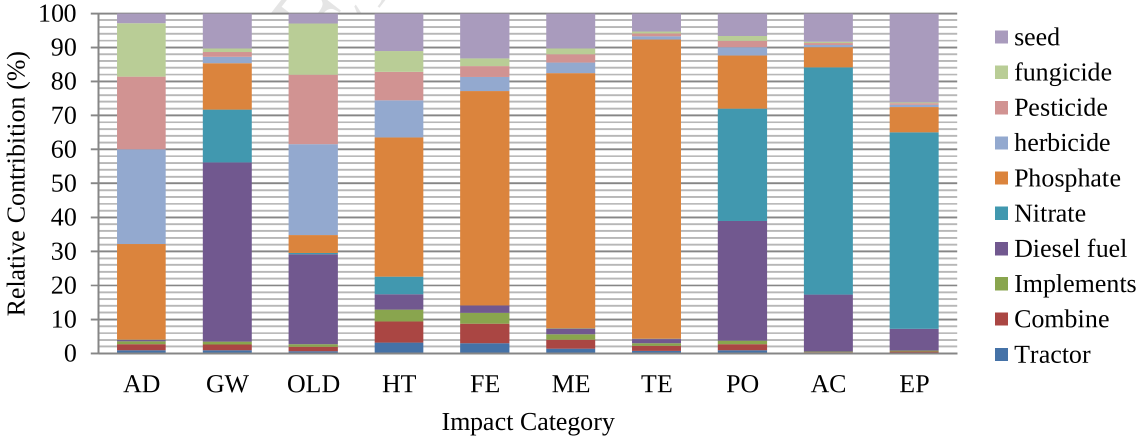
**Fig.7.** Relative contributions of irrigated wheat production (%) to each impact category (Combine means combine harvester and implements are agricultural machineries expect tractor and combine harvester)



**A: <2 ha farms**



**B: 2-4 ha Farms**



**C: >4 ha Farms**

**Fig.8.** Relative contributions of rainfed wheat production (%) to each impact category (Combine means combine harvester and implements are agricultural machineries expect tractor and combine harvester)

**Table.7.** Environmental hotspots for irrigated and rainfed wheat production in each impact category.

| Impact categories | Irrigated wheat | | | Rainfed wheat | | |
|---|---|---|---|---|---|---|
| | <2 ha | 2-4 ha | >4 ha | <2 ha | 2-4 ha | >4 ha |
| AD | Phosphate, Herbicide, Pesticide | Phosphate, Herbicide and Pesticide | Phosphate, Herbicide and Pesticide | Phosphate, Herbicide, Pesticide | Phosphate, Herbicide, Pesticide | Phosphate, Herbicide, Pesticide |
| GW | Diesel fuel, Nitrate and Phosphate | Diesel fuel and Electricity | Diesel fuel, Nitrate and Electricity | Diesel fuel, Nitrate | Diesel fuel, Nitrate and Phosphate | Diesel fuel, Nitrate and Phosphate |
| OLD | Diesel fuel, Herbicide and Pesticide | Diesel fuel, Herbicide and Pesticide | Herbicide, Diesel fuel and Pesticide | Diesel fuel, Herbicide and Pesticide | Diesel fuel, Herbicide and Pesticide | Herbicide, Diesel fuel and Pesticide |
| HT | Phosphate and Electricity | Phosphate and Electricity | Phosphate and Electricity | Phosphate and Seed | Phosphate and Herbicide | Phosphate and Seed |
| FE | Phosphate, Seed and Electricity | Phosphate, Electricity and Seed | Phosphate and Electricity | Phosphate and Seed | Phosphate and Seed | Phosphate and Seed |
| ME | Phosphate, seed and Electricity | Phosphate, Electricity and Seed | Phosphate and Electricity | Phosphate and Seed | Phosphate and Seed | Phosphate and Seed |
| TE | Phosphate and Seed | Phosphate and Seed | Phosphate | Phosphate | Phosphate | Phosphate |
| PO | Nitrate, Diesel fuel and Phosphate | Nitrate, Diesel fuel and Electricity | Nitrate, Diesel fuel and Electricity | Nitrate, Diesel fuel and | Nitrate, Diesel fuel and | Diesel fuel and Nitrate |
| AC | Nitrate and Diesel fuel | Nitrate, Diesel fuel and | Nitrate, Diesel fuel and | Nitrate, Diesel fuel and | Nitrate, Diesel fuel and Seed | Nitrate, Diesel fuel and |
| EP | Nitrate, Seed and Phosphate | Nitrate, Seed | Nitrate, Seed and Phosphate | Nitrate and Seed | Nitrate and Seed | Nitrate and Seed |

Toxicity assessment with LCA method is widely used to evaluate agricultural input toxicity. The leachate can increase the potential toxic compounds in groundwater and surface water (Kjeldsen et al., 2002). As it can be seen in Figs. 6 and 7, the most crucial factors in creating the pollution are phosphate and electricity. For this reason, innovative ideas for using the chemical fertilizers and irrigation system in sustainable wheat production should be proposed. The region where wheat production is made is very good in terms of solar energy potential. Solar energy-assisted electricity can be applied in the irrigation as a solution proposal. In terms of agro-chemical pollutions, variable rate technologies and precision application of pesticides and fertilizers can be considered as a potential alternative. Özilgen (2017), noted that microbial fertilizers could replace the chemical fertilizers in the context of sustainable agricultural practices. In this context, the use of microbial fertilizers instead of chemical fertilizers in the wheat production process could be an innovative application for agricultural applications in this region.

Hoshyar and Grundmann (2017) reported that more than 40 and 70% of total toxicities could be due to ploughing, harrowing, planting and combine harvesting in wheat production by conventional tillage method. The authors reported that planting and combine harvesting applications have higher impacts on the toxicities in no-tillage wheat production system (around 70%). Adom et al. (2012) found that $N_2O$ released from total farm application can cause 65% of GHG emissions, whereas 35% was produced by fertilizer manufacture. As it can be seen in Table 6, GW was obtained as 317.81 and 380.17 kg $CO_2$ eq. for 1 ton irrigated and rainfed wheat, respectively. This was comparable with the results of other studies (Biswas et al., 2008). According to Nabavi-Pelesaraei et al. (2016), the optimum carbon footprint was identified about 81 kg $CO_2$ eq. per ton for irrigated wheat. It shows inefficient use of inputs in wheat production in the region.

In this study, the rate of greenhouse gas (GHG) produced by irrigated and rainfed wheat production systems is estimated at 317.81 and 380.17 kg $CO_2$ eq per 1 ton, respectively. This was comparable with the results of other studies (Biswas et al., 2008). It was found that in this study, diesel fuel followed by nitrate and electricity are the main sources in this index. Some researchers reported that synthetic N fertilizers for cropping is the main factor for calculating the GHG index (Sheehan et al. 1998; Braschkat et al. 2003; Robertson et al, 2000).

The rate of AD impact was found to be 0.002 kg Sb eq. for irrigated and 0.003 kg Sb eq. for rainfed wheat system and the main contribution was due to phosphate followed by electricity and pesticide for both cropping systems. Fantin et al. (2016) calculated AD as 0.0034 kg Sb eq. in Italian wheat production system that is comparable with present results. It can be attributed because of nitrate and phosphate fertilizers used in farm. Based on Hoshyar and Grundmann (2017), nitrate and phosphate are the main factors which affect the AD index on conventional wheat production.

The rate of EP impact was found to be 2.23 and 3.18 kg $PO_4^{3-}$ eq. for irrigated and rainfed wheat production system, respectively. NOx and $NH_3$ depositions have the highest impact on terrestrial eutrophication (Potting et al., 2000). Minimizing the phosphorus and nitrogen losses is an effective method to reduce EP. Since the impact of nitrogen on EP was higher than phosphorous, it is suggested that excessive nitrogen consumption should be avoided to achieve better environmental outcome. Hoshyar and Grundmann (2017) reported that farm machinery operations, nitrogen and seed are the key influencing parameters for calculating EP index in wheat production.

Acidification index can explain the climate change. The major compounds of acidification index are $SO_2$, $NO_X$, HCl and $NH_3$. (Nabavi-Plesaraei et al, 2017). As indicated in Table 6, the values of AC were 8.991 kg $SO_2$ eq. for irrigated and 11.863 kg $SO_2$ eq. for rainfed wheat production system, respectively. The microbial oxidation of fertilizers is the main acid forming reaction for fertilizers (Taki et al, 2016). In this research, more than 60% of this index was due to nitrate and phosphate uses and about 20% is because of diesel fuel and machinery.

Ozone layer depletion is a major problem in climate change and one of the main reasons of global warming. Chlorofluorocarbons (CFCs) have a major impact on ozone layer depletion. (Taki et al, 2012a). In this study, OLD was calculated about 0.00002 and 0.00004 kg CFC11 eq. for irrigated and rainfed wheat production system.

Photochemical oxidation is often a secondary parameter in air pollution. The amounts of PO were calculated 0.145 kg $C_2H_4$ eq. for irrigated and 0.174 kg $C_2H_4$ eq. for rainfed wheat production system, respectively. Nitrate and diesel fuel had the highest impact on PO in both of irrigated and rainfed wheat production. Decreasing the amount of fertilizer and using of farm machinery operation also well pumps can affect this factor.

A general comparison is carried out to compare results of the environmental assessment of wheat production in Iran and other countries using LCA method. Meisterling et al. (2009) investigated the conventional and organic wheat production systems in the USA. The authors reported that, considering global warming, production of 1 kg bread under organic system, can produce only 30 kg $CO_2$ eq., which is less than the conventional cropping system. Wang et al. (2015) analyzed the GWP of wheat production in north China. GWP value per hectare was reported 2.99-4.59 ton $CO_2$ eq $ha^{-1}$.

Overall comparison of two wheat production systems (rainfed and irrigated) in this research showed that rainfed system may cause more environmental burdens than irrigated one and using irrigated system can reduce environmental impacts about 24% compared with rainfed. Results showed that the size of farms has no significant effect on environmental pollutions in both systems. In irrigated system, small farms, created more environmental pollution than other sizes (about 4%), but in rainfed system, environmental burdens were almost same in all three farm size categories.

The overall results of this study indicated that rainfed wheat could produce more environmental pollution than irrigated wheat production system.

Considering the quality of inputs can lead to different results from the findings of this study. One of the methods that can use to optimize the energy and environmental pollutants in terms of the quality of inputs, is thermodynamic approach (Yildizhan, 2017a,b). As a further research, it is recommended to used exergy approach for wheat and other agricultural products for calculation the impact of production on environmental pollution according to the quality of each input. Also a detailed analysis of agro-chemicals (fertilizers and pesticides) is necessary in terms of emissions to each compartment such as soil, water and crop.

## 4. Conclusion

This paper presented a LCA study of irrigated and rainfed wheat production systems in center of Iran, Mahyar plain, throughout the first phases of their life cycle. The study was used a comprehensive data collection include 210 irrigated and 90 rainfed wheat farms. Based on the results, it has been found that the total input energy for irrigated and rainfed wheat production were 23.41 and 9.35 GJ/ha, respectively. Diesel fuel and total chemical fertilizer were the major inputs in all irrigated and rainfed farm lands. Results showed that energy productivity in irrigated and rainfed wheat production were 132.63 and 133.50 kg $GJ^{-1}$, respectively. Also the results showed that the share of renewable energy in irrigated was higher than rainfed system. In all categories, the average of renewable energy in irrigated and rainfed wheat production is 4.80 and 1.16 GJ/ha, respectively. The results of LCA method indicated that the rate of greenhouse gas (GHG) produced by irrigated and rainfed wheat production is estimated at 317.81 and 380.17 kg $CO_2$ eq per 1 ton of produced wheat, respectively. LCA showed that based on 1 ton of wheat production as FU, rainfed system could actually cause more environmental burdens compared to irrigated system. The most crucial factors in creating this pollution are phosphate and electricity. For this reason, innovative ideas for using of chemical fertilizers and irrigation water in sustainable wheat production should be proposed. As a solution for decreasing the GHG emission, incentive policies for the use of renewable energy in agriculture must be presented by decision-makers. It is recommended that farmers be educated about the use of chemical fertilizers. As another recommendation, the use of microbial fertilizers should be widespread rather than the use of chemical fertilizers during the crop production process. Finally, for sustainable agriculture, farmers need to change their irrigation systems and increase harvesting efficiency to reduce energy consumption.

## Acknowledgments

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