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Research article

Evaluation of energy consumption of corn agro-ecosystem associated with greenhouse gas emissions in semi-arid conditions

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Abstract

Importance of the work: Extension innovation in up-scaling climate-resilient farming technology needs an integrated framework for existing mitigation options to reduce greenhouse gas (GHG) emissions in agricultural practices.

Objectives: To investigate the energy dynamics and global warming potential (GWP) of corn grain and stover production systems in a corn field.

Materials & Methods: The energy dynamics and GWP for corn grain and stover production systems were studied based on 2011–2016 Ministry of Agriculture statistical data in Iran per hectare of corn production system.

Results: The amount of energy output in stover production was significantly higher, with a significant difference between observed renewable and non-renewable energies in the grain and stover production systems. Energy efficiency, energy productivity and net energy in the corn grain production system were significantly higher than from stover production, while the amount of specific energy in grain production significantly increased compared to the stover production system. Total GWP was 3,782.95 ± 1,088.28 kg CO_2-eq/ha and 3,529.60 ± 970.77 kg CO_2-eq/ha for the corn grain and stover production systems, respectively. In terms of CO_2 equivalents approximately 22% and 23% of the GWPs came from CO_2, 73% and 71% from N_2O and 5% and 6% from CH_4 for the corn grain and stover production systems, respectively. Therefore, the grain production system had the highest potential for global warming. For the grain and stover production systems, the GWP rates per unit weight were 0.56 ± 0.16 kg eq-CO_2/ha and 0.04 ± 0.01 kg eq-CO_2/ha, respectively, and per unit output energy were 0.20 ± 0.04 kg eq-CO_2/ha and 0.05 ± 0.00 kg eq-CO_2/ha, respectively, and per unite input energy were 0.16±0.04 kg eq-CO_2/ha and 0.14±0.03 kg eq-CO_2/ha, respectively.

Main finding: Nitrogen fertilizer was the most important factor in GHG emissions from the corn grain and stover production systems. It is necessary to promote sustainable agro-ecosystems for the optimized use of production resources and reduced energy inputs and to reduce GWP in the agricultural sector, particularly regarding high-consumption inputs, such as fertilizers, seeds and irrigation water.

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Introduction

In recent years, efforts to make better application of energy resources have come to the attention of governments, with the agricultural sector being no exception. Thus, although the basic goal of any agricultural system is to increase yield, agro-ecosystem functions should be able to guarantee long-term crop production, conserve basic resources, reduce environmental pollution and ultimately stabilize production (Shabani et al., 2015). Therefore clearly, an activity should be sustainable both economically and environmentally (Barbier, 1987; Ilkaee et al., 2011; Mardukhi et al., 2015; Davaran-Hagh et al., 2016). As such, the environmental impacts of various agricultural activities should be analyzed on a range of spatial scales, from farm to national levels.

Corn stover consists of the leaves, stalks and cobs of maize (corn, *Zea mays* L.) plants left in a field after harvest. Such stover makes up about one-half of the yield of a corn crop and is similar to the straw produced from other cereal grasses; in Britain, it is sometimes called corn straw (Koundinya, 2017). Corn stover is a very common agricultural product in areas where there are large amounts of corn produced (Koundinya, 2017). It is most often harvested as a dry product and packaged in large round or large square bales, typically involving as many as seven steps after grain harvesting (Shinners et al., 2007).

Global warming because of greenhouse gas (GHG) emissions is one of the most important environmental challenges in the world today (Parry et al., 2007) and is endangering future life on Earth. The agricultural sector also has a significant share in greenhouse gas emissions and, consequently, in global warming (Intergovernmental Panel on Climate Change [IPCC], 2007, Parry et al., 2007). The largest factor in GHG emissions into the atmosphere is the energy sector (IPCC, 2007), and in recent years, in addition to energy evaluation in agricultural systems, the issue of greenhouse gas emissions has been very important as agriculture is a well-known and significant source of greenhouse gas emissions (IPCC, 2007, Parry et al., 2007). Nitrous oxide is about 60% and methane is 39% of global emissions, with 1% being for nitrogen dioxide (IPCC, 2007, Parry et al., 2007). The most important GHGs include carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (IPCC, 2007, Parry et al., 2007). The use of fertilizers and chemical pesticides, fossil fuels, management of agricultural soils, management of livestock manure and burning of organic waste are the most important sources of N_2O production in the agricultural sector (Fathi et al., 2020). On the other hand, because crop production is directly dependent on climatic conditions, agriculture is one of the first sectors to be affected by climate change. Developing farming systems with lower inputs and higher productivity could help reduce CO_2 emissions in the agricultural sector. In most developed countries, and even in developing countries, by studying the energy imported per unit area to produce different agricultural products and calculating the energy efficiency index, attempts have been made to optimize agricultural ecosystem in terms of energy consumption (Nasirian et al., 2006). Although farmers are unable to control climatic conditions, changes in management related to irrigation methods, soil preparation, other activities, and technologies used in crop cultivation can reduce the harmful effects of climate change on yield production (Ozkan and Akcaoz, 2002). Intensive ecosystems, such as those in the agricultural sector produce higher yields than natural ecosystems, of which a considerable component is auxiliary energy consumed by humans in planting, irrigation, fertilizer use and the control of pests, diseases and weeds. Given that the agricultural sector, on the one hand, is facing limited production resources and, on the other hand, is providing food security to the growing population, a balance must be struck between harvest and productivity of agricultural production resources (Beheshti-Tabar, 2008). Thus, it is necessary to evaluate the energy consumption in agricultural ecosystems to increase production and stabilize it in the ecosystem in the long term, while observing ecological principles and maintaining the stability of production systems. This was the first study in Iran to evaluate the energy performance and global warming potential over a five-year period. This issue is very important considering the increasing application and cultivation of corn grain and stover. Therefore, this study aimed to analyze energy flow and dynamics of grain and stover production in an agricultural area in Iran, and to evaluate whether energy consumption in corn agro-ecosystems was in line with ecological principles and maintaining the sustainability of production systems.

Materials and Methods

The energy dynamics and global warming potential (GWP) were investigated for corn grain and stover production systems. Data, average input and the energy of inputs during different planting, growing and harvesting operations were obtained per hectare of the corn production system in the Karaj region in Iran based on statistical data for 2011–2016 from the Ministry of Agriculture. The Karaj region is one of main agricultural centers of Iran and is located 20 km west of Tehran in Alborz province. Karaj city (51°0'30"E; 35°48'45"N for Karaj historic bridge, Karaj-Chalous Road entrance), at a height of 1,297 m above sea level (railway station) is located 48 km northwest of Tehran (35°48'N, 51°00'E). This region is considered to have a warm and dry Mediterranean climate because of its 150–180 dry days, warm and dry summers and cold and humid winters; According to the 30 year meteorological information, the average annual rainfall is 243 mm in the region, which occurs mainly in late autumn and early spring and the average annual maximum and minimum temperatures are 28°C and 1°C, respectively, in July and January, respectively (Local meteorological station).

As this research focused only on the agricultural process, the functional unit was defined as dry biomass and 1 kg/ha of dry grain and dry stover. The systematic range of this study extended from the nursery to farm input, including all data processes for the grain and stover production systems and raw materials extracted from the land at the time of leaving the field. Farm equipment production systems were not included within the scope of this system due to their minor role in the overall impact (Kardooni, 2011).

The numbers of grain and stover farmers among the existing statistical population were determined based on a simple random sampling method and a table in Krejcie and Morgan (1970). Accordingly, 30 and 25 samples were estimated for corn grain and stover production, respectively, in each year of 2011–2016. GHG emissions and energies associated with corn grain and stover were calculated separately in the corn grain and corn stover production systems. The results of this method estimated the gradual effects of harvesting corn stover and grain.

The mean ± SD (a measure of how widely values are dispersed from the mean) was used to compare and evaluate the accuracy of results.

The SD was calculated using Equation 1:

$$SD = \sqrt{\left([\Sigma|x-\mu|]^2/N\right)} \quad (1)$$

where x is a value in the dataset, μ is the mean of the dataset and N is the number of data points in the population.

Where the two groups of corn grain and stover were compared and comparatively evaluated, in addition to using the SD, a t test was used with the significance threshold at 0.05.

Calculation of auxiliary energies

Important inputs in the production of studied operators were labor, direct energy (fossil fuels), fertilizer (chemical and animal), seeds, biocides and water. The equivalents of labor, diesel fuel, seeds, water, fertilizers and chemical pesticides were used to calculate the input energy with the average yield of each operator per year calculated according to their energy equivalents (Table 1). After collection, the data were analyzed in terms of input and output energies using the Excel software (Microsoft Corp.; Redlands, WA, USA). Average values were calculated to obtain the energy level of each input using the equivalent energy table (Table 1).

Labor energy

Human resources are a component of the ecological resources consumed in agro-ecosystems. The average value of labor per hour was estimated as 1.96 MJ/ha based on available resources (Ozkan et al., 2004), as shown in Table 1.

Fuel energy

Fossil fuels are among the sources of industrial energy used in agro-ecosystems to produce crops. The amount of fuel (measured in liters per hectare) consumed in each specific operation was calculated to obtain the equivalent energy stored in fuels using the equivalent fuel energy (in megajoules per liter), as shown in Table 1, according to Equation 2 (Beheshti-Tabar, 2008):

Table 1 Energy equivalents for inputs and outputs used for corn grain and stover production systems

Input	Unit	Energy equivalent (MJ/unit)	Input	Unit	Energy equivalent (MJ/unit)
Herbicide	kg or L	238.00	Labor	hr	1.96
Pesticide	L	101.20	Fuel	L	56.31
Irrigation water	m^{-3}	0.63	Nitrogen	kg	60.00
Grain	kg	14.70	Phosphate (P_2O_5)	kg	11.10
Grain yield output	kg	14.70	Potassium (K_2O)	kg	6.70
Stover yield output	kg	18.00	Manure	kg	0.30

$$Efp = Qi \times Efi \quad (2)$$

where E_{fp} is the fuel energy (in megajoules per hectare), Q_i is the amount of consumed fuel (in liters per hectare) and E_{fi} is the equivalent energy of each fuel unit (in megajoules per hectare). Energy equivalence for different fuels was obtained according to Table 1.

Energy of machinery

Apart from the fuel used in each operation, the embodied energy of agricultural machinery and equipment was calculated to estimate the input energy of the production process. This type of energy is one of the agro-industrial energy sources. Due to the lack of accurate information on machinery components and, on the other hand, as the machinery energy has a very low and inconsequential share of the total input energy, the energy estimates of machinery were ignored in this study.

Energy of fertilizer inputs

Chemical inputs are among the major energy inputs as part of agro-industrial energy sources used indirectly on farms. The equivalent energy stored in fertilizers was calculated based on the information in Table 1, which shows the equivalent energy of fertilizer use based on an equation similar to Equation 2, with the difference being that in this case, E_{fp} is the fertilizer energy (in megajoules per hectare/ha), Q_i is the amount of consumed fertilizer (in kilograms per hectare) and E_{fi} is the energy equivalent (in megajoules per kilogram) of each fertilizer unit. The equivalent energy stored in chemical biocides, including pesticides and herbicides, was also calculated based on the above method, except that the equivalent energy of each toxin unit was used instead of fertilizers.

Organic fertilizer energy

Organic fertilizers are renewable resources and one of the biological agricultural energies that can replace chemical fertilizers in Iranian farmlands and improve fertilizer use efficiency because only 0.3 MJ/kg of energy is consumed for the use of organic fertilizer sources, but several orders of magnitude energy is consumed for the use of each chemical fertilizer source (Beheshti-Tabar, 2008).

Seed energy

Seed energy as a component of the total input energy is one of the bioenergy inputs. To calculate this energy, the average seed consumed per hectare of the crop was multiplied by the energy equivalent of each kilogram of seeds to obtain the input energy for seed consumption. Energy equivalent to 25 MJ/kg was considered for consumed seeds (Beheshti et al., 2004), as shown in Table 1.

Irrigation water energy

Irrigation water energy is another energy source that has a major contribution to total input energy. At first, the required data on irrigation water use was collected for each operator during different years and then irrigation energy was obtained using Equation 3:

$$Ew = Q \times \varepsilon w \times Ewi \quad (3)$$

where E_w is irrigation water energy (in megajoules per hour), Q is the amount of consumed water (in cubic meters per hectare), ε_W is irrigation water efficiency with an average of 0.32% in Iran (Ehsani and Khaledi, 2003) and E_{wi} is the energy equivalent (megajoules per cubic meter) of each irrigation water unit (Table 1).

Total energy (input and output)

The energy content for all inputs and outputs was estimated using energy equivalents (Table 1) and then the following energy indices were calculated using their relevant equations:

Output energy resulting from grain and stover production

To calculate the energy output of produced seeds, the yield (in kilograms per hectare) of each operator was converted to its energy equivalent. The energy values of the produced grain were 14.7 MJ/kg and 25 MJ/kg for grain and stover production, respectively (Vural and Efecan, 2012), as shown in Table 1.
Energy use efficiency index

This index indicates the amount of consumed energy (in megajoules) harvested per hectare according to Equation 4. The larger this ratio is, the higher the energy efficiency in the agricultural sector. This index is dimensionless and therefore it is possible to compare energy use efficiency (EUE) values (in megajoules per hectare) between different crops (Khan et al., 2009; Pishgar-Komleh et al., 2013).

EUE = (Output energy / Input energy) (4)

Energy productivity

This indicates the amount of output (in kilograms) derived from each unit of consumed energy (in megajoules per hectare). The greater the ratio is, the higher the consumed energy productivity (Khan et al., 2009; Pishgar-Komleh et al., 2013). The formula for energy productivity is shown in Equation 5:

Energy productivity = Output value / Input value (5)

Net energy index

This index represents the net energy output from the field. A negative value indicates that the output energy is not as much as the input energy to the field, leading to an inefficient EUE (Khan et al., 2009; Pishgar-Komleh et al., 2013). The formula for net energy is shown in Equation 6:

Net energy = Output energy – Input energy (6)

Specific energy

This denotes the amount of energy (in megajoules) consumed to produce 1 kg of a crop per hectare according to Equation 7. A large value indicates high energy consumption for crop production.

Specific energy = Input energy / Yield (7)

Direct, indirect, renewable and non-renewable energies

The contributions of direct, indirect, renewable and non- renewable energies to total consumed energy were calculated based on farming activities and inputs. Direct energies included labor, fuel and water, and indirect energies were seeds, manure, chemical fertilizers, herbicides, pesticides and machinery. The energies of labor, seeds, water and manure were considered as renewable energies and those of fuel, chemical fertilizers, herbicides, pesticides and machinery as non-renewable energies (Zahedi et al., 2015). Contribution charts were drawn using the Excel 2010 software (Microsoft Corp.; Redlands, WA, USA).

Greenhous gas emissions and global warming potential for corn grain and stover production systems

As mentioned, the main GHGs are carbon dioxide, nitrous oxide, methane and other gases; among these, carbon dioxide, methane and nitrous oxide are the most important due to their longevity and infrared radiation (Ehhalt et al., 2001). In order to calculate the global warming potential in the first stage, the results of energy calculation in the previous section for corn were used in each of the two production systems of grain and stover. In other words, the first amounts determined for agricultural operations were for the fuel consumed and the energy consumption related to the production and transportation of inputs, including fertilizers and chemical pesticides, manure fertilizer and fuel consumption (Tzilivakis et al., 2005; Parry et al., 2007). Then, the amount of GHG emissions related to each section was calculated using the corresponding emissions coefficients (Table 2). Finally, the total GHG emissions were calculated based on Equation 8 (Kramer et al., 1999):

$$\text{Greenhouse effect} = \sum GWPi \times mi \quad (8)$$

where m_i is the mass (in kilograms) of GHGs. Score and criterion were expressed in terms of kilograms equivalent to carbon dioxide (CO_2-eq).

The emissions of CO_2, N_2O and CH_4 GHGs were calculated using the emission coefficients (Table 2) obtained through the coefficients extracted from various sources. However, in relation to herbicides and manure, only the CO_2 emission coefficient was available from the sources. After calculating total GWP, the following GHG emissions were calculated:

Table 2 Emissions of greenhouse gases (g) per unit of different input and their global warming potential (GWP) in corn grain and stover production systems

Input	CO_2	N_2O	CH_4	Reference
Diesel (L)	3,560	0.7	5.2	(Kramer et al., 1999)
Nitrogen fertilizer (kg)	3,100	0.03	3.7	(Snyder et al., 2009)
Phosphate (P_2O_5) (kg)	1,000	0.02	1.8	(Snyder et al., 2009)
Potassium (K_2O) (kg)	700	0.01	1	(Snyder et al., 2009)
Manure-fertilizer (kg)	0.126	-	-	(Pishgar-Komleh et al., 2013)
Pesticides (kg)	5,100	0.02	0.01	(Green, 1987)
Herbicides (kg)	6.3	-	-	(Lal, 2004)
GWP CO_2 equivalence factor	1	310	21	(Tzilivakis et al., 2005)

per unit area (in kilograms CO_2 equivalents per hectare); per unit weight (kilograms CO_2 equivalents per hectare based on kilograms output of corn grain and stover); per unit of input energy (kilograms CO_2 equivalents per hectare per megajoule); and per unit of output energy (kilograms CO_2 equivalents per hectare per megajoule), according to Soltani et al. (2013).

Results and Discussion

In response to rising global energy costs in recent years, governments have tried to optimize the use of resources in all sectors, including the agricultural sector. In addition, attempts are being made to reduce the use of out-of-field inputs, particularly energy inputs, due to environmental considerations (Al-Mohammad, 2001).

Total input energy

The results of this study showed a total input energy of 22,998.66±972.57 MJ to produce 1 kg of corn grain (Tables 3 and 4), while an amount of 24,772.74±1,680.96 MJ was required to produce 1 kg of corn stover; these two amounts were not significantly different. The input energy for grains or stover production includes labor, fuel, biocides, fertilizers and irrigation, among which most of the energy consumed for grain production belongs to nitrogen fertilizer use, seeds and manure, respectively (Tables 3 and 4). In both the production systems, these three inputs were significantly different from the other inputs, indicating that corn grain and stover production are highly dependent on nitrogen fertilizer, seeds, manure and also irrigation water. However, the difference in the nitrogen fertilizer and manure energy inputs was not significant between the grain and stover production systems (Tables 3 and 4). Nitrogen fertilizer (chemical fertilizers) accounted for the largest component (57%) of input energy into corn grain production, with 54% being the equivalent amount for nitrogen fertilizer in stover production, followed by a high share related to the seed energy (15% and 21%, respectively, in grain and stover production). However, the differences in the amounts of energy inputs for nitrogen and manure were not significant between the grain and stover systems (Tables 3 and 4). The differences between values reported in different parts of Iran could have resulted from differences in management and agricultural operations and climatic conditions; in general, the energy consumption of such inputs as fertilizer and fuel was clearly high. As mentioned above, the ratios of energy throughout the country and in regional studies depend on the amount of crop yield (input energy), which is in turn dependent on the amount of regional rainfall.

Total output energy

Total input energies of 99,568±3,719.87 MJ/ha and 322,286.4±7,783.92 MJ/ha were required to produce 1 kg of corn grain and stover, respectively (Tables 3 and 4). In addition, Tables 3 and 4 shows a markedly significant difference in the ratio of total input energy to output energy. Borin et al. (1997)

Table 3 Input and output energies in corn grain and stover production systems

Input	Unit	Energy amount (MJ/ha)			Total energy (%)		
		Grain (mean±SD)	Stover (mean ± SD)	t-test *p*-value	Grain (mean±SD)	Stover (mean±SD)	t test *p*-value
Labor	hr	112.18±4.61	94.00±5.44	0.5	0.49±0.02	0.38±0.03	0.5
Fuel	L	489.47±20.12	452.82±53.62	0.26	2.13±0.05	1.83±0.18	0.49
Nitrogen	kg	13,120.00±606.60	13,425.6±1,111.37	0.65	57.10±2.64	54.15±1.72	0.11
P_2O_5	kg	810.67±56.57	822.29±51.66	0.77	3.53±0.24	3.34±0.34	0.43
K_2O	kg	267.60±47.58	378.68±72.22	0.49	1.17±0.33	1.55±0.41	0.16
Manure	kg	2,666±923.72	2,412±725.54	0.68	11.48±3.68	9.59±2.43	0.42
Herbicides	kg or L	184.45±17.10	151.46±15.07	0.49	0.80±0.05	0.61±0.05	0.5
Pesticides	L	84.01±17.24	89.08±22.92	0.73	0.37±0.08	0.36±0.11	0.96
Irrigation water	m^{-3}	1,626.91±35.14	1,544.26±76.37	0.1	7.09±0.42	6.26±0.50	0.04
Seed							
Total input	kg	3,637.37±75.88	5,402.54±18.93	0	15.84±0.59	21.91±1.57	0
Output as	kg	22,998.66±972.5718	24,772.74±1,680.96		-	-	
Grain yield							
Stover yield	kg	99,568±3,719.87	-		-	-	
	kg	-	322,286.4±7,783.92		-	-	

and Kuesters and Lammel (1999) reported increases in output energy with rising input energy and vice versa. The generation of a higher output energy than a lower input energy in the production systems indicates high system efficiency, as was confirmed by the finding of this study (Tables 3 and 4).

Energy use efficiency (energy ratio) and energy productivity

These two parameters are discussed together due to the similarity between the energy efficiency and productivity trends in the studied crops. The energy productivity and use efficiency of the studied products are shown in Table 4. In general, the average energy efficiency values in corn grain and stover production were 4.34±0.21 and 13.06±0.76, respectively, with significantly greater energy efficiency in the stover than the grain system ($p < 0.05$) (Table 4). The increased energy efficiency in the stover production system reflected an upward trend in output energy (due to higher yield) than input energy growth. Improvements in the efficiency of chemical pesticides, seed and fertilizer applications were some reasons for such an increase per hectare (Table 3). Compared with other regions, the differences for the present results for a 5 year study in Karaj were due to the specific conditions of each region, the average cultivated area and the climatic conditions in Karaj. Wang et al. (2019) revealed that low energy use efficiency in the wolfberry production system resulted from high energy inputs, such as electricity use, chemical fertilizers and biocides consumption.

The average energy productivity in corn grain and stover production (0.29±0.01 kg/MJ and 0.73±0.04 kg/MJ, respectively, Table 4) followed the energy efficiency rule, with 0.29 kg of corn stover being produced per unit of energy consumed in the stover production system, which was 10% more than that of grain production per unit of energy.

Specific energy

In general, the average specific energy (3.40±0.17 MJ/kg) in corn grain production was significantly greater than that (1.38±0.07 MJ/kg) from the stover production system ($p < 0.05$) (Table 4). For comparison, a higher specific energy value of 8.84 MJ/kg was calculated in a canola irrigated system (Dargahi et al., 2016).

Table 4 Indicators of energy use in corn grain and stover production systems

Energy indices	Unit	Energy amount			Percentage (%)		
		Grain (mean±SD)	Stover (mean±SD)	t-test *p*-value	Grain (mean±SD)	Stover (mean±SD)	t-test *p*-value
Input energy	MJ/ha	22,998.66±972.57	24,772.74±1,680.96	0.11	-	-	-
Output energy	MJ/ha	99,568.00±3,719.87	322,286.40±7,783.92	0.00	-	-	-
t test *p*-value (input versus output)		0.00	0.00				
Energy Efficiency	-	4.34±0.21	13.06±0.76	0.00	-	-	-
Energy Productivity	kg/MJ	0.29±0.01	0.73±0.04	0.00	-	-	-
Specific Energy	MJ/kg	3.40±0.17	1.38±0.07	0.00	-	-	-
Net Energy	MJ/ha	76,569.34±3,597.62	297,513.66±6,666.81	0.00	-	-	-
Direct energy	MJ/ha	2,228.56±29.47	2,091.08±54.97	0.50	9.71±0.46	8.47±0.48	0.50
Indirect energy	MJ/ha	20,770.10±981.62	22,681.66±1,643.65	0.09	90.2±0.469	91.53±0.48	0.50
t test *p*-value (direct versus indirect)		0.00	0.00		0.00	0.00	
Renewable energy	MJ/ha	8,042.46±898.01	9,452.80±752.34	0.48	34.90±2.88	38.15±1.31	0.09
Non-renewable energy	MJ/ha	14,956.20±591.74	15,319.93±1,053.85	0.57	65.10±2.88	61.85±1.31	0.09
t test *p*-value (renewable versus non-renewable)		0.00	0.00		0.00	0.00	

The tests were considered significant when p value < 0.05

Net energy

This index represents the net energy output from the field, which is positive in the production process of crops in sustainable agriculture due to the optimal use of resources and sustainable production. Net energy values of 76,569±3,597.62 MJ/ha (76.56 GJ/ha) and 297,513±6,666.81 MJ/ha (297.51 GJ/ha) were recorded for the corn grain and stover production systems, respectively (Table 4) that were significantly different ($p < 0.05$) (Table 4). Negative or low net energy indicates that the output energy is not as much as the input energy to the system, leading to inefficient energy consumption (Singh et al., 2010). According to Canakci et al. (2005), the average yield of corn in Turkey was close to that of Iran and consequently, the output energy from corn cultivation was almost the same in both countries. However, net energy is low in Iran because of a higher (61.32 GJ/ha) input energy than that in Turkey (25.58 GJ/ha). Average net energy levels have been reported as 35.69 GJ/ha and 71.62 GJ/ha in Iran and Turkey, respectively.

Direct, indirect, renewable and non-renewable energy

For 1 kg of corn grain and stover production, the direct energy values were 2,228.56±29.47 MJ/ha and 2,091.08±54.97 MJ/ha, and the indirect energy values were 20,770.10 ± 981.62 MJ/ha and 22,681.66±1,643.65 MJ/ha, respectively. The indirect energy levels were significantly different from the direct energies in both grain and stover systems ($p < 0.05$); however, the difference between the indirect energy of the grain and stover systems was not significant, which was also true for direct energy (Table 4). Significant differences were observed in the percentages of total direct and indirect energies (9.71% and 90.29%, respectively) for production of 1 kg/ha of corn grain and (8.47% and 91.53%, respectively) for the production of 1 kg/ha of corn stover (Table 4). Clearly, the percentages of indirect energy were greater than the direct energy sources in both production systems. In other words, the grain and stover production systems were not significantly different in the direct and indirect energy levels (Table 4). Wang et al. (2020) revealed that indirect energy use from fertilizer consumption for crop growth made the greatest contribution in rice and wheat production systems with average values of 69.5% and 75.4%, respectively, of the total energy. The production of 1 kg/ha in the corn grain and stover production systems required renewable energy amounts of 8,042.46±898.01 MJ/ha and 9,452.80±752.34 MJ/ha, respectively, and non-renewable energy amounts of 14,956.2±591.74 MJ/ha and 15,319.930±1,053.85 MJ/ha (Table 4). The total percentages of renewable and non-renewable energy were 34.90% and 65.10%, respectively, for 1 kg in the corn grain production system and 38.15% and 61.85%, respectively, for 1 kg in the corn stover production system. These energy differences and percentage differences of total energy were significant for both the grain and stover production systems ($p < 0.05$), but there were no significant differences between the energy levels and percentages of renewable and non-renewable energy values for the two systems (Table 4). There were non-significant differences in the percentages of renewable energies in the grain and stover systems; in other words, the grain and corn production systems were not significantly different in their amounts of renewable and nonrenewable energies (Table 4). Nonetheless, increases were observed in the percentages and amounts of total non-renewable energy compared to renewable energy in the corn and stover production systems, indicating the dependence of agriculture in this region on non-renewable energy sources for the production of corn grain and stover. The higher share of indirect and non-renewable energies revealed that indirect non-renewable energies had higher effects on the yield increase than direct renewable energies.

Greenhouse gas emissions and global warming potential in corn grain and stover production systems

The amounts of GHGs produced in the two grain production systems in the study area were 3,782.95±1,088.28 kg CO_2-eq/ha and 3,529.60±970.77 kg CO_2-eq/ha , respectively, but this difference between the grain and stover systems was not significant (Tables 5 and 6). The percentage share of each GHG is presented in Table 6, with the largest share in greenhouse gas emissions in the grain and stover production systems being related to nitrogen fertilizer (678.68±319.36 kg CO_2-eq/ha and 694.49±326.80 kg CO_2-eq/ha , respectively) (or 81% and 80%, respectively). After nitrogen fertilizer, phosphorus and diesel fuel inputs were the most effective. Elsoragaby et al. (2019) reported that among different types of chemical fertilizers, nitrogen represented the highest contributor by 85% with phosphate and potassium in GHG emissions being 6% and 9%, respectively. Other inputs had the least impact on GWP. The impact of these inputs between the grain and stover production systems was not significant. However, in either the grain or stover production system, chemical fertilizers were significantly more effective than other inputs (Table 5).

Table 5 Global warming potential (GWP) for corn grain and stover production systems

Input	Unit	Grain		Stover		t-test
		mean±SD	Total (%)	mean ± SD	Total (%)	*p*-value
Diesel fuel	(kg CO_2-eq/ha)	31.00±14.58	3.72	28.68±13.48	3.30	0.96
Manure-fertilizer	(kg CO_2-eq/ha)	18.89±3.66	2.27	17.09±3.31	1.97	0.87
Nitrogen	(kg CO_2-eq/ha)	678.68±319.36	81.38	694.49±326.80	80.04	0.99
Phosphorous	(kg CO_2-eq/ha)	73.17±34.40	8.77	74.21±34.89	8.55	0.99
Potassium	(kg CO_2-eq/ha)	28.00±13.17	3.36	39.62±18.64	4.57	0.82
Herbicides	(kg CO_2-eq/ha)	0.02±0.00	0.00	0.02±0.00	0.00	0.84
Pesticides	(kg CO_2-eq/ha)	4.23±2.00	0.51	13.59±3.72	1.57	0.37
Total	(kg CO_2-eq/ha)	833.99±229.51	100	867.70±233.95	100	
GWP	(kg CO_2-eq/ha)	3,782.95±1,088.28	100	3,529.60±970.77	100	

The tests were considered significant when *p*-value < 0.05

Table 6 Gaseous emissions (kg/ha) from chemical sources and their global warming potential (GWP) in corn grain and stover production systems

Production system	Input	CO_2 (mean±SD)	N_2O (mean±SD)	CH_4 (mean±SD)	Total GWP (kg CO_2-eq) (mean±SD)	(%)
Grain	Diesel fuel (L)	30.94±1.27	0.01±0.00	0.05±0.00	33.78±14.58	3.93
	Manure-fertilizer (kg)	1.12±0.39	8.89±3.08	8.89±3.08	18.89±3.66	2.20
	Nitrogen (kg)	677.87±31.3	0.01±0.00	0.81±0.04	696.89±319.36	81.13
	Phosphorous (kg)	73.03±5.10	0.00±0.00	0.13±0.01	76.25±34.40	8.88
	Potassium (kg)	27.96±4.974	0.00±0.00	0.04±0.01	28.92±13.17	3.37
	Herbicides(kg)	0.00±0.00	0.00±0.00	0.00±0.00	0.01±0.00	0.00
	Pesticides (kg)	4.23±0.87	0.00±0.00	0.00±0.00	4.24±2.00	0.49
	Total GHG (kg)	815.16±43.94	8.90±3.08	9.91±3.13	858.98±379.84	100
	Total GWP (kg CO_2-eq)	815.16±230.42	2,759.61±2.94	208.18±5.91	3,782.95±1,088.28	100
Stover	Diesel fuel (L)	28.63±3.39	0.01±0.00	0.04±0.00	31.25±13.48	3.53
	Manure-fertilizer (kg)	1.01±0.30	8.04±2.42	8.04±2.42	17.09±3.31	1.93
	Nitrogen (kg)	693.66±57.42	0.01±0.00	0.83±0.07	713.12±326.80	80.65
	Phosphorous (kg)	74.08±4.65	0.00±0.00	0.13±0.01	77.34±34.89	8.75
	Potassium (kg)	39.56±7.55	0.00±0.00	0.06±0.01	40.93±18.64	4.63
	Herbicides(kg)	0.00±0.00	0.00±0.00	0.00±0.00	0.01±0.00	0.00
	Pesticides (kg)	4.49±1.16	0.00±0.00	0.00±0.00	4.49±2.12	0.51
	Total GHG (kg)	841.43±74.47	8.06±2.42	9.10±2.51	884.23±392.61	100
	Total GWP (kg CO_2-eq)	841.43±235.40	2,497.06±2.65	191.10±5.93	3,529.60±970.77	100
	t test *p*-value (grain versus stover)	0.41	0.01	0.69		

The tests were considered significant when *p* value < 0.05

The contribution of each greenhouse gas related to the inputs is presented in Tables 6 and 7. The levels of CO_2, N_2O and CH_4 in both the grain and stover production systems were 815.16±230.42 kg/ha, 2,759.61±2.94 kg/ha and 208.18±5.91 kg/ha, respectively, in the grain production system and 841.43±235.40 kg/ha, 2,497.06±2.65 kg/ha and 191.10±5.93 kg/ha, respectively, in the stover production system. As can be seen in Table 6, the comparison between the grain and stover production systems showed that the CO_2 gas content was significantly higher in the grain production system than in the

Table 7 Greenhouse gas emissions for corn grain and stover production systems

Global warming potential	Unit	Grain (mean±SD)	Stover (mean±SD)	t-test *p*-value
per unit area	kg eq-CO_2/ha	3,782.95±1,088.28	3,529.60±970.77	0.94
per unit weight	kg eq-CO_2/ha	0.56±0.16	0.20±0.04	0.01
per unit energy input	kg eq-CO_2/MJ	0.16±0.04	0.14±0.03	0.37
per unit energy output	kg eq-CO_2/MJ	0.04±0.01	0.05±0.00	0.01

The tests were considered significant when *p* value < 0.05

stover production system; however, there was no significant difference in GHG emissions related to inputs. Nonetheless, for each grain or stover production system and in each input, the CO2 content was significantly higher than for the other GHGs (Table 6). Fathi et al. (2020) found that for different tillage systems of corn production, the highest amount of GHG emissions was related to the amount of CO2. The N_2O emissions were lower than CO_2 emissions; but the impact of N_2O on GWP is greater than CO_2 and the overall N_2O percentages of GWP for both the grain and stover production systems were significantly higher than for CO_2 and CH_4 at 73% and 71%, respectively ($p < 0.05$) (Table 6).

Another reason for the high nitrogen impact was the higher nitrogen fertilizer usage than for other inputs, in both grain and stover production. As a result, nitrogen fertilizers have a greater impact on GWP and GHG emissions than other inputs. Kahrl et al. (2010) examined the emissions of greenhouse gases from nitrogen fertilizers in China and reported that with the increase in nitrogen fertilizers, the emissions increased significantly. In this regard, the GWP (per unit area, per unit weight and per unit input energy) in the grain production system was higher than in the stover production system. However, the rate of global warming per unit of output energy in the stover production system was higher than for the grain production system. These differences between the grain and stover production systems were significant only for the global warming per unit weight and output energy ($p < 0.05$) (Table 7). Due to the higher output energy in the stover production system, the global warming rate per unit of output energy (0.05±0.00 kg CO_2-eq/MJ) was significantly higher than for the grain production system (0.04±0.01 kg CO_2-eq/MJ). However, in either the grain or stover production systems, global warming per unit area was significantly higher than other indicators of global warming potential ($p < 0.05$) (Table 7). Mohammed et al. (2019) studied the contribution of the agricultural sector to GHG emission in the EU-27 countries. They found that most countries applied policies to reduce GHG emissions and most countries had recorded significant reductions in 1990 and 2016. Pishgar-Komleh et al. (2013) also reported higher global warming per unit area than other indicators of global warming potential (in units of weight and in units of output energy). As noted in the section on input energy and energy efficiency, the amount of non-renewable energy in the stover production was expected to be lower than the grain system due to the low consumption of chemical fertilizer and the increased energy efficiency in the stover production system compared to the grain production system; however, this decrease was not significantly different between the two systems (Table 4). Chemical inputs are among the major energy inputs that are a part of agro-industrial energy sources used indirectly on farms. Biocides (pesticides and herbicides) and chemical fertilizers (nitrogen, potash and phosphorus) are among the chemicals used in agriculture and are one of the inputs affecting the energy efficiency of agricultural systems because of high energy consumption for their production and processing. Nitrogen fertilizer is one of the widely used fertilizers in agricultural systems, the production of which accounts for nearly half of the energy consumed in modern agriculture. In addition to chemical fertilizers, pesticides play an important role in increasing the indirect energy input into agro-ecosystems (Koocheki et al., 2011). The results of the current study showed that the energy efficiency of a corn crop has increased in the Karaj region over time; however, this increased efficiency has been associated with rises of such inputs as chemical fertilizers, seed energy and livestock manure, indicating an increasing dependence of Iranian agro-ecosystems on non-renewable resources. Given the significant difference between renewable and non-renewable energies in the corn grain and stover production systems investigated in the current study and the higher energy content and percentages of indirect renewable energy than renewable direct energy, this high consumption of non-renewable energy should not be neglected in either cultivation system. Energy management and the development of sustainable agricultural systems with minimum dependence on inputs and of low-input management are important issues in terms of efficiency, productivity, sustainability and the economical use of energy and for the reduction of GHG emissions. Low energy efficiency and productivity in a production system indicate a greater dependence on inputs and higher energy consumption, with an increase in specific energy that reflects a further energy loss in that system. Therefore, the corn stover production system was a low-input system with lower energy consumption and higher efficiency and productivity toward sustainable development than the grain system in the domains of energy and environment. The grain production system was a high-input system with comparatively lower efficiency and productivity (and possibly ecologically unstable).

Accordingly, energy efficiency enhancement is a valuable goal to be pursued in line with energy management objectives. Producers at the local and national levels should try to gain more produced (output) energy in return for less consumed (input) energy. Energy productivity of cereal production in Iran is lower than in other countries, which can be attributed to low fuel prices, subsidies for fertilizers and the poor role of agricultural extension and training for the proper use of available resources (Kardooni et al., 2018). Sustainable agriculture is one of the ways to reduce the damage and losses caused by agriculture to the environment and climate (Shabani et al., 2015). Thus, knowledge of environmental information and global warming potential can prevent these disadvantages and provide new strategies for agricultural production and climate protection.

Conclusion

Based on the amount and type of inputs and geographical, climatic, and environmental conditions similarities for the area in the current study to other areas and countries in the world, it is necessary to direct and promote agro-ecosystems toward sustainable agriculture for the optimized use of production resources and reduced energy inputs and to reduce global warming potential in agricultural sector production systems, particularly regarding high-consumption inputs such as fertilizers, seeds and irrigation water. Further utilization of renewable resources, such as organic, compost or poultry fertilizers, for better absorption of micronutrients and reduced industrial energy use, will reduce the use of chemical fertilizers. The current results showed that among the inputs used, nitrogen fertilizer was the most important factor in greenhouse gas emissions in corn grain and stover production systems; thus, higher consumption of this input in corn led to greater emissions than for other outputs.

Based on the current study, the following strategies can be considered to reduce greenhouse gas emissions and mitigate the negative effects of climate change on corn grain and stover production systems:

1. Improve the efficiency of nitrogen consumption by changing the amount, type and time of consumption of this input.
2. Implement useful crop rotations.
3. Use organic resources (manure, compost, green manure, plant and biological residues) microorganisms that stabilize nitrogen (chemical fertilizers).
4. Use ecological and biological methods in the management of pests and weeds.
5. Use mixed cultivation systems.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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