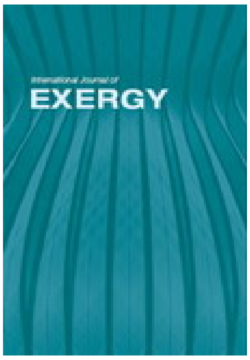

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Sustainability assessment of sugarcane and sugar beet production systems by energy and exergy approaches: a case study

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Sustainability assessment of sugarcane and sugar beet production systems by energy and exergy approaches: a case study

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Abstract: This study aims to determine cumulative energy and exergy consumption in sugarcane and sugar beet production systems in Iran and evaluate their environmental performance. Cumulative energy and exergy consumption, cumulative degree of perfection, and renewability index for sugarcane production were 66,500 MJ/ha, 82,561 MJ/ha, 6.21, and 0.86, respectively, and these values were 48,267 MJ/ha, 67,984 MJ/ha, 165,831 MJ/ha, 6.42, and 0.84 for sugar beet production, respectively. The GHG emissions for sugarcane and sugar beet production were 4,785 kg $CCO_{2\text{-eq}}$/ha and 2,851 kg $CCO_{2\text{-eq}}$/ha, respectively, of which about 90% is due to direct and indirect energy consumption for irrigation.

Keywords: cumulative degree of perfection; CDP; cumulative exergy consumption; CExC; energy efficiency; renewability index; sugar beet; sugarcane; sustainability.

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1 Introduction

Input energy in agriculture has increased in response to resource limitations, arable lands, technological changes, and population growth. For example, from 1900 to 2000, the world's cultivated area had enhanced by 80%–100% while energy use in farms had increased by 85 times. During this period, energy production by farms had been enhanced by six times (Safa and Samarasinghe, 2011). This increase in the consumption of input and energy has left many adverse effects on the environment, including intensive use of non-renewable energy sources, biodiversity reduction, greenhouse gas (GHG) emission, and contamination of the aquatic environments by nutritive such as nitrogen and phosphorus (Nikkhah et al., 2015), leading to reduced sustainability of agricultural ecosystem production. Efficient use of energy as one of the most momentous principles in advanced agriculture systems should be taken into consideration as the agriculture system relies heavily on non-renewable resources, especially in developing countries. Many studies have been conducted on various aspects of energy in agriculture production systems, such as increasing energy efficiency, evaluating energy consumption, the effect of energy use, optimising energy consumption, energy saving, and energy management. However, the energy analysis methods, which are based on the first law of thermodynamics, cannot clearly show the quality of energy consumption and energy losses of inputs (Sartor and Dewallef, 2017). The quality of energy is evaluated by the second law of thermodynamics. The central concept of the second law of thermodynamics is the exergy or availability. Exergy analysis can be applied to distinguish between high-quality and low-quality energy sources and to determine the amount of energy loss of different inputs by identifying the actual amount of energy consumed in a process (Juárez-Hernández et al., 2019). Cumulative exergy consumption (CExC), which is the total exergy of the inputs used in all the processes necessary to produce the final product, can evaluate various energy consumption problems in the agricultural production process (Yildizhan and Taki, 2018). So, several researchers have used the exergy analysis to better understand efficient energy use in the agricultural system (Esmaeilpour-Troujeni et al., 2021; Ahamed et al., 2011; Ordikhani et al., 2021). Ahamed et al. (2011) introduced exergy analysis as a tool that can detect the amount of energy loss that occurred in each sector. In evaluating tomato production in open fields and greenhouses using CExC, the best region for tomato production was identified. This evaluation also showed that CExC analysis could be an effective method for enhancing the renewability of tomato production processes (Yildizhan and Taki, 2018). Juárez-Hernández et al. (2019) used CExC analysis to compare resource utilisation and environmental performance of different corn production systems in Mexico.

Many studies have been conducted on various aspects of energy consumption in agricultural production in Iran, drawing mainly on input energy methods and the first law of thermodynamics. However, limited studies have been performed on the exergy analysis of agricultural production systems in Iran. Esmaeilpour-Troujeni et al. (2021) used the exergy analysis to optimise canola production in Mazandaran province (Iran) and reported that CExC in canola production in this province is equal to 22,348 MJ/ha. Exergy analysis showed that the ecological sustainability of the spring potato production system is higher than the autumn production system in Golestan province, Iran, due to lower consumption of inputs such as diesel fuel (Shahhoseini et al., 2021). In Khorramabad, Iran, the extended analysis of the exergy of commercial and traditional canola production systems showed that the commercial system has a higher economic value and higher thermodynamic efficiency than the traditional system. The high cumulative exergy in the traditional system reduced its thermodynamic parameters (Amiri et al., 2020). Analysis of cumulative exergy requirements in different horticultural production systems in Qazvin province, Iran, showed that the use of organic fertilisers and replacement of worn-out machines can help produce more sustainable horticultural crops (Ordikhani et al., 2021).

Due to the intense consumption of inputs and energy in sugarcane and sugar beet production, many studies have been conducted in the field of energy analysis in the production of these two crops (Asgharipour et al., 2012; Erdal et al., 2007; Kaab et al., 2019), all of which were based on the first law of thermodynamics and did not consider exergy analysis. Literature review showed that despite many studies, no study has been conducted in the field of exergy analysis and evaluation of exergy indicators on sugarcane and sugar beet production systems. Therefore, due to the great importance of these two crops in Iran, the integrated analysis of cumulative energy and exergy consumption indices and environmental assessment of sugarcane and sugar beet is necessary to determine their environmental performance and compare the efficiency of resources consumed. In this study, cumulative energy and exergy analysis were used to investigate the inflows to the sugarcane and sugar beet production systems in Iran. In addition, the cumulative emission of GHGs based on CO_2-eq was investigated for these production systems. The results of this study will help develop a more sustainable production pattern for these crops with fewer adverse effects on the environment.

2 Materials and methods

2.1 Data collection of two crop production systems

The amount of sugarcane production in 2020 was about 7.75×10^6 tons (9.24% of total agricultural crop production) (Anonymous, 2020). Due to low rainfall, sugarcane farms in Iran are completely irrigated. Sugarcane data were collected from sugarcane agro-industries from 2015 to 2019 (a five-year sugarcane cultivation period). Since the sugarcane cultivation period lasts five years, the life cycle inventory data for sugarcane cultivation over five years were collected, and the average for one year was calculated. Iran was about $108 * 10^3$ hectares, of which $5.6 * 10^6$ tons of sugar beet was obtained. Like sugarcane, farms of sugar beet are irrigated. This crop is cultivated in many regions of Iran. Sugar beet data were collected from Iran's ministry of agriculture, as well as farmers in Khuzestan, Lorestan, Razavi Khorasan, and West Azerbaijan provinces using a questionnaire. These provinces accounted for the large amounts of sugar beet production in Iran (Anonymous, 2020). Based on Cochran formula (Cochran, 1991), 263 farmers (sample size) who cultivate sugar beet on a large scale were randomly selected.

In the current study, all inputs used in the production of sugarcane and sugar beet systems (including chemical materials and chemical fertilisers, seeds, machinery and equipment, electricity, diesel fuel, lubricant, and mineral products), crops performance, and information about manufacturers were collected from agro-industries and farmers.

2.2 Energy and exergy analysis

Direct and indirect types of cumulative energy and exergy consumption (CEnC and CExC) are used in the production of sugarcane and sugar beet. Direct CEnC and CExC in the production of these crops include diesel fuel and electricity, and indirect type includes agricultural machinery, lubricant, fertilisers, labour, seed, biocides, and biomass (stalk of sugarcane). Also, CEnC and CExC in the sugarcane and sugar beet production systems include renewable and non-renewable types. Renewable CEnC and CExC include human labour, seeds, and stalk and the rest are non-renewable. In this study, only energies and inputs for which energy has been consumed are considered, and other input energies, such as solar energy, are not considered. In agricultural systems, the ratio of output to input energy (O/I) is one of the indicators of energy efficiency (Yuan et al., 2018). If the value of the O/I is more than one, it indicates that the output energy is more than the CEnC (Ordikhani et al., 2021). Specific energy (SE) represents the amount of CEnC to produce each unit of the crop, which, in this study, has been calculated based on MJ/kg, while energy productivity indicates the amount of production per unit of CEnC. These energy indicators were obtained based on equations (1)–(3) (Kaab et al., 2019).

$$\text{Output-input ratio(O / I)} = \frac{\text{Output energy(MJ / ha)}}{\text{CEnC(MJ / ha)}} \tag{1}$$

$$\text{Specific energy(SE)} = \frac{\text{CEnC(MJ / ha)}}{\text{Yield(MJ / ha)}} \tag{2}$$

$$\text{Energy productivity(EP)} = \frac{\text{Yield(MJ / ha)}}{\text{CEnC(MJ / ha)}} \tag{3}$$

CEnC, CExC, and output energy and exergy were calculated based on the amount of input and output and specific CEnC and CExC equivalents of each input and output (Table 1). In this study, exergy analysis and cumulative exergy approach were used to evaluate the renewability and sustainability of sugarcane and sugar beet production processes. The specific exergy equivalent of labour (ee_L) in MJ/h was estimated using equation (4) (Unal et al., 2022).

$$ee_L = \frac{365 N_h E_{surv} HDI}{HDI_0 N_{wh}} \tag{4}$$

where E_{surv} is the minimum exergy required for a person to survive (10.46 MJ/day/person), N_h is the total population, HDI is the human development index (HDI of pre-industrial society is about 0.055), and N_{wh} is the total working hours per year.

Specific chemical exergy per unit mass of lubricant (ee_{LU}) was calculated based on equation (5) (Çakmak and Bilgin, 2017), where LHV_{lu} stands for the lower heating value of lubricant, and β, α and γ stand for the mass fractions of H, C, and O, respectively.

$$ee_{LU} = LHV_{lu}\left[1.041 + 0.1728\frac{\beta}{\alpha} + 0.0432\frac{\gamma}{\alpha}\right] \tag{5}$$

Exergy efficiency and cumulative degree of perfection (CDP) are important indicators used to evaluate the stability of the principal types of processes, which can be defined by equations (6) and (7). The difference between these indicators is that in calculating the exergy efficiency, all controllable and uncontrollable inputs (such as energy received from the sun, soil, etc.) are considered while in the CDP calculation, only the amount of controllable inputs are considered. Since the products of sugarcane and sugar beet are in equilibrium with the environment, the output exergy is equal to the chemical exergy of the products (Esmaeilpour-Troujeni et al., 2021).

$$\text{Exergy efficiency} = \frac{\text{Exergy in products}\left((m \times b)_{\text{products}}\right)}{\text{Total exergy input}} \tag{6}$$

$$CDP = \frac{\text{Exergy in products}\left((m \times b)_{products}\right)}{\sum (m \times CExC)_{Rawmaterials} + \sum (m \times CExC)_{Fuels}} \tag{7}$$

Table 1 CEnC, CExC, and emission factors of $CCO_{2\text{-eq}}$ of inputs and outputs

Items	*Specific CEnC*	*Specific CExC*
A. Inputs		
Diesel fuel	57.5 MJ/lit (Yildizhan and Taki, 2018)	53.2 (Esmaeilpour-Troujeni et al., 2021)
Lubricant	81.1 (MJ/lit) (Mrini et al., 2002)	47.42[a] MJ/kg
Electricity	12 MJ/kWh (Ordikhani et al., 2021)	4.17 MJ/MJ (Amiri et al., 2020)
Nitrogen fertiliser (N)	78.2 MJ/kg (Esmaeilpour-Troujeni et al., 2021)	32.7 MJ/kg (Amiri et al., 2020)
Phosphate fertiliser (P_2O_5)	13.8 MJ/kg (Esmaeilpour-Troujeni et al., 2021)	7.52 MJ/kg (Amiri et al., 2020)
Potassium fertilisers (K_2O)	11.15 (Ordikhani et al., 2021)	4.7 MJ/kg (Pelvan and Özilgen, 2017)
Biocides		
Herbicides	198.8 MJ/lit (Yildizhan and Taki, 2018)	32.7 (Esmaeilpour-Troujeni et al., 2021)
Pesticides	363.6 MJ/lit (Kaab et al., 2019)	7.52 (Yildizhan and Taki, 2018)
Fungicides	198 MJ/lit (Yildizhan and Taki, 2018)	4.56 (Yildizhan and Taki, 2018)
Machinery	9 MJ/kg year (Kaab et al., 2019)	7.1 MJ/kg (Michalakakis et al., 2021)
Irrigation	0.00102 MJ/kg (Yildizhan and Taki, 2018)	0.00425 MJ/kg (Amiri et al., 2020)
Human labour	1.96 MJ/h (Kaab et al., 2019)	36.45[a] MJ/h
Stalk of sugarcane	1.2 MJ/kg (Kaab et al., 2019)	5.297 MJ/kg (Ensinas et al., 2009)
Sugar beet seed	50 MJ/kg (Erdal et al., 2007)	21 MJ/kg (Michalakakis et al., 2021)
B. Output		
Sugarcane	1.2 MJ/kg (Kaab et al., 2019)	5.297 MJ/kg (Ensinas et al., 2009)
Sugar beet	16.8 MJ/kg (Erdal et al., 2007)	20.2b MJ/kg (Song et al., 2011)

Note: [a]Calculated, [b]per dry matter.

The cumulative net exergy gain (CNEx), which represents the output exergy minus the CExC, is an important indicator to analyse the accumulation of exergy consumption (Juárez-Hernández et al., 2019).

Renewability assessment is very important in determining ecosystem sustainability and sustainable development. Renewability assessment is either used directly to calculate the input/output ratio of a specific renewable resource only in renewable systems based on benefits analysis or to assess the sustainability of a system by identifying the renewable resource components from its entire resource utilisation. Exergy analysis is used to evaluate the renewability of the process and renewability index (RI). This index is one of the important indicators for assessing environmental sustainability, which is calculated based on equation (8) (Pelvan and Özilgen, 2017).

$$RI = \frac{E_{ch} - W_r}{E_{ch}} \tag{8}$$

where E_{ch} is the chemical exergy of the final output of sugarcane (sugarcane stalk) and sugar beet, and W_r is the restoration work that can be obtained via CExC accounting of non-renewable resource inputs. As *RI* increases, the resource stress on the environment decreases. A completely renewable process has a *RI* = 1. In a process where the work produced is equal to the restoration work, the value of this index is equal to zero, and with increasing its amount, the renewability of the process increases. The *RI* with a value less than zero indicates the non-renewability of the production process (Esmaeilpour-Troujeni et al., 2021).

2.3 GHG emission

Carbon footprint is the total GHG emissions caused by an activity, event, product, process, or organisation, expressed as CO_2-eq. The functional unit (FU) is connected to the inputs and outputs and provides a condition for comparison. Land and product-based FU were considered meaning that CO_2-eq was calculated and reported per one hectare and one ton of products. The system boundary encompassed the total inputs from the cradle (i.e., production of lubricant, fertilisers, and pesticides from raw materials) to the farm gate (harvested crops). The amount of CO_2-eq emissions from each input per hectare was calculated using the specific cumulative carbon dioxide emissions ($CCO_{2\text{-eq}}$). The specific $CCO_{2\text{-eq}}$ for each input is illustrated in Table 1.

In this study, in addition to the amount of GHG emission based on $CCO_{2\text{-eq}}$ per hectare, the amount of GHG emission per ton of crop production (GHGI) and the amount of GHG emissions per unit of energy consumed in crop production (GHGEn) were calculated based on $CCO_{2\text{-eq}}$ using equations (9) and (10), respectively (Juárez-Hernández et al., 2019).

$$\text{GHGI} = \frac{\text{CCO}_{2\text{-eq}}(\text{kg / ha})}{\text{Yield(ton / ha)}} \tag{9}$$

$$\text{GHGen} = \frac{\text{CCO}_{2\text{-eq}}(\text{kg / ha})}{\text{CenC(GJ / ha)}} \tag{10}$$

3 Results and discussion

3.1 Energy and exergy analysis

The amount of inputs consumed on farms in the production of sugarcane and sugar beet and their CEnC and CExC is shown in Table 2. The total CEnC on the farm for sugarcane and sugar beet production is 66,500 and 49,044 MJ/ha, respectively. The total energy consumed in the field for sugar beet production in Tokat province of Turkey, Khorasan Razavi province of Iran, and Kermanshah province of Iran is 39,685 (Erdal et al., 2007), 42,232 (Asgharipour et al., 2012), and 49517 (Yousefi et al., 2014) MJ/ha, respectively. Consumption of more water for irrigation of sugarcane than sugar beet has increased the direct and indirect CEnC in sugarcane production. The amount of energy consumed in irrigation of sugarcane was about 1.75 times that of sugar beet. In both production systems, electricity was the main direct CEnC, which is used for irrigation. In sugarcane and sugar beet production systems in Iran, a surface irrigation system is used, which has increased water consumption and electricity for water pumping. Sugarcane is mostly irrigated in summer and hot months of the year when high evapotranspiration and lack of rainfall have increased water consumption for sugarcane irrigation compared to sugar beet, which is cultivated in cold months. The second-largest CEnC in sugarcane and sugar beet production systems was chemical fertilisers [22.48% (14950 MJ/ha) and 29.65% (14,541 MJ/ha) for sugarcane and sugar beet production, respectively], in which nitrogen fertiliser had the largest share. Nitrogen is a major component of chlorophyll in plants and is vital for vegetative growth and increased yield, without which plants will wither. The use of broadcaster equipment for fertiliser distribution, which increases nitrogen desorption and ammonia escape, along with nitrogen leaching due to surface irrigation systems has increased the chemical fertiliser losses in sugarcane and sugar beet production systems. This has led to an increase in the use of chemical fertilisers, especially nitrogen. In many studies, the use of organic fertilisers has been suggested to reduce the use of chemical fertilisers and increase the sustainability of agricultural production systems (Esmaeilpour-Troujeni et al., 2021). In both production systems, CEnC of chemical fertilisers is followed by CEnC of diesel fuel used in agricultural machinery and transportation. The electricity, fertilisers, and diesel fuel constitute 83.14% and 82.98% of the CEnC in the sugarcane and beet production farms, respectively. Similar results have been reported in other studies in which fuel, electricity, and chemical fertilisers had the highest input energy in the production of sugarcane (Kaab et al., 2019; Taghinezhad et al., 2014) and sugar beet (Asgharipour et al., 2012; Yousefi et al., 2014). In study cunducted by Kaab et al. (2019) the total energy of these inputs in plant farm of sugarcane was about 85.56% of the total input energy. This value was reported by Taghinezhad et al. (2014) to be 73% of the total energy input in sugarcane farms. In the production of sugar beet, this value was obtained 81.4% and 75.1% of the total input energy by Asgharipour et al. (2012) and Yousefi et al. (2014), respectively. In general, in Iran, agricultural operations in the sugarcane production system are more mechanised than those in the sugar beet production system. As a result, more machinery, diesel fuel, and lubricants are consumed in sugarcane fields while more labour is consumed in sugar beet fields.

Table 2 Input-output energy in sugarcane and sugar beet production

Items	*Sugarcane*					*Sugar beet*				
	Quantity per ha	*CEnC*		*CExC*		*Quantity per ha*	*CEnC*		*CExC*	
		(MJ/ha)	*%*	*(MJ/ha)*	*%*		*(MJ/ha)*	*%*	*(MJ/ha)*	*%*
Inputs										
Diesel fuel (li)	249.5	14,346	21.57	13,273.4	16.08	197.4	11,351	23.16	10,501.7	15.45
Lubricant (kg)	8.6	697	1.05	407.8	0.49	1.56	127	0.26	74.0	0.11
Electricity (kWh)	2,166.1	25,993	39.09	32,517.5	39.39	1,233.9	14,807	30.22	18,523.3	27.25
N-based fertilizers (kg)	168.9	13,208	19.86	5,523.0	6.69	156.3	12,223	24.94	5,111.0	7.52
P-based fertilisers (kg)	126.2	1,742	2.62	949.0	1.15	111.8	1,543	3.15	840.7	1.24
K-based fertilisers (kg)	0	0	0	0	0.00	69.5	735	1.50	326.7	0.48
Biocides (kg)	2.1	762	1.14	68.7	0.08	7.4	2,686	5.48	242.0	0.36
Machinery (kg/year)	201.1	1,810	2.72	1,427.8	1.73	102	922	1.88	727.0	1.07
Labour (h)	352.9	690	1.04	12,826.7	15.54	764.6	1,499	3.06	27,869.7	40.99
Irrigation (indirect)	20% of direct	5,199	7.82	21.7	7.88	20% of direct	2,961	6.04	12.3	5.45
The stalk of sugarcane (kg)	1711	2,053	3.09	9,063.2	10.98	-	-	-	-	-
Sugar beet seed (kg)		-	-			3	150	0.31	63.0	0.09
Total input	-	66,500	100	82,560.7	100	-	48,267	100	67,983.7	100
Output										
Sugarcane stalk (kg)	74,200	89,040	100	393,037.4	100	-	-	-		
Sugar beet (kg)	-	-	-			46,300	777,840	100	23,3815	100

Table 3 Energy and exergy evaluation indicators in the farms of sugarcane and sugar beet production

Items	*Unit*	*Sugarcane*	*Sugar beet*
O/I	-	1.34	15.87
SE	MJ/kg	0.896	1.058
EP	kg/MJ	1.12	0.94
CNEn	MJ/ha	22,540	728,838
Direct input energy	MJ/ha	41,029 (61.70%)	27,656 (56.44%)
Indirect input energy	MJ/ha	25,471 (38.30%)	21,346 (43.56%)
Renewable input energy	MJ/ha	2,743 (4.12%)	1,649 (3.36%)
Non-renewable input energy	MJ/ha	63,757 (95.88%)	47,353 (96.64%)
CDP	-	4.76	3.44
CNEx	MJ/ha	310,476.7	165,831.3
RI	-	0.86	0.84

On the other hand, only the crop yield was considered to calculate the total energy produced in two production systems, and the energy of straw and leaves was not considered. The total output energy in sugarcane was calculated to be 89,040 MJ/ha, considering the average yield as 74.2 tons/ha. The average yield of sugar beet was 46.3 tons/ha, and thus, the energy output was calculated at about 777,840 MJ/ha. Due to the high energy equivalent of sugar beet, energy production in the sugar beet production system is higher than that for sugarcane, despite its lower yield. Energy evaluation indicators in the farms of sugarcane and sugar beet production are shown in Table 3. Because sugar beet has a high energy equivalent, its output-input energy ratio is higher than that of the sugarcane production system. The O/I value indicates that for each unit of CEnC in the sugar beet and sugarcane production systems, the energy produced was 15.86 and 1.34 times, respectively. The O/I and NEG show that the output energy in the two production systems is more than the total CEnC. In evaluating the output-input energy of agricultural production systems, O/I is often used as an indicator to evaluate the energy efficiency of the production systems (Asgharipour et al., 2012). In similar studies, O/I for sugar beet production has been reported as 13.4 and 22.12 in Khorasan Razavi of Iran (Asgharipour et al., 2012) and Kermanshah of Iran, respectively. This ratio for sugarcane is reported to be 1.38 (Taghinezhad et al., 2014) and 0.81 (Kaab et al., 2019), respectively. The difference between these values and the obtained value is mostly due to the difference in product performance and different use of inputs.

The SE shows that 0.896 and 1.059 MJ of energy are consumed to produce one kg of sugarcane and sugar beet, respectively, indicating that less energy is used to produce per unit weight of sugarcane. Energy productivity of sugarcane and sugar beet fields was calculated as 1.12 and 0.94 MJ/kg, respectively. CNEn shows that the difference between output and input CEnCs in sugar beet production fields is much greater than that for sugarcane fields. Therefore, considering energy use, the sugar beet production system is more efficient than the sugarcane production system. However, sugar beet yield is lesser than sugarcane, and the SE and EP indexes in the sugarcane production system are roughly better. Table 3 also shows the types of CEnC in sugar beet and sugarcane production systems in terms of direct, indirect, renewable, and non-renewable energies. The results show that the majority of CEnC in both production systems is based on non-renewable energy, so non-renewable energies constitute more than 95% of the input energies of both production systems. The results also show that 61.70% and 56.39% of the total CEnC in the sugarcane and sugar beet production systems belong to direct types of energies. In similar study 56.9% (Asgharipour et al., 2012) and 58.1% (Yousefi et al., 2014) of input energy in sugar beet production and about 61% (Taghinezhad et al., 2014) and 63.32% (Kaab et al., 2019) of input energy in sugarcane production was related to direct energy.

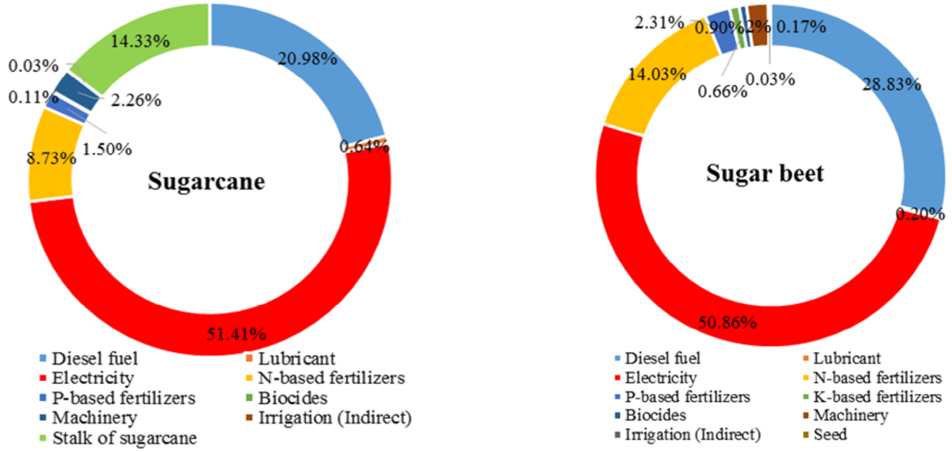
Based on the specific exergy equivalent of inputs (Table 1) and the values obtained for inputs, the total CExC in sugarcane and sugar beet production systems per hectare was calculated, which were 82,561 and 67,984 MJ/ha, respectively. Unlike energy consumption, in which labour accounts for a small share of total CEnC, regarding exergy, labour constitutes a large part of the CExC. This is due to the high specific exergy equivalent of labour (ee_L) compared to other inputs. The average of eeL in sugarcane and sugar beet production systems was calculated as 36.45 MJ/h. Amiri et al. (2020) calculated the ee_L for canola production in Khorramabad, Iran, to be about 37.9 MJ/ha. The ee_L in Portugal in 2000 and 2012 was reported to be 51.5 MJ/h and 89.0 MJ/h, respectively (Manso et al., 2017). Unal et al. (2022) reported ee_L as 42.68 MJ/h. The value of ee_L in developed countries is higher than in developing countries, indicating that lifestyle in developed countries has increased the exergy content of a one-hour work by the labour force (Sciubba, 2011).

In addition to labor, the CExC of electricity is higher than its energy in both production systems. Except for these two inputs, the amount of CExC for other inputs in the sugar beet production system is less than their CEnC content. In the sugarcane production system, in addition to labour and electricity, the CExC of the sugarcane stalk is more than its CEnC level. Labour accounts for 15.54% and 40.99% of the total exergy consumption of sugarcane and sugar beet production systems, respectively. In the sugar beet production systems, electricity, diesel fuel, and nitrogen fertilisers are in the next ranks with 27.25%, 15.45% and 7.52% of the total CExC, respectively. About 91.21% of the total CExC of the sugar beet production system belongs to these four inputs.

In the sugarcane production system, the highest CExC belongs to electricity (32,517.5 MJ/ha), diesel fuel (13,273.4 MJ/ha), and labour (12,826.8 MJ/ha), respectively. The total CExC per hectare of sugarcane farms is 21% (14,577 MJ/ha) more than that for sugar beet production systems. However, the exergy production in the sugarcane production system is about 68% (159,222.40 MJ/ha) more than that of the sugar beet production system. Therefore, the CDP of the sugarcane production system (4.76) is higher than that of the sugar beet production system (3.44), indicating a higher exergy efficiency, and stability of the sugarcane production process. The CDP of rapeseed production in Mazandaran province of Iran, and commercial canola production systems in Lorestan province, Iran, were reported to be 2.19 (Esmaeilpour-Troujeni et al., 2021) and 1.8 (Amiri et al., 2020), respectively. The CNEx in a sugarcane field is about 1.68 times that of a CNEx in sugar beet fields. The CNEx indicates that in both production systems, the output exergy is more than the CExC. Since the sugarcane and sugar beet production systems provided more yield than that of maize, the CNEx obtained for these two production systems is higher than the CNEx reported for maize production systems in Mexico (Juárez-Hernández et al., 2019).

The lower CDP and CNEx of the sugar beet production system are mainly due to the high consumption of labour and the high specific exergy equivalent of labour. In most studies evaluating input exergy in agricultural production systems, labour is not considered while diesel fuel, chemical fertilisers, biocides, irrigation, and electricity were taken into account (Esmaeilpour-Troujeni et al., 2021; Juárez-Hernández et al., 2019; Ordikhani et al., 2021; Pelvan and Özilgen, 2017). Excluding labour, the CDP of the sugar beet production system was calculated to be 6.42, which is higher than the CDP of the sugarcane production system (6.21). The percentage of CExC without considering the labour in the two production systems is shown in Figure 1. In this case, the sum of electricity, diesel fuel, and nitrogen fertiliser exergy constitutes 81.13% and 93.72% of the total CExC in the sugarcane and sugar beet production systems, respectively, all of which are non-renewable energy sources. In this case, electricity (used for water pumping in irrigation) alone accounts for 51.41% and 50.86% of the total CExC in the sugarcane and sugar beet production systems, respectively. Therefore, by improving the consumption management of irrigation water and modifying the irrigation system, the CDP of both production systems can be increased, and as a result, the systems will be more environmentally friendly. The use of water pumping equipment with higher efficiency and the use of pressurised irrigation systems instead of surface irrigation systems will reduce water consumption and electricity.

Figure 1 The percentage of CExC without considering the labour (see online version for colours)



A large part of CExC in the two production systems is related to diesel fuel consumption. The use of old and conventional methods, heavy tillage, harvesting, and transportation operations, as well as worn-out agricultural machinery and equipment, have increased diesel fuel consumption, especially in the sugarcane production system. Studies have indicated that the use of conservation tillage methods (minimum tillage, no-tillage, etc.) significantly reduces fuel consumption and depreciation of agricultural machinery and equipment (Esmaeilpour-Troujeni et al., 2021; Ordikhani et al., 2021). Decreasing the depreciation of agricultural machinery and equipment means that the efficiency of the machines does not decrease significantly and as a result, the fuel consumption does not increase. Therefore, adopting conservation tillage and using new machines will reduce diesel fuel consumption in sugarcane and sugar beet production systems. Excluding labour, diesel fuel and chemical fertilisers account for 31.22% of the total CExC of the sugarcane production system and 47.07% of the CExC of the sugar beet production system. In similar studies, electricity for irrigation, diesel fuel, and chemical fertilisers have been reported as the main exergy inputs in the production of rapeseeds in Mazandaran province, Iran (Esmaeilpour-Troujeni et al., 2021), horticultural crops in Qazvin province, Iran (Ordikhani et al., 2021), tomato in Turkey (Yildizhan and Taki, 2018), and maize in Mexico (Juárez-Hernández et al., 2019). In order to increase the sustainability of production systems, in addition to improvement of the consumption management of chemical fertilisers, it is necessary to supply the energy required for the production of chemical fertilisers and electricity from renewable energy sources instead of fossil fuels. According to Pelvan and Ozilgen (2017), by replacing non-renewable resources with renewable resources in a process, CDP values increase.

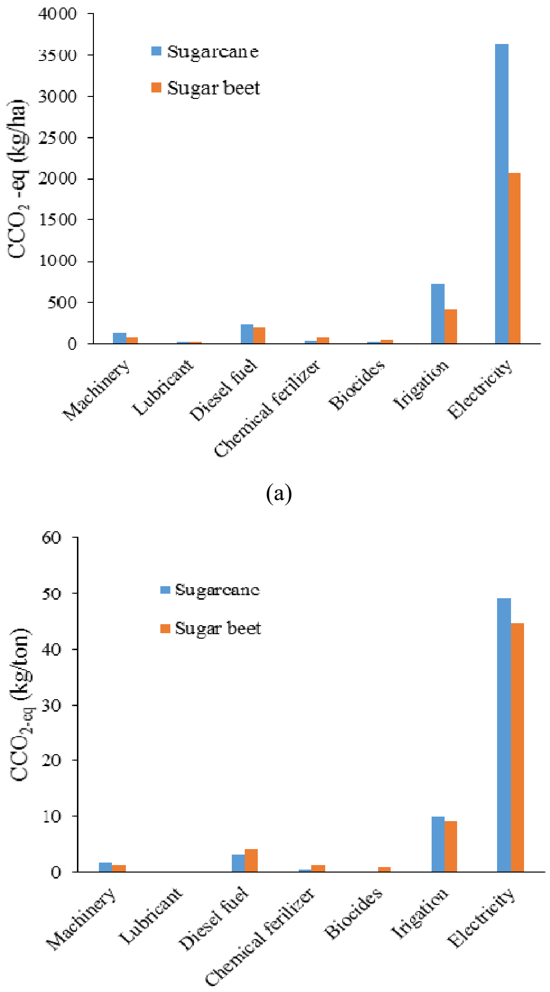
RI is an important indicator for assessing the harmful effects of environmental processes and an indicator for measuring the environmental sustainability of processes (Esmaeilpour-Troujeni et al., 2021). This indicator was calculated in sugarcane and sugar beet production fields at 0.86 and 0.84, respectively, which suggests the relative renewability of the sugarcane and sugar beet production systems in Iran. Reducing the consumption of electricity, diesel fuel, agricultural machinery, chemical fertilisers and pesticides, as well as replacing these non-renewable inputs with renewable inputs, increases the renewables of sugarcane and sugar beet production on farms. As mentioned, electricity is the main CExC in the production of these two crops, which is mainly generated in Iran from fossil sources. Generating electricity from renewable sources increases the share of renewable CExC in sugarcane production from 14.33% to 65.74% and from 0.17% to 51.03% in sugar beet production.

In this scenario, the RI of sugarcane and sugar beet production processes will be equal to 0.94 and 0.92, respectively. The RI indexes reported for rapeseed (0.72) (Esmaeilpour-Troujeni et al., 2021), and tomato (–0.12 to 0.38) (Yildizhan and Taki, 2018) are less than the values obtained in this study. This is attributable to the high yield of sugarcane and sugar beet compared to the mentioned crops, which results in higher output exergy for the sugarcane and sugar beet production systems compared to the above crops.

3.2 GHG emission

The $CCO_{2\text{-eq}}$ emission values for the two production systems are shown in Figure 2. The amount of $CCO_{2\text{-eq}}$ emission per hectare for sugarcane production is 1.68 times that of sugar beet production. The total annual value of $CCO_{2\text{-eq}}$ emissions per hectare for sugarcane and sugar beet production were 4,785 and 2,851 kg, respectively [Figure 2(a)], most of which is related to electricity consumption for irrigation. As mentioned, only a small part of the electricity in Iran is generated from renewable energy sources. Therefore, by replacing fossil energy sources with renewable energy sources in electricity generation for sugarcane and sugar beet production systems, GHG emissions can be significantly reduced. Electricity consumption and water for irrigation were reported as the largest emitters of GHG in crop production systems in Turkey (Yildizhan and Taki, 2018). The amount of $CCO_{2\text{-eq}}$ emission per hectare of irrigated rapeseed production system was 1,809 kg (Esmaeilpour-Troujeni et al., 2021). The amount of GHG emissions in maize production systems in Mexico was found to be 152.9–3475.8 kg CO_2-eq per hectare in a study by Juárez-Hernández et al. (2019). In rainfed farms, the consumption of inputs and energy is low, and as a result, GHG emissions in these farms are lower than that of irrigated farms, where the consumption of inputs is extremely high.

Figure 2 $CCO_{2\text{-eq}}$ emission from sugarcane and sugar beet fields, (a) $CCO_{2\text{-eq}}$ emission per hectare, (b) $CCO_{2\text{-eq}}$ emission per tone (see online version for colours)



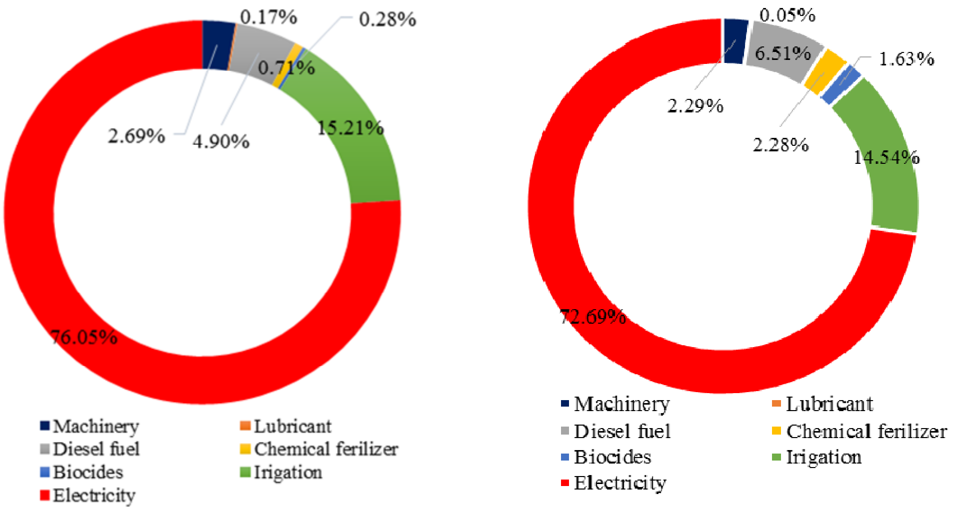
(a)

(b)

To produce one ton of sugarcane and sugar beet, 64 kg and 62 kg of $CCO_{2\text{-eq}}$ were emitted, respectively [Figure 2(b)]. In similar studies, this value was 25.8 kg $CCO_{2\text{-eq}}$/ton for black tea (Pelvan and Özilgen, 2017), and 116.5–601.9 kg $CCO_{2\text{-eq}}$/ton for maize production systems in Mexico (Juárez-Hernández et al., 2019). Similar to the results of the current study, the highest GHGI of intensive maize production systems was related to the energy used for irrigation (Juárez-Hernández et al., 2019). The GHGEn values in sugarcane and sugar beet production systems were 71.96 kg $CCO_{2\text{-eq}}$/GJ and 58.19 kg $CCO_{2\text{-eq}}$/GJ, respectively, which indicates the more GHG emission per unit of input energy in the sugarcane production system. In a study by Juárez-Hernández et al. (2019), this index was calculated to be 63.1–117.2 kg/GJ of $CCO_{2\text{-eq}}$ for maize production systems. High electricity consumption (generated from non-renewable sources) in the sugarcane production system compared to the sugar beet production system yielded more GHG emissions per unit of energy consumption in the sugarcane production system.

The contribution of different sources of input consumption to GHG emissions in sugarcane and sugar beet production systems is shown in Figure 3. This figure shows that 91.26% of GHG emissions in the sugarcane production system and 87.23% of GHG emissions in the sugar beet production system belong to direct and indirect input energy for irrigation. Therefore, the use of renewable energy sources for irrigation along with the improvement of irrigation systems will play a significant role in reducing GHG emissions.

Figure 3 The contribution of input consumption to GHG emission in sugarcane and sugar beet production systems, (a) sugarcane, (b) sugar beet (see online version for colours)



(a) (b)

4 Conclusions

In this study, energy indices, CExC, and GHG emissions for sugarcane and sugar beet production systems, which are the most important industrial crops in Iran, were calculated. The conclusions of this study can be stated as follows:

- The values of CEnC, CExC and GHGI, in the sugarcane production system were 66,500 MJ/ha, 22,540 MJ/ha, and 64 kg $CCO_{2\text{-eq}}$/ton, respectively and these values were 48,267 MJ/ha, 728,838 MJ/ha, and 62 kg $CCO_{2\text{-eq}}$/ton in the sugar beet production system, respectively.
- Electricity, chemical fertilisers, and diesel fuel constituted a major share of CEnC while labour, electricity, and diesel fuel accounted for the largest share of the CExC.

- The O/I, CDP, and RI were 1.34, 6.21, and 0.86 in the sugarcane production system and 15.87, 6.42, and 0.84 in the sugar beet production system, respectively.
- About 91.26% of GHG emissions in the sugarcane production system and 87.23% of GHG emissions in the sugar beet production system belong to energy consumption in irrigation.
- Efficient management of chemical fertilisers and irrigation water, improving the irrigation system, and replacement of non-renewable energy sources with renewable sources for electricity generation increases the CDP and RI of both production systems and the environmental compatibility of these two systems.

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Nomenclature

CDP	Cumulative degree of perfection	HDI	Human development index
CEnC	Cumulative energy consumption	LHV_{lu}	Lower heating value of lubricant
CExC	Cumulative exergy consumption	N_h	Total population
CNEx	Cumulative net exergy gain	N_{wh}	Total working hours per year
E_{ch}	Chemical exergy	O/I	Output-input ratio
ee_L	Specific exergy equivalent of labour	RI	Renewability index
ee_{LU}	Specific chemical exergy per unit mass of lubricant	SE	Specific energy
EP	Energy productivity	W_r	Restoration work
E_{surv}	Minimum exergy required for a person	α	Mass fractions of C
GHGEn	GHG emissions per unit of energy consumption	B	Mass fractions of H
GHGI	GHG emission per ton of crop production	γ	Mass fraction of O