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Environmental life cycle assessment and energy use efficiency in cumin and fennel production

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Abstract

Energy use efficiency is a measure of how efficiently energy is used in an agricultural production system. It considers the amount of energy inputs required to produce a given output, such as a unit of cumin or fennel. We selected Qazvin Province, Iran for studying the cultivation of medicinal plants in 2022. A life cycle assessment (LCA) is a comprehensive analysis of the environmental impact of a product or process throughout its entire life cycle, from raw material extraction to disposal. It considers the environmental impact of various stages, including production, transportation, use, and disposal, and assesses the impact on categories such as climate change, water use, and land use. The present study investigates energy use and environmental impacts of cumin and fennel production through LCA. The results showed that fennel had higher productive energy and that its energy output was 18206.04 MJ ha^{-1}. The highest consumption of inputs, which was over 40%, was related to nitrogen fertilizers. The negative addition of net energy indicates that more care should be taken in medicinal plant farms as to how energy inputs, especially chemical fertilizers and diesel fuel, are consumed. LCA is a suitable instrument to investigate and quantify the environmental effects of agricultural products and food industries. The effects of environmental emissions of medicinal plant production were calculated as an important part of human health. The weighting results showed that the human health category has more environmental emissions for both crops, and direct environmental emissions played a major role in data quantification.

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Introduction

There are various challenges associated with the use of medicinal plants. One major challenge is the difficulty in ensuring the quality and safety of the products derived from medicinal plants. The presence of contaminants such as heavy metals, pesticides, and other toxic substances in soil and water can affect the safety and efficacy of medicinal plants. There is also the issue of adulteration, where lower quality or incorrect plant species are used, which can lead to negative health effects (Hishe et al., 2016). Another challenge is the sustainability of medicinal plant use. Overharvesting of medicinal plant species can lead to their depletion and can disrupt the ecosystems they inhabit. This can have negative impacts on both the environment and the communities who rely on these plants for their livelihoods and healthcare. Despite these challenges, medicinal plants continue to be used for their therapeutic benefits. There are many different types of medicinal plants, each with its own unique chemical properties and health benefits (Neergheen-Bhujun, 2013).

The increasing use of medicinal plants and their extensive application in various fields has fueled the expansion of their production and processing. Cumin is an annual plant that is suitable for arid and semi-arid regions of Iran. This plant species has attracted the attention of farmers in recent years due to its low water requirement and growing season. Iran is one of the richest and most diverse sources of medicinal plants in the world and is among the most important exporters of fennel in the world. Considering the importance of medicinal plants in terms of their high added value, this study examines the relative advantage of medicinal plants in terms of energy and environment (Ministry of Jihad-e-Agriculture of Iran, 2020).

Management is considered an important factor in all economic sectors, especially agriculture, so it has been added to the three factors of land, labor, and capital. The importance and role of management in agricultural production in similar conditions are evident in terms of the availability of physical inputs for some farmers (Jamali et al., 2021). Improving productivity in various fields of the energy sector is one of the basic solutions. The strategic sector of agriculture is highly dependent on energy consumption to respond to the ever-increasing need for food and to provide adequate and suitable food (Kaab et al., 2019a). The global increase in fuel prices, the ever-increasing demand for energy, and concerns about global warming are the key factors increasing the competition for bioenergy resources worldwide (Powar et al., 2020). Increasing energy use efficiency in crop cultivation is one of the most important parts of energy studies in agriculture. If the efficiency of energy consumption in various crop cultivation operations can be improved, valuable energy resources will be used more optimally (Royan et al., 2012). Increasing information on the importance of environmental protection related to the product has increased the interest in developing better methods and identifying the consequences (Yodkhum et al., 2017).

To deal with the concerns about environmental degradation, it is necessary to model the environmental impact by the life cycle assessment (LCA) approach (Darzi-Naftchali et al., 2022). Managers of production units use the guidelines to improve their decision-making in the design and start-up phase of production units to choose the best combination and type of inputs for cleaner production (Wowra et al., 2021). This technique quickly estimates environmental damage before starting production and provides an appropriate estimate of the amount of environmental damage. As a result, the speed at which production units are established and changed is effective in ensuring food safety and security (Yodkhum et al., 2017). In recent years, LCA has become a suitable tool for assessing and determining the extent of environmental impacts on agricultural production and the food industry. In many countries, the LCA is used as a tool for macro decision making in agricultural planning (Sanderson et al., 2019). Oğuz and Oğuz (2022) determined the energy usage efficiency and greenhouse gas emissions of lemon production in turkey, and showed the total input energy was 35,273.60 MJ ha^{-1}. Energy usage efficiency, specific energy, energy productivity and net energy calculations were calculated as 2.24, 0.85 MJ kg^{-1}, 1.18 kg MJ^{-1} and 43,779.87 MJ ha^{-1}, respectively. Total GHG emissions were calculated as 1524.04 kg CO^2 ha^{-1} for lemon production. Table 1 shows some of the results related to energy and environmental analysis.

The scope of the study is to examine the environmental impact and energy use efficiency of the production process of cumin and fennel. We will use the LCA to analyze the environmental impacts of cumin and fennel production. Energy use efficiency, on the other hand, refers to the ratio of energy input to output in a production process. The energy use efficiency of cumin and fennel production will be evaluated to determine how efficiently energy is used in the process. Overall, the study aims to provide insight into the environmental impact and energy use efficiency of cumin and fennel production, which can help identify areas for improvement and inform sustainable production practices.

Table 1. Literature review of previous studies about energy use and LCA in agricultural crops production.

Investigated research	Country	Crop	Energy use	LCA	Hotspot
Liu et al. (2010)	Belgium	Apple	No	Yes	Chemical fertilizers and biocides
Alaphilippe et al. (2013)	France	Apple	No	Yes	Pesticides
Vazquez-Rowe et al. (2013)	Spain	Grape	No	Yes	Diesel fuel and fertilizer
Cerutti et al. (2013)	Italy	Apple	No	Yes	Fertilizers
Soode et al. (2015)	Germany	Strawberri	No	Yes	Electricity
Nikkhah et al. (2015b)	Iran(Guilan)	Kiwifruit	No	Yes	Urea fertilizer
Pérez Neira et al. (2018)	Spain	Tomato	Yes	No	Electricity
Mohseni et al. (2018)	Iran (Arak)	Grape	No	Yes	Poultry manure
Yildizhan and Taki, (2018)	Turkey	Tomato	No	No	Electricity
Grados et al. (2019)	Peru	Potato	No	No	Chemical fertilizers

Materials and Methods

Sampling method

First, the sample size required for the statistical analysis was calculated. Then, statistical sampling methods were used to take samples. One of the decisions after choosing the research topic and stating the problem is to choose the study area for which we selected Qazvin Province, Iran for studying the cultivation of medicinal plants. The required information was collected face-to-face using a questionnaire. The questionnaire included questions about the use of different inputs, the amount of land cultivated by the farmer, the yield of medicinal plants, the total working hours from land preparation to harvesting, the total working hours of machinery and equipment, etc. In order to collect information about the type and amount of consumption of inputs and outputs, the number of samples was determined using Equation 1 (Cochran, 1977). The number of samples in cumin and fennel production was estimated equal to 40 and 50, respectively.

$$n = \frac{\frac{z^2 pq}{d^2}}{1 + \frac{1}{N}\left(\frac{z^2 pq}{d^2} - 1\right)} \quad (1)$$

where, N is the number of population, z is the reliability coefficient, p is the estimated proportion of an attribute that is present in the population, q is 1-p, and d is the permitted error ratio deviation from the average population.

Energy use analysis

Energy analysis in agriculture helps to evaluate the effect of human activities on the balance and stability of the environment resulting from energy flow patterns and their changes (Payandeh et al., 2021). In this study, human labor, machinery, diesel fuel, chemical fertilizers, biocides, and electricity were considered the inputs, and the yields of the medicinal plants were considered the outputs (Truong et al., 2017). The equivalence of inputs and outputs has been reported by many researchers (Naderloo et al., 2012; Soni et al., 2018). To calculate the energy consumption per hectare, the values of each input were multiplied by the corresponding energy equivalent. Various energy indicators are used in production systems to provide a comprehensive understanding of the agricultural situation. Efficient use of energy in agricultural ecosystems reduces environmental challenges, prevents the destruction of valuable natural resources, and strengthens sustainable agriculture as an economic production system (Yuan et al., 2018).

Energy indices analysis including energy use efficiency (Equation 2), energy productivity (Equation 3), specific energy (Equation 4) and net energy gain (Equation 5) were calculated using the following equations. When the energy consumption efficiency is more than one, the amount of energy output is more than the input energy. The amount of crop production for cumin and fennel production per unit of energy consumed is called energy efficiency. We also used the intensity of energy (Mohammadshirazi et al., 2012).

$$\text{Energy use efficiency} = \frac{\text{Output energy (MJ)}}{\text{Input energy (MJ)}} \quad (2)$$

$$\text{Energy productivity} = \frac{\text{Production (kg)}}{\text{Input energy (MJ)}} \quad (3)$$

$$\text{Specific energy} = \frac{\text{Input energy (MJ)}}{\text{Production (kg)}} \quad (4)$$

$$\text{Net energy} = \text{Output energy (MJ)} - \text{Input energy (MJ)} \quad (5)$$

LCA technique

LCA is an approach for environmental impact assessment of the products from "cradle to grave" (Morandini et al., 2020). The term "cradle to grave" means start from the process of extracting raw materials from the earth for production in one or more stages and end with the return of the consumed product (waste) to the earth (Wang et al., 2021). This particular type of assessment process allows for examining and estimating the cumulative environmental effects resulting from all stages of the product's life cycle (Sanjuán et al., 2014). LCA has emerged as a valuable decision support tool for policymakers and industry in assessing the cradle-to-grave impacts of a product. The producer is not only responsible for the direct effects of production but also for the effects associated with the input, use, transportation, and disposal of the product (Xue et al., 2015). The main applications of LCA include choosing between several comparable products about negative environmental impacts, analyzing the source of problems associated with the production and consumption of a particular product, and environmentally friendly design (Renouf et al., 2010). The steps of LCA include (1) preparing an inventory list of relevant inputs and outputs, (2) assessing the potential environmental effects of inputs and outputs, (3) interpreting the results of these two stages concerning the study objectives (Ghimire et al., 2017)

The scope of the study usually includes the definition of the system, its boundaries (conceptual, geographical, and temporal), the quality of the data used, the main hypothesis, and a priori limitations (Wowra et al., 2021). Energy and raw material consumption, as well as emissions to air, water, and soil by the system, is calculated for the entire life cycle of the product or service (Brodt et al., 2014). LCA is a process to identify and characterize the potential effects on the environment by the studied system. The starting point of the life cycle impact assessment (LCIA) is the information obtained in the inventory phase, so the quality of the data collected is key for this assessment (Dijkman et al., 2017). All stages of the production chain for one ton of medicinal plants are drawn. The boundary of the system in this research is related to the input and output flows shown in Figure 1. Input streams include raw materials and energy consumption, and output streams include emissions from the process. We used the ReCiPe2016 method in SimaPro to evaluate the environmental effects in the third stage (Huijbregts et al., 2017). SimaPro is an economic software package that provides professional tools to collect, evaluate, and monitor the environmental performance of products, processes, and services.

Characterization involves weighing different substances that contribute to the same environmental impact. Therefore, for each impact category included in the LCIA, an aggregated result is obtained in a given unit of measurement. Normalization involves relating specified data to a larger dataset or situation. Weighting for different impact categories is converted into points using numerical factors based on values. This is the most subjective stage of LCA and is based on value judgments. The advantage of this step is that the different criteria (impact categories) are converted into a numerical score of environmental impacts, thus making decision-making easier (Niero et al., 2015).

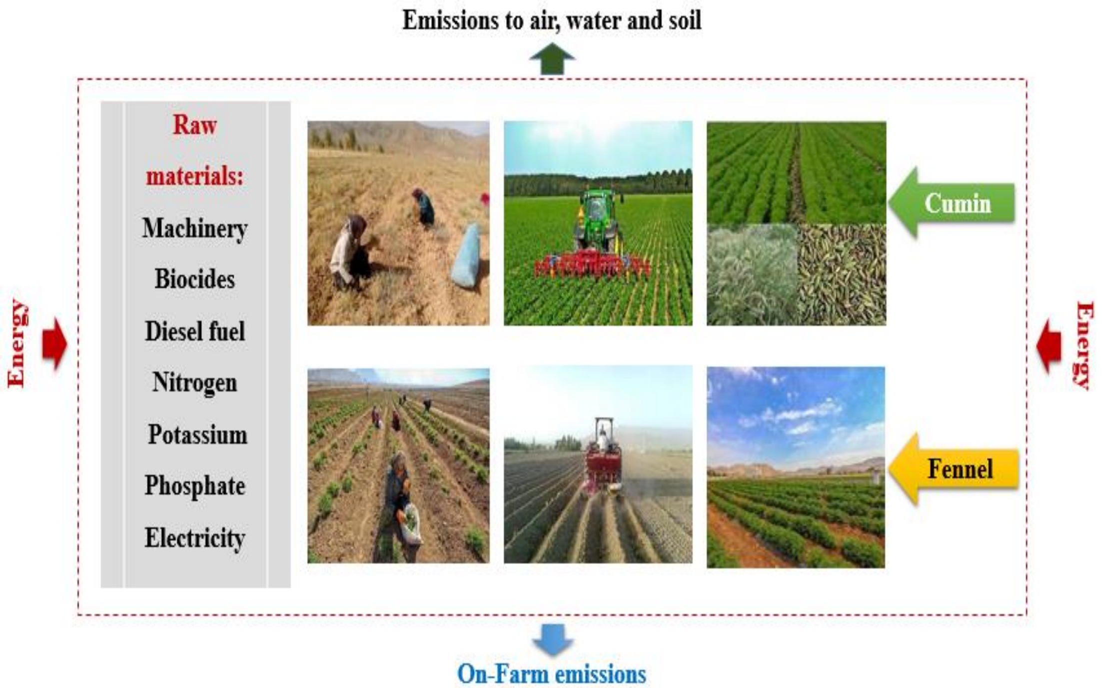


Figure 1. The system boundary of cumin and fennel production.

Results and Discussion

Energy result

Table 2 presents the amount of each input, the unit of input, and the energy produced and consumed in this process. The total energy consumption of fennel and cumin is 34814.81 MJ ha^{-1} and 26214.17 MJ ha^{-1}, respectively. The cultivation of fennel, except for phosphate and potassium consumption, has more energy in other inputs than cumin. The production energy of fennel is also 8600.64 MJ ha^{-1} more than that of cumin. Fennel has a higher yield per hectare by consuming more inputs. Normally, the preference is the maximum production of medicinal plants with the lowest energy consumption. As a result, to keep the optimal yield of fennel, there is a need for management in the field. Figure 2 depicts the percentage of input energy. The results show that nitrogen energy, diesel fuel, and electricity consume more than 80% of energy. Also, diesel fuel has made a greater difference in the cultivation of fennel (36.97%) than in the cultivation of cumin (23.25%). As a result, it is necessary to reduce the use of machinery, especially in the tillage stage, to reduce the consumption of diesel fuel in fennel cultivation. More potassium and phosphate fertilizers are used in cumin production to gain a higher yield. The cultivation of cumin does not produce much energy per hectare. As a result, excessive use of chemical fertilizers will have adverse effects in the future.

Table 2 and Figure 2 presented in this discussion provide valuable information about the energy consumption and production in fennel and cumin cultivation. The results indicate that fennel requires more energy inputs than cumin, except for phosphate and potassium consumption. Additionally, fennel has a higher yield per hectare than cumin, but also has a higher production energy. It is essential to consider the optimal yield of medicinal plants while minimizing energy consumption. Therefore, effective management in the field is necessary to maintain the optimal yield of fennel. The results also indicate that nitrogen energy, diesel fuel, and electricity are the most significant energy-consuming inputs, accounting for more than 80% of energy consumption. Diesel fuel consumption is higher in fennel cultivation than in cumin cultivation, particularly during the tillage stage. To reduce energy consumption in fennel cultivation, it is necessary to reduce the use of machinery, especially during the tillage stage, and explore alternative energy sources such as renewable energy. Additionally, it is crucial to use chemical fertilizers judiciously and avoid excessive use to avoid adverse effects on the environment. In summary, the results presented in this discussion provide valuable insights into the energy consumption and production in fennel and cumin cultivation. Effective management practices and the judicious use of inputs can help minimize energy consumption while maintaining optimal yields of medicinal plants.

Table 2. Input-output energy analysis in cumin and fennel production.

Items	Energy equivalent	Cumin		Fennel	
		Unit per ha	Energy use (MJ ha^{-1})	Unit per ha	Energy use (MJ ha^{-1})
1. Human labor (h)	1.96 (Unakitan et al., 2010)	155.20	304.19	174.89	342.80
2. Machinery (kg)	62.7 (Kaab et al., 2019b)	14.71	922.86	25.17	1578.61
3. Diesel fuel (L)	56.31 (Nabavi-Pelesaraei et al., 2014)	82.50	4645.57	228.58	12871.46
4. Chemical fertilizers(kg)					
(a) Nitrogen	66.14 (Unakitan et al., 2010)	139.98	9258.56	226.46	14978.61
(b) Phosphate (P_2O_5)	12.44 (Unakitan et al., 2010)	73.10	909.48	67.94	845.17
(c) Potassium (K)	11.15 (Unakitan et al., 2010)	79.71	888.86	45.29	505.02
5. Biocides (kg)	120 (Ozkan et al., 2004)	5.29	635.62	8.65	1038.98
6. Electricity (kWh)	12 (Ozkan et al., 2004)	201.42	2417.06	221.17	2654.12
Total energy use (MJ)		**-**	**26214.17**	**-**	**34814.81**
B. Output (kg)					
1. Cumin	14.7 (Unakitan et al., 2010)	897.01	13186.12	-	-
2. Fennel	14.7 (Unakitan et al., 2010)	-	-	1238.50	18206.04

Table 3 presents the energy indices calculated based on the energy results. Although the energy input and output of fennel are more than those of cumin, the energy ratio of cumin is 0.66. The energy ratio of cumin shows that a lot of energy is consumed per unit of energy produced. But for each kilogram of cumin, 22.36 MJ of energy is consumed. The results of the net added an index for cumin and fennel are 6796.10 MJ ha^{-1} and -16608.77 MJ ha^{-1}, respectively. The energy ratio of cumin being 0.66 indicates that a lot of energy is consumed per unit of energy produced, which is not desirable from an energy use efficiency perspective. However, it is important to note that the absolute amount of energy consumed per kilogram of cumin is relatively low, at 22.36 MJ, which suggests that cumin production may still be a viable option from an energy use perspective. On the other hand, the energy input and output of fennel being higher than those of cumin is an important finding as it suggests that fennel production requires more energy to produce the same amount of output as cumin. The net added index results reveal that fennel production has a significantly higher environmental impact than cumin production, with a net added index of -16608.77 MJ ha^{-1} compared to -6796.10 MJ ha^{-1} for cumin. It should be noted that the results of this study are specific to cumin and fennel production in the particular context of the study, and may not be generalized to other contexts or crops. Furthermore, it is important to consider the limitations of the study when interpreting the results. It is also important to consider the broader implications of the findings. While energy use efficiency and environmental impact are important considerations, other factors such as economic viability, social impacts, and nutritional value may also need to be taken into account when making decisions about crop production. Therefore, a comprehensive and holistic approach that considers multiple factors may be necessary to ensure sustainable and responsible crop production.

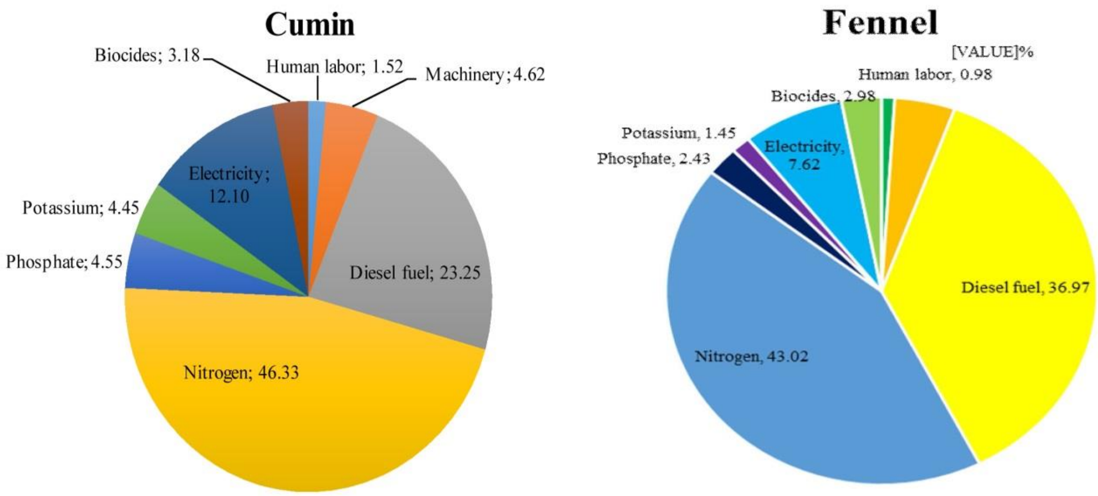


Figure 2. Energy contribution in cumin and fennel production

Table 3. Energy indices in cumin and fennel production.

Items	Cumin	Fennel
Energy use efficiency (ratio)	0.66	0.52
Energy productivity (kg MJ^{-1})	0.04	0.03
Specific energy (MJ kg^{-1})	22.36	28.55
Net energy gain (MJ ha^{-1})	-6796.10	-16608.77

LCA result

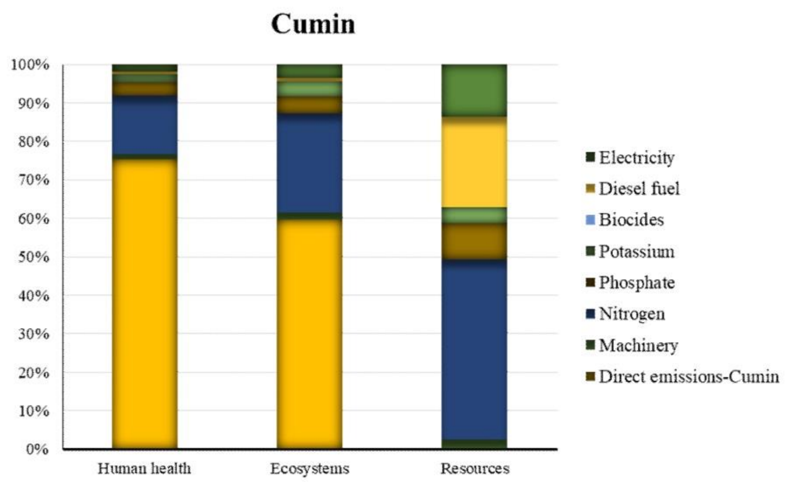
Environmental emissions were estimated using the ReCiPe2016 model. The endpoints of the model using the previously reported midpoints are shown in Table 4. Three main points of environmental emissions for cumin and fennel were compared. Environmental emissions for the category of human health in cumin cultivation is 0.15 Disability Adjusted Life Years (DALY). Ecosystems do not show any special difference in the environmental emissions of medicinal plants. The difference in the environmental emissions of human health products is insignificant. Fennel production has 237.77 USD_{2013} environmental emissions in the resource category. As a result, the cultivation of cumin compared to fennel is suggested to reduce environmental emissions and damage to water, air, and soil. A considerable share of the emissions of all three categories of medicinal plants is related to the direct emissions from crop cultivation showed in Figure 3. Nitrogen has a significant share in emissions after direct emissions. More than 50% of human health emissions are caused by nitrogen consumption. The share of environmental emissions of electricity from cumin cultivation is more than 10%. As a result, in cumin cultivation, apart from reducing the consumption of chemical fertilizers, electricity should also be reduced. The impact of agricultural activities on global warming is mainly due to the emission of

CO_2, CH_4, and N_2O into the atmosphere. CO_2 emission is related to the use of diesel fuel and the production of chemical fertilizers. The production of methane is due to the production and consumption of animal manure and the emission of N_2O to the air is due to the production and consumption of fertilizers. The share of N_2O in global warming is about 6%, and about 80% of its emissions were related to agriculture (Robertson and Vitousek, 2009; Tilman et al., 2001). Leaching of nitrates to surface and underground water sources, acidification of agricultural soils, emission of various greenhouse gases, and accumulation of chemical residues are other important consequences of consuming various types of energy-rich inputs in common systems (Kirchmann and Thorvaldsson, 2000). Chemical fertilization left significant environmental effects in the form of eutrophication and soil acidity impact groups in evaluating the life cycle of tomato production (Bojacá et al., 2014). Nitrogen fertilizer used from the source of urea for peanut production was also one of the factors with negative effects on the environment in the category of eutrophication and acidity (Nikkhah et al., 2015a). In other studies, it was found that organic fertilizers and reducing the consumption of chemical inputs reduce the environmental effects of agricultural production (Abeliotis et al., 2013; Liu et al., 2009). Figure 4 displays the weighting of LCA by considering the weight of the categories. The human health category has more environmental emissions than the ecosystem and resource categories. As a result, the production of medicinal plants with the use of chemical fertilizers and no field management endangers human health. The amount of acidification for the production of each ton of canola and sunflower was estimated at 19 and 23 kg of SO_2, respectively (Iriarte et al., 2010).

Table 4. Values of the environmental impact per one ton of cumin and fennel production.

		Cumin	Fennel
Human health	DALY [a]	0.15	0.13
Ecosystems	species.yr [b]	0.0001	0.0001
Resources	USD_{2013}	191.82	237.77

[a] DALY: disability-adjusted life years. Damage of 1 is equal to the loss of 1 life year of 1 individual, or 1 person suffers 4 years from a disability with a weight of 0.25.
[b] species. yr: the unit for ecosystems is the local species loss integrated over time.



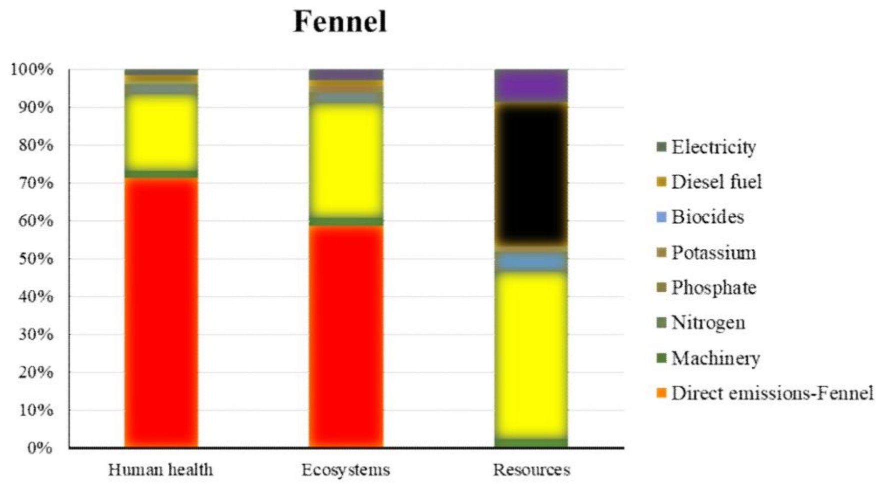


Figure 3. Contribution of different inputs in the damage categories of cumin and fennel production.

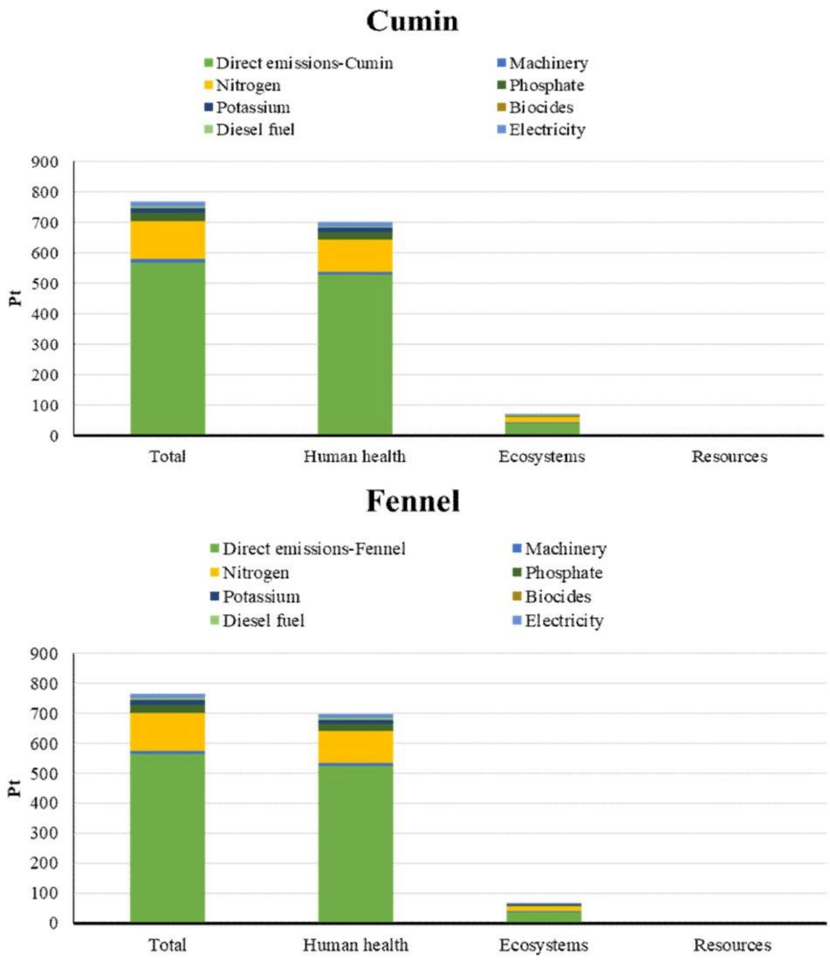


Figure 4. Weighting results of the damage categories in cumin and fennel production.

Conclusions

The production of medicinal plants was investigated in terms of energy flow management and environmental effects. Information related to life cycle audits and energy consumption was extracted from the sample through questionnaires and face-to-face interviews. The results showed that the total energy consumption of fennel and cumin was 34814.81 MJ ha^{-1} and 26214.17 MJ ha^{-1}, respectively. Also, the LCA results showed that the human health category had more environmental emissions than the ecosystem and resource categories. As a result, the production of medicinal plants with the use of chemical fertilizers and no field management endangers human health. The suggestions in this study emphasize the need to reduce the use of chemical fertilizers, diesel fuel, and consumed electricity to cut down the environmental burdens in the production process. Hence, we suggest use of the renewable energy for the involved processes in the production of medicinal plants.

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