applied sciences

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Life Cycle Assessment for Environmental Impact Reduction and Evaluation of the Energy Indices in Lettuce Production

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Abstract: Since the supply of basic needs, especially food, is among the strategic priorities of each country and conventional food production methods no longer suffice, food production methods are now transforming into industrial approaches. Industrialization, however, requires higher energy usage. Greater energy demand brings about the issue of energy sustainability. In particular, the depletion of fossil fuels results in serious challenges in food production processes. On the other hand, the utilization of energy carriers is accompanied by environmental contamination. In this regard, evaluating energy consumption and environmental pollution in the production systems can be a proper approach to finding the energy consumption and pollution centers for presenting applicable solutions to decrease pollution. In this study, energy indices of ER, EP, SE, and NEG were assessed to evaluate the energy consumption of lettuce production. The results showed values of 0.4, 17.28 kg/MJ, 0.06 MJ/kg, and 29,922 MG/ha for ER, EP, SE, and NEG, respectively. Among the consumption inputs, diesel fuel and nitrogen fertilizer had the highest consumption rate. Pollutants were also explored by the life cycle assessment method. Accordingly, chemicals and agricultural machinery led to the highest contaminating emissions. To reduce environmental contaminants, lowering the application of chemical pesticides, using biological approaches to combat pests, determining the proper amount of chemical fertilizers, using animal fertilizers, and using the proper agricultural machines should be considered.

Keywords: energy; environmental contamination; lettuce; life cycle assessment

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Citation: Mousavi, A.; Aghbolaghi, E.A.; Khorramifar, A.; Gancarz, M.; Darvishi, Y.; Stasiak, M.; Miernik, A.; Karami, H. Life Cycle Assessment for Environmental Impact Reduction and Evaluation of the Energy Indices in Lettuce Production. *Appl. Sci.* **2022**, *12*, 10348. https://doi.org/10.3390/app122010348

Academic Editor: Stefano Loppi

Received: 13 September 2022
Accepted: 11 October 2022
Published: 14 October 2022

1. Introduction

Pressing problems have arisen in meeting basic human needs, including food, due to the daily increase in population, urban growth, and the reality of public welfare. Existing resources cannot meet the needs of people today [1,2]. Advanced agricultural approaches have been developed to meet that urgent need [1,2]. Food production processes are industrialized because traditional methods can no longer produce enough food [3,4]. Industrialization, however, requires higher levels of the limited resources of currently available energy [5,6]. This raises the issue of energy non-sustainability, especially fossil fuels, posing a serious challenge for food production processes [7,8]. Until renewable energy is better utilized, attention should be paid to energy efficiency in the production process [9,10]. In addition to higher energy consumption, reducing energy efficiency will lead to a higher energy loss from the production cycle, thereby contributing to global warming. An increase in energy efficiency can help to reduce the dire environmental consequences; it can promote the goals of sustainable agriculture. Therefore, proper use of energy in agriculture and breeding can result in sustainable production, cost-effectiveness, and slower depletion of fossil fuel sources while preventing air pollution [11]. Management of energy consumption is the only approach to this goal. One of the methods of energy management involves the analysis of energy consumption and the determination of the energy consumption indices [10,12]. Additionally, determining the emission of environmental pollutants per energy consumption can be an analytical tool to calculate the pollution induced by energy consumption, along with the energy consumption-related analysis [8,13]. There is a lack of literature on the management of energy consumption in lettuce production; thus, it will be discussed in this research.

Environmental indicators, as one of the sustainability criteria in various production and service activities, are of interest to researchers. One of the limitations of considering inputs in the agricultural sector is the release of various pollutants that have negative effects on the environment. Numerous studies on the determination of agricultural energy inputs and outputs and environmental pollution highlight the significance of this issue in agriculture and its subunits regarding agricultural strategies [14]. In the following paragraph, some of these studies are mentioned. Moraditochaee [15] evaluated the energy indices of cultivating tobacco under dryland farming in the north of Iran. They obtained a mean yield of 1112 kg/ha, corresponding to an energy input of 890 MJ/ha. The energy efficiency (the ratio of output energy to input energy) was determined as 0.03, indicating the inefficient use of energy in the tobacco production system. The share of nonrenewable energy in the total input energy was 94.09%. They finally concluded that tobacco production requires a modification of the energy consumption and application of renewable energies. Abeliotis et al. [16] addressed the life cycle assessment of different bean varieties in Greece. After evaluation based on product volume (kg), it was established that varieties with higher input requirements have higher yields and less environmental impact. Bartzas et al. [17] explored the life cycle assessment of lettuce production in Spain and Italy. They showed that the use of compost could be a proper strategy to maintain efficiency and increase sustainability in the agricultural sector. Additionally, compost production, irrigation systems, and greenhouse construction and maintenance were recognized as three steps with the highest energy consumption and environmental pollution. In this study, the energy and environmental indices of lettuce production will be assessed in Karaj, Iran.

The interest of communities in agriculture and sustainable foods is growing, which will increase the demand (from farmers, policymakers, agricultural jobs, media, public suppliers, and consumers) for information about the environmental performance of the agricultural systems, food chain, and food products [18,19].

Production of nutritious foods for humans and animals and economic development of the benefit-holders are among the main objectives of agriculture [20,21]. These goals can remarkably affect economic growth, such that the publications in bio-economics rose from 1000 papers in 2017 to about 3500 in 2021 [22].

Life cycle assessment (LCA) is a method to evaluate the environmental sustainability during the life cycle of a product which has been standardized by ISO 14040 and 14044 [23,24]. Energy and material flows, as well as environmental releases, are quantified and converted into environmental consequences. The LCA method includes four different steps (Figure 1) [25]:

- Goal and scope definition: This step defines the boundaries of the system and functional unit and establishes some of the assumptions made.
- Life cycle inventory (LCI): This step includes data collection (inputs, intermediate processes, and outputs).
- Life cycle impact assessment (LCIA): This step interprets the potential environmental effects such as acidification, global warming, ozone layer destruction, and ecotoxicity.

- Interpretation: LCI and LCIA results are summarized in this step. The critical points are identified and analyzed. Conclusions and recommendations are also presented for the future.

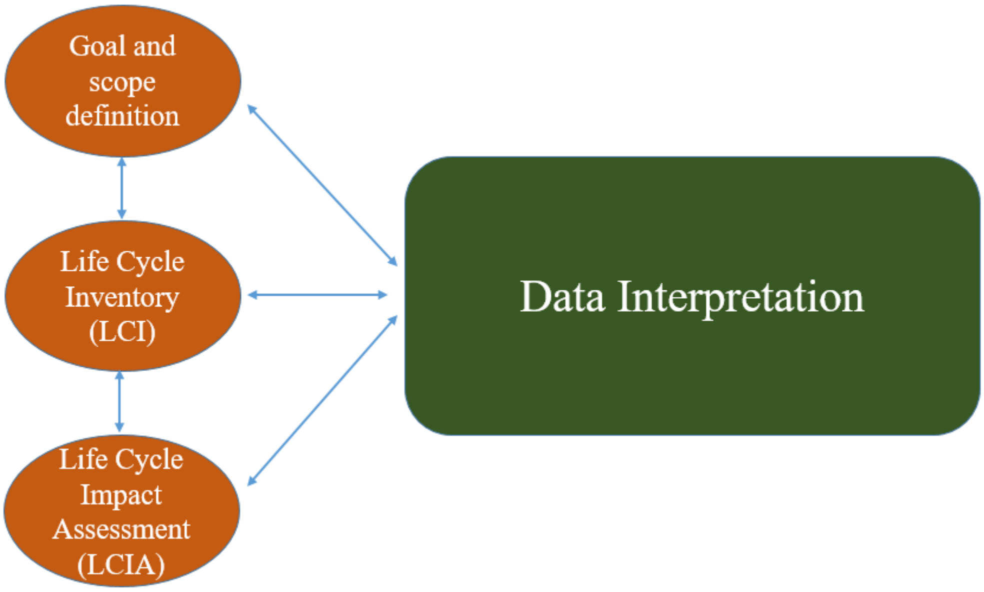

Figure 1. The framework of the life cycle assessment (LCA).

Today, LCA is the major method in the European Union's (EU's) development of a harmonized methodology for the determination of the environmental footprint of products (PEF), including several food classes [26].

Climate change, the consequences of the extraction of fossil fuels, the depletion of resources, and energy shortages are the most significant environmental concerns throughout the world. These concerns should be considered in addition to the current challenges in discovering renewable energy solutions [27].

The purpose of the present study was to evaluate the life cycle of lettuce production and estimate the extent of various environmental effects on the production process.

2. Materials and Methods

The required information for this study was collected by filling out the questionnaires at lettuce farms by the researcher. Local experts in the ministry of agriculture were also interviewed to obtain their opinion on the conditions and issues associated with lettuce cultivation. The equation proposed by Cochran (Equation (1)) was utilized to determine the sample size [28]:

$$n = N(S^*t)^2/((N-1)d^2 + (S^*t)^2) \tag{1}$$

2.1. Evaluation of Energy Indices

The energy ratio (ER), energy productivity (EP), specific energy (SE), and neat energy (NEG) were calculated by Equations (2)–(5) employing the energy-equivalent inputs and outputs (Table 1) [29].

$$ER = E_{out}\ E_{in} \tag{2}$$

$$EP = Y/E_{in} \tag{3}$$

$$SE = E_{in}/Y \tag{4}$$

$$NEG = E_{out} - E_{in} \tag{5}$$

In the above equations, E_{out} represents the output energy (MJ/ha), E_{in} (MJ/ha), and Y (kg/ha) represent the input energy and product yield, respectively. ER is a dimensionless value, while EP, SE, and NEG were reported in kg/ha, MJ/kg, and MJ/ha, respectively.

Table 1. All the energy value inputs and outputs in lettuce production.

Input and Output	Unit	Energy Equivalent (Megajoules per Unit)	Source
		Inputs	
Labor	H	1.96	Mobtaker, et al. [30]
Machines	Kg	142.7	Pimentel, et al. [31]
Diesel	L	56.31	Nabavi-Pelesaraei, et al. [32]
Electricity	kWh	12	Albright and de Villiers [33]
Nitrogen	Kg	66.14	Mousavi-Avval, et al. [34]
Phosphorous	Kg	12.44	Unakitan, et al. [35]
Potassium	Kg	11.15	Pahlavan, et al. [36]
Pesticide	Kg	120	Kitani [37]
Seeds	Kg	16.7	Albright and de Villiers [33]
		Output	
Lettuce	Kg	0.7	Razavinia, et al. [38]

The required energy for agricultural activities can be classified into direct and indirect groups. In this research, direct energy includes the labor force, electricity, and diesel fuel, while seeds, fertilizers, pesticides, and machines are classified as indirect energies. Energy can also be categorized into two types (renewable and nonrenewable). While diesel, fertilizers, pesticides, electricity, and agricultural machines are nonrenewable energies, the human workforce and seeds can be regarded as renewable energies [29].

2.2. Life Cycle Assessment

Life cycle assessment follows the trend presented in the ISO 14044 standard [24]. LCA includes four stages: goal and scope definition, life cycle inventory, evaluation of the consequences, and interpretation of the results. The goal and scope definition discusses how (scope) and why (goals) an LCA is carried out. The goal definition determines the benefits of the study; the scope determination copes with the description of the studied functional unit, production system and its boundaries, data collection and processing, and the environmental consequences. The inventory step examines the natural sources and other inputs of the system, as well as pollutant emissions and the other outputs of the process. The consequence evaluation step involves the presentation of the natural sources and environmental emission inputs in terms of their contribution to the intended sector. The results of the previous steps are finally interpreted in the last step [39].

The functional unit is a key concept in LCA studies; it enables the comparison of various products and services (ISO, 2006). The functional unit of the present research is based on mass and is determined as the production of one ton of lettuce within one agricultural year.

Selection of the system boundaries is one of the prominent and essential steps in goal and scope determination. Determination of the boundaries of the research is essential for a more precise calculation of the emission due to the consumption of the farm or after harvesting and exiting the farm during the processing steps [40]. LCA is an insight from start to finish, but it is possible to consider the system boundary as a part of the total system for more focus on the processes. In this way, the results are expressed based on their selected boundaries on a smaller scale [38]. In this study, the farm gate was taken as the system boundary. The boundary of the system is shown in Figure 2.

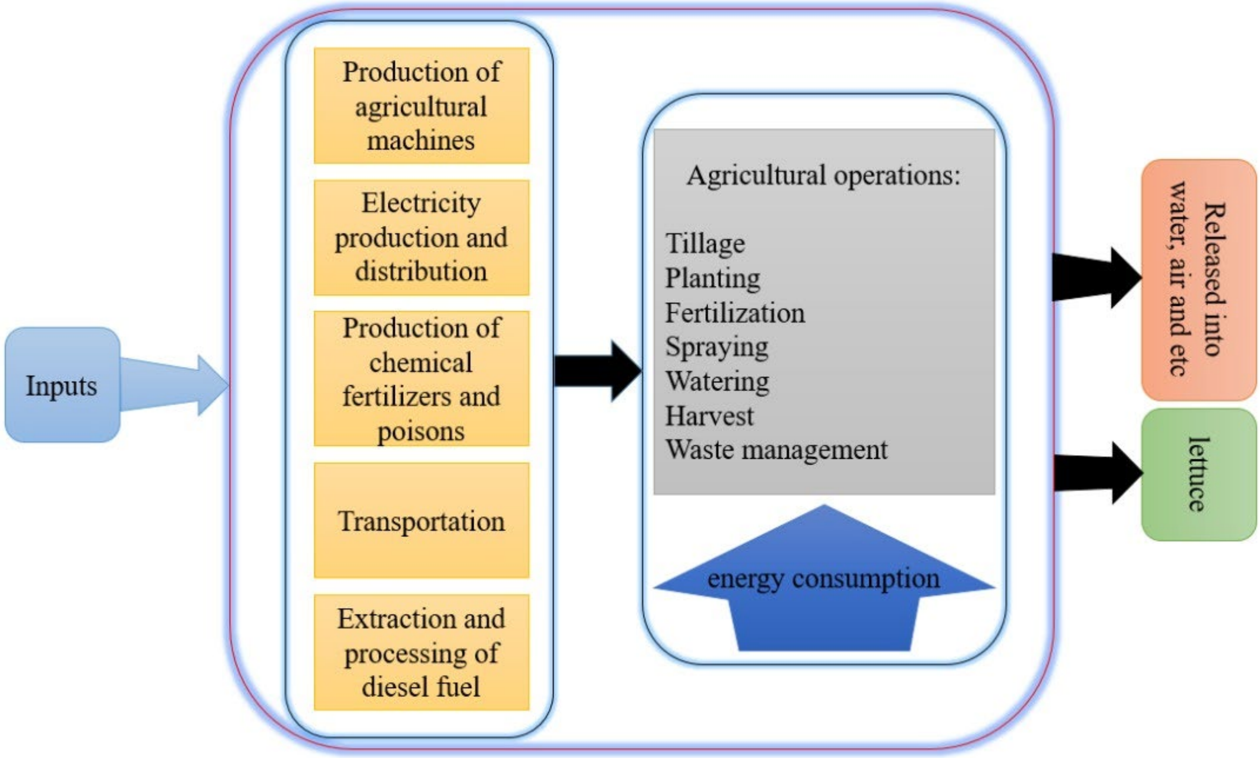

Figure 2. The boundary of the lettuce production system in the field.

Table 2 lists the impact categories of this study. The environmental consequences of lettuce production were analyzed based on the CML 2 baseline 2000 (Pere 2013).

Table 2. Impact categories and unit of measurement of each section.

Impact Categories	Symbol	Unit of Measurement
Reduction of inorganic substance	AD	kg Sb eq
Acidification	AC	kg SO_2 eq
Eutrophication	EU	kg $PO_4{}^{3-}$ eq
Global warming	GW	kg CO_2 eq [a]
Ozone layer defect	OD	kg CFC-11 eq
Human toxicity	HT	kg 1,4-DCB eq [b]
Surface water toxicity	FAET	kg 1,4-DCB eq [b]
Free water toxicity	MAET	kg 1,4-DCB eq [b]
Soil toxicity	TE	kg 1,4-DCB eq [b]
Phytochemical oxidation	PhO	kg C_2H_4 eq

[a] Considering 100 years. [b] DCB = dichlorobenzene.

Data used to assess the environmental impact of a production process are divided into two categories: data related to farm operations and data related to the production of inputs used. The data relating to farm operations are the energy assessment data collected by completing the questionnaire. The data associated with producing consumable inputs were also obtained from the databases available in the SimaPro life cycle assessment software.

3. Results

Table 3 summarizes the average amount of energy consumed and produced on lettuce farms. As seen below, diesel fuel and nitrogen, with approximate values of 38 and 24%, respectively, had the highest rate of consumption, while the labor force and seeds possessed the lowest energy consumptions, with contributions below 1%.

Table 3. Amount and percentage of input and output energies in lettuce production.

Input and Output	Energy	Percentage
Labor force	452.76	0.9
Agricultural machines	5708	11.37
Diesel	19,145.4	38.14
Electricity	8400	16.74
Nitrogen	11,905.2	23.72
Phosphorous	1007.64	2.01
Potassium	903.15	1.8
Chemical pesticides	2664	5.31
Seeds	5.01	0.01
Lettuce	20,269.2	100

Table 4 presents the energy indices and their contribution to lettuce production. The ER was 0.4, leading to the negative value for the NEG, indicating the low energy consumption efficiency in lettuce production. The share of direct energy in lettuce production is equal to 55%, and the share of indirect energy is equal to 45%.

Table 4. Indicators and classification of energy types.

Index or Type of Energy	Unit	Average Value	Percent
Energy ratio	-	0.4	-
Energy productivity	kg/MJ	17.28	-
Specific energy	MJ/kg	0.06	-
NEG	MJ/ha	−29,922	-
Direct energy	MJ/ha	27,998.16	55.78
Indirect energy	MJ/ha	22,193	44.22
Renewable energy	MJ/ha	457.77	0.91
Nonrenewable energy	MJ/ha	49,733.39	99.09

The environmental consequences of lettuce production were also analyzed in the region, and the results were reported for each impact category for one ton of lettuce in Table 5. The contribution of each consumption input is depicted in Figure 3 for the impact categories. One of the most important parts of the effect investigated in this study is the global warming potential. Global warming potential is a way to express the share of gases released from agricultural systems. In this study, the amount of global warming potential per ton of produced product is estimated to equal 96.01 kg of carbon dioxide equivalent. As can be seen when comparing the sections of the eutrophication effect, acidification, soil toxicity, surface water toxicity, and the global warming potential of pollution caused by direct farm emissions (caused by burning diesel fuel, using chemical and organic fertilizers, atmospheric decomposition of fertilizers, mixing product residues with soil, using chemical poisons, and human breathing) the latter had the largest values of the mentioned indicators. With respect to the effect of reducing inorganic substances, the most impact is related to the process of diesel fuel and nitrogen fertilizer. In terms of the effect of the ozone layer defect, the biggest effect is related to the pesticides. In the areas of human toxicity and surface water toxicity, the production process of pesticides and the use of agricultural machinery in the farm has the greatest effect. In the field of photochemical oxidation, the greatest effect is related to pesticides, nitrogen fertilizer and agricultural machinery.

Table 5. Life cycle evaluation indicators in lettuce production.

Impact Categories	Unit	Estimated Value
Reduction of inorganic substances	kg Sb eq	0.64
Acidification	kg SO_2 eq	0.37
Eutrophication	kg $PO_4{}^{3-}$ eq	0.07
Global warming	kg CO_2 eq	96.01
Ozone layer defect	kg CFC-11 eq	2.47×10^{-5}
Human toxicity	kg 1,4-DCB eq	31.51
Surface water toxicity	kg 1,4-DCB eq	5.6
Free water toxicity	kg 1,4-DCB eq	13,795.21
Soil toxicity	kg 1,4-DCB eq	0.08
Phytochemical oxidation	kg C_2H_4 eq	0.02

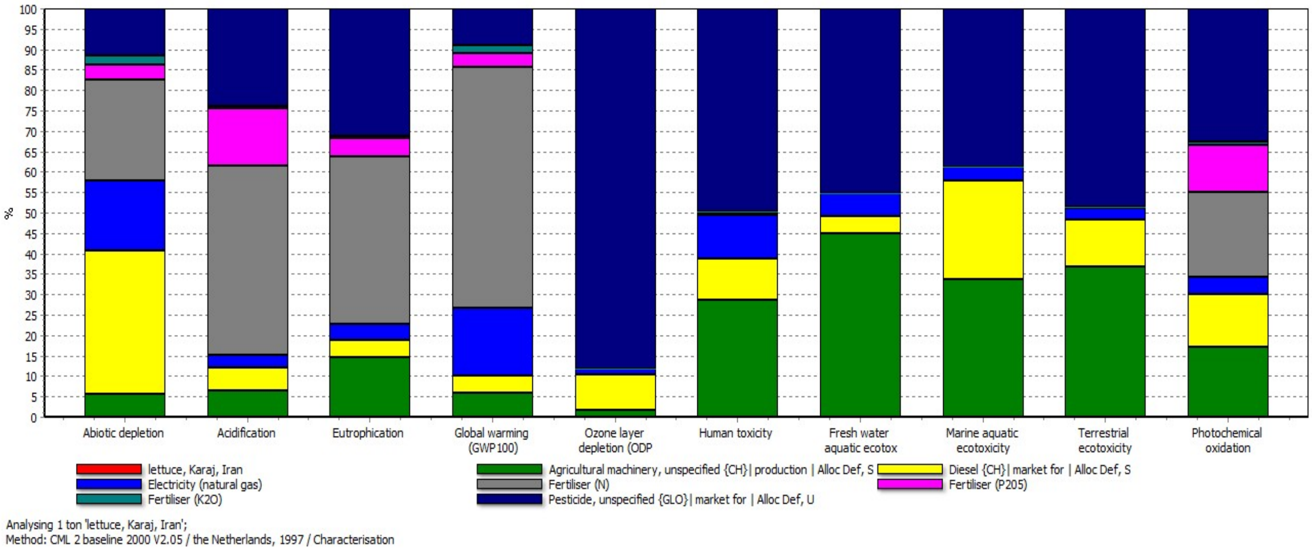

Figure 3. The share of consumption inputs in each of the sections of the studied work.

In terms of acidification, eutrophication, and global warming, nitrogen fertilizer had the highest impact. For the rest of the categories, the chemical pesticides had the highest pollution. After chemical pesticides, agricultural machines had the highest pollution for the impact categories of human toxicity, surface water toxicity, free water toxicity, soil toxicity, and phytochemical oxidation.

Each impact category had different units of measurement, making it impossible to compare their significance. Therefore, the impact categories were normalized to reach similar units of measurement, making their comparison possible, even for non-experts. The normalization results can be found in Figure 4. As seen, the environmental toxicity effect of marine aquatics with a normal value of 4.4×10^{-9} had the highest environmental load in lettuce production. For this category, the chemical pesticides had the highest pollution. After chemical pesticides, agricultural machines and diesel fuel had the next highest pollution contribution.

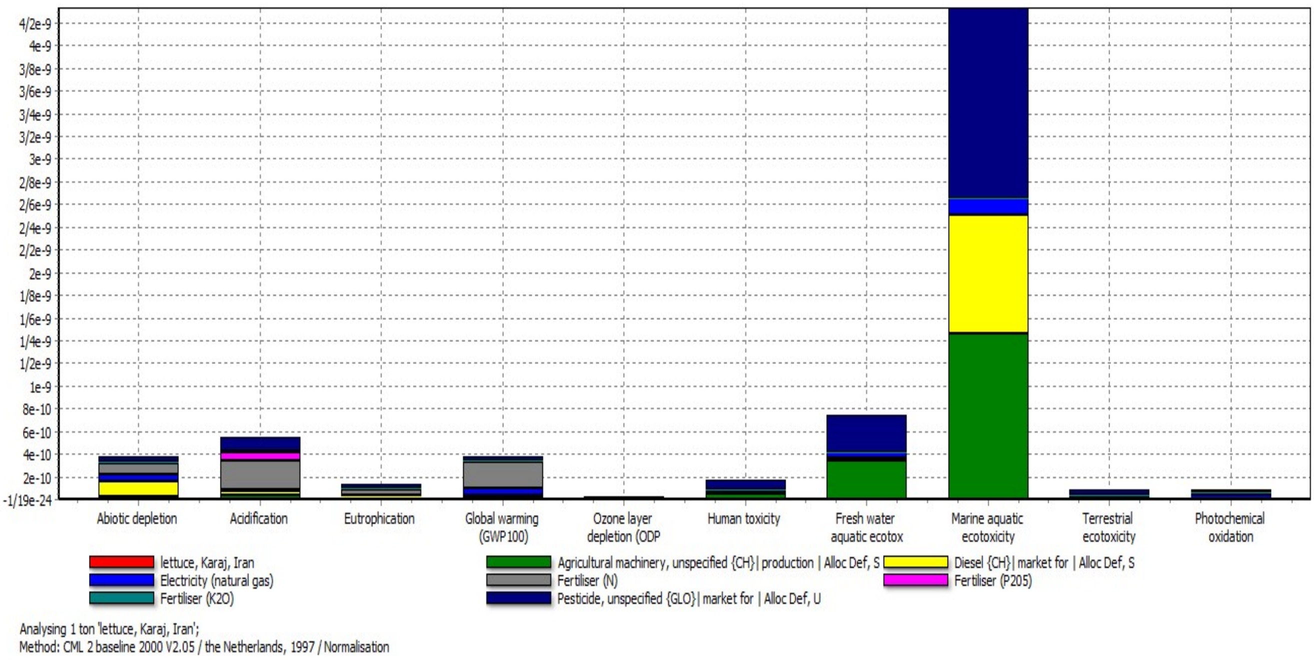

Figure 4. Parts of the normalized effect in lettuce production.

4. Discussion

This study was carried out in the Alborz province to evaluate the energy consumption and environmental pollution of lettuce production. The total energy consumption for lettuce production was 50,191.16 MJ/ha while the output energy of this system was 20,269.2 MJ/ha. The calculated energy indices indicated that lettuce production is not efficient. On the other hand, diesel fuel and chemical fertilizers had the highest energy consumption. Therefore, avoiding the use of old machines (to lower fuel consumption) and the use of the proper amount of chemical fertilizers can improve lettuce production. The share of nonrenewable energies in the production of lettuce was above 99%. The use of animal waste and green fertilizers can preserve soil fertility while decrementing environmental pollution. Razavinia, Fallah and Niknejad [38] explored the energy consumption for lettuce production in the Mazandaran province of Iran and declared that the highest energy consumption was for diesel fuel (47%). In one recent study (2018), researchers stated that the main processes are responsible for 51% of GW potential and almost entirely responsible for abiotic discharge (99%); both are related to the use of fossil fuels during a jam-production process [41]. For the research that Anthony Rouault et al. (2020) performed in the grape industry, they concluded that, for freshwater ecotoxicity and terrestrial ecotoxicity, an important contribution to the effects was related to the release of pesticides into the environment, and that was one of the reasons it was considered as fuel consumption. Finally, due to fuel consumption, mechanical operations also had a very important contribution to several impact categories, including: ozone depletion, climate change, particulate matter formation, and photochemical oxidant formation [42]. Grapes are one of the most important agricultural products around the world, which have been widely researched [43,44].

The ER in the production of processed products, such as bread and sugar, have higher values (0.52) [45]. The EP was 17.28 kg/MJ, suggesting the production of 17.28 kg product when consuming one MJ of energy. The SE (0.06) showed an inverse relationship with the EP, in the research results of Dekamin et al. [46], who reported energy efficiency in the production of coriander seeds as 0.06. Table 4 also indicates that about 56% of the consumed energy is direct, while 44% of that is indirect. The contribution of renewable energy is below 1%, so nonrenewable energy accounts for more than 99% of the consumed energy. Pourmehdi and Kheiralipour [47] reported the share of renewable energy in the production of wheat flour as 99.19%, and so the amount of indirect and renewable energy was far more than nonrenewable and direct energy.

It should be noted that in this study and other similar studies that are conducted with the approach of evaluating the life cycle of plant products, only the release of pollutants is examined, although plants can also absorb environmental pollutants. For example, plants absorb a great deal of carbon dioxide during their growth period, so the amount of carbon dioxide absorbed by the plant may be greater than its emission. The noteworthy point is that the agricultural sector is not the only emitter of this gas but it is the only absorber of this gas. In other words, plants have the ability to balance carbon in nature; therefore, due to the large volume of carbon dioxide emission from other sectors, the emission of pollutants in the agricultural sector should be minimized so that plants can establish a carbon balance.

5. Conclusions

The environmental consequences of lettuce production were explored by life cycle assessment; the results indicated that the highest contribution to emissions was from chemical pesticides and agricultural machines. Also, the toxicity of surface water, acidification, global warming, and abiotic depletion, respectively, have the largest contributions to the release of pollutants in lettuce production. Therefore, lower amounts of chemical fertilizers should be employed through the use of biological approaches in the combat against pests. Determining the correct amount of chemical fertilizers and the use of animal fertilizers and proper machinery should also be considered.

Author Contributions: Conceptualization, H.K. and A.K.; methodology, H.K.; software, A.M. (Ali Mousavi) and E.A.A.; validation, H.K., Y.D. and M.G.; formal analysis, A.K. and Y.D.; investigation, H.K.; resources, H.K.; data curation, H.K. and M.G.; writing—original draft preparation, A.K., A.M. (Ali Mousavi) and E.A.A.; writing—review and editing, H.K., M.S., A.M. (Anna Miernik) and Y.D.; visualization, M.G.; supervision, H.K.; project administration, H.K..; funding acquisition, M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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