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Title:

Exergoenvironmental damage assessment of horticultural crops using ReCiPe2016 and cumulative exergy demand frameworks

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Abstract

Horticultural inputs have various potential environmental impacts, which can be simultaneously evaluated by using the life cycle assessment (LCA) method. It is considered an appropriate evaluation tool to analyze ecosystems through recognizing, quantifying, and appraising resources depleted and released within the environment. Accordingly, in this work, environmental damages of horticultural crops are evaluated by using LCA technique and CExD analysis under different cropping systems including citrus, hazelnut, kiwifruit, tea, and watermelon in Guilan Province of Iran. By applying LCA method and ReCiPe2016, three environmental indicators including human health, ecosystem and resources of the horticultural crops are determined. Functional unit is considered as 10 ton of horticultural crops yield. From the environmental viewpoint, On-Orchard emission and nitrogen fertilizer have the highest emissions in all systems, whilst more pollution is generated in hazelnut production than those in other horticultural crops. Results in CExD show that, amongst all studied horticultural crops, the hazelnut production entails higher energy amount. A comparison of environmental impacts and energy forms show that citrus production is the best, owing to the lowest values of emissions among horticultural productions. As such, this crop is suggested for horticultural crop cultivation. Generally, it can be concluded that modeling of citrus cropping system for other crops, utilization of organic fertilizers, replacement of worn out equipment and improvement of irrigation system can attain more sustainable horticultural production.

Keywords: Cumulative exergy demand, Environmental damage, Life cycle assessment, Horticultural crop, ReCiPe2016

1. Introduction

In recent years, horticulture has gained higher significance amongst agriculture globally [1,2]. Being a significant sector of Iran dietary system, horticulture, particularly for growing vegetables and fruits, is furnished new impetus for their development [3]. In this research, studied products together with their associated statistics are detailed as follows.

A genus of flowering trees is citrus and shrubs in the rue family, *Rutaceae*. Those plants which are in this genus generate citrus fruits comprising momentous crops like lemons, oranges, limes and grapefruits [4]. The production of citrus in Iran was 26561 hectare (ha), and the average yield was about 23165.2 kilogram (kg) ha^{-1} in 2017 [5]. Hazelnut is the nut of hazel and accordingly contains nuts coming from species of *Corylus genus*, particularly nuts related to *Corylus avellana* species. The production of hazelnut in Iran was 17589 ha, and the average yield was about 889.5 kg ha^{-1} in 2017 [5]. Kiwifruit is a great source of vitamin C according to food statistics. This nutritious fruit is a primitive antioxidant, which is soluble in water within our body. It neutralizes free radicals, which can result in cell damages and cause difficulties like inflammation and cancer. The production of kiwifruit in Iran was 10771 ha, and the average yield was about 28903.4 kg ha^{-1} in 2017 [5]. Tea is a kind of drink, which has aromatic compounds and is usually gotten ready via adding boiling water to its leaves. Tea is native to East Asia and is an evergreen shrub. Tea is the second most popular drink in the world, just after water. Various kinds of tea are available in the world. Chinese greens and Darjeeling that have a cooling, faintly bitter and astringent taste whereas others have widely various profiles, including sweet, nutty, flowery or grassy characteristics [6]. The production of tea in Iran was 15848 ha, and the average yield was about 6346.5 kg ha^{-1} in 2017 [5]. Watermelon (*Citrullus lanatus*) is a kind of scrambling and trailing vine plant, which belongs to flowering plant family of *Cucurbitaceae*. It was thought for a long time that the species were originated from southern

Africa [7]. The production of watermelon in Iran was 136190 ha, and the average yield was about 29809.6 kg ha^{-1} in 2017 [5].

There have been increased studies on environmental impacts caused by different agricultural activities in soil, water and weather [8]. Agricultural emissions strongly contribute to fine particulate matter pollution and associated effects on human health [9]. Life cycle assessment (LCA) is considered a worthwhile decision-support method, which is helpful for industry as well as policy makers in evaluating cradle-to-grave effects of a product [10]. It can also be applied for evaluating sustainability of different systems [11]. LCA, as an environmental management tool, is generally used to evaluate all indirect as well as direct greenhouse gas emissions of production systems [12]. There are three forcing factors that are compelling this assessment. Firstly, government rules are taking action in the direction of life-cycle responsibility, and the idea is that a producer is in charge of not only for direct impacts of a production, but also for those impacts that are connected with the usage of a product, its inputs, transport and access. Secondly, business is taking part in voluntary initiatives that include LCA and product management constituents [13]. Thirdly, environmental preference has appeared as a standard in consumer bazaars and also government preparation guidance [14]. These progresses have located LCA in a central role as a tool for recognizing cradle-to-grave effects for both products and substances from which they are built [15].

Cumulative exergy demand (CExD) is a gadget significant in this investigation. It denotes the simulated energy use for specific production methods. It integrates system features and related emissions since it is dependent on the status of system and also environment [16]. In fact, CExD has been considered as one of the best methods to reduce exergy. A cycle's exergy destruction denotes the summation of exergy destruction in all processes constituting the cycle [17]. For ascertaining the exergy destruction of a cycle, a specific exergy destruction equation is employed and the whole cycle is recognized as a single process [18]. To date, several studies have been undertaken to compute environmental impacts and CExD by LCA approach. Table 1 shows some of these studies in agricultural and horticultural crop production.

Table 1

In the literature, no report has been made on LCA application for horticultural crops in Guilan Province. Since this province is an important area for producing horticultural crops in Iran, a comprehensive investigation of energy, environmental life cycle assessment (LCA) and cumulative exergy demand in different horticultural systems is considered as a main purpose of this study. To attain this objective, the following evaluation phases is implemented:

- Analysis of environmental impacts and evaluation of CExD analysis for the mentioned horticultural crops.
- Selection of hotspots from inputs to manage and mitigate environmental impacts and CExD for horticultural crops.
- Comparison of environmental impact categories and attained CExD with computed LCA.
- Determination of the best crop with respect to the least amount of contamination and exergy use from production processes in horticultural crops.

2. Materials and Methods

2.1. Data Gleaning and Case Study and

Guilan Province at northern Iran is chosen for data collection in this research. Guilan is located at longitudes and latitudes between 48° 53′and 50° 34′ E and between 36° 34′and 38° 27′ N, respectively [52]. Fig. 1 shows the location of the studied region.

Fig. 1

Cochran method is used to compute sampling size in this study [53]. The sampling size of each crop is demonstrated in Table 2. Then, primary data, including planting land used by orchardists, all agricultural input variables (amounts of chemical fertilizer, biocides, etc.), yield of horticultural crops, machineries and equipment, etc. are collected at random for horticultural crops (hazelnut, citrus, tea, kiwifruit and watermelon).

Table 2

2.2. LCA Approach

LCA is a cradle-to-grave approach for evaluating processes, products, industrial systems and so on. LCA facilitates the assessment of accumulative environmental impacts resulted from all steps in the product's life cycle to direct an environmentally more desirable way or process [55].

2.2.1. Scope, Goal and Definition Statement

The target definition is a statement created via an organization (like industry or trade groups, companies, environmental offices) commissioning LCA. Product system contains, above all, functions of the systems as a basis to define functional unit (FU). Another significant stage in LCA is to define system boundaries. The accessibility of data and quality are substantial matters in life cycle inventory (LCI) analysis [56].

All environmental impacts are computed for producing 10 ton (t) of horticultural crops as FU. System boundaries for cultivating different horticultural crops in the present study are defined in Fig. 2.

Fig. 2

2.2.2. LCI

LCI analysis entails making flow inventory of a product. It contains energy, inputs, crude substances and releases to air, water and land. The system's flow model is made by applying pertinent output and input data. Output and input data required for building the model are gleaned for all activities inside system boundaries [57]. LCI is divided two categories, namely, On-Orchard emissions and Off-Orchard emissions, for life cycle of horticultural crop production, which are described as follows.

Indirect emissions or Off-Orchard emissions cover environmental damages of production process for each input that is applied in the farming system. In this study, inputs of the system comprise utilization of agricultural machinery, lubricating oil, fertilizers, biocides, diesel fuel, and electricity. Moreover, outputs of the system consist of horticultural crops (hazelnut, citrus, tea, kiwifruit and watermelon). On the other hand, direct or On-Orchard emissions include emission factors related to direct use of inputs in the orchard for production process of horticultural crops. Several categories are considered for On-Orchard emission computation in the present research. The mostly used agricultural machineries are tillers and tractors, which are used for orchard operations like spraying, fertilization and plowing. Diesel fuel combustion in the mentioned operations cause several emission factors to air and soil and their quantities are obtained from standard coefficient of EcoInvent®3.6 [58], as demonstrated in Table 3.

Table 3

Other On-Orchard emissions include the emissions related to chemical fertilizer usage to air and water, human labor activity to air, and biocide application to air, water and soil. All of them are computed by multiplying related input amounts with their equivalent coefficients; which are shown in Table 4.

Table 4

In this research, PestLCI 2.0 model is used for the computation of biocides emissions related to air and water. It is an inventory model tailored to compute pesticide, herbicide and fungicide emissions from the environment (ecosphere) to arable land (technosphere) for use in life cycle impact assessment (LCIA) modeling [63].

Applications of FYM and chemical fertilizers for improving the soil in horticultural production will cause direct emissions of heavy metals to the soil. Amounts of soil emissions are computed by multiplying amounts of inputs for chemical fertilizers and FYM with emission coefficients [64], which are shown in Table 5.

Table 5

2.3. LCIA

LCIA recognizes and assesses the value and importance of potential environmental impacts caused by LCI. Inputs and outputs are classified into appropriate impact categories. According to the characterization factors, their potential impacts are then determined [65].

During the stage in defining the scope of a study, some elements are described for LCIA [14]. Choosing pertinent characterization, classification and impact categories are some mandatory elements. Weighting, grouping and normalization are optional elements of a study [66].

In this study, ReCiPe2016 is applied. The purpose of this evaluation is the analysis of outputs and inputs of horticultural crop production. In the inventory, impacts are analyzed through various impact categories and then damage evaluation is measured in terms of human health, ecosystems and resource categories [67].

2.3.1. ReCiPe2016 Method

Several models are available for different impact categories, especially in the use of water and land, formation of photochemical ozone and creation of fine particulate matter. Herein, models are practically selected and ReCiPe2016, which is capable of integrating several impact categories, is adopted [67].

Since three protection areas, namely, human health, resource shortage and ecosystem quality, were chosen in ReCiPe2008 [68], these three areas of protection are retain for the execution in ReCiPe2016y. Endpoints cover three areas of protection. Disability adjusted life year (DALY), which is related to human health, express a period (in years) for a personal disability owing to an illness or incident or a period that are missed. The species year denotes a unit for ecosystem quality. The unit for resource scarcity is United States dollars for 2013 (USD2013) that demonstrates additional expenses associated with the extraction of prospective fossil and mineral resource [67].

Relationships among environmental mechanisms, endpoints, three areas of protection and 17 midpoint impact categories included in ReCiPe2016 are demonstrated in Fig. 3.

Fig. 3

2.4. CExD

CExD has been proposed to denote energetic quality of resources. A resources' exergy expresses the highest attainable amount of work or the minimum work that is essential to make the resource whilst turning the resources to their natural state [69]. The EcoInvent center [70] furnishes a method to enhance the CExD method for LCA. EcoInvent 2.2 databases provide the required additional data on this. Six impact categories of CExD, which are applied in this study, are shown in Fig. 4.

Fig. 4

In this study, Excel 2019 spreadsheet, Analytica 5.0 and SimaPro V.9.0.0 software are applied for statistical analysis, PestLCI 2.0 model evaluation, and exergoenvironmental damages appraisal, respectively.

3. Results

3.1. LCI Analysis

Amounts of different inputs required for producing horticultural crops in one hectare and used in LCA analysis are presented in Table 6. These inputs are known to have negative effects on environment. According to results among horticultural crops, hazelnut production consumes more inputs than other horticultural products.

Table 6 shows On-Orchard emissions in the process of horticultural crop production in one hectare under different systems. The highest amount of CO_2 gas released from diesel fuel is related to hazelnut production due to high consumption of diesel fuel in this system from land preparation to harvesting. The highest amount of nitrate emission from nitrogen consumption is related to hazelnut production. Besides, the highest levels of emissions of heavy metals from chemical fertilizers are associated with hazelnut production. Nikkhah et al. [71] investigated environmental impacts of peach cultivation in Iran and reported that high rates of On-Orchard emission were mainly related to diesel fuel and nitrogen fertilizer usage. In another study, Mohseni et al. [37] studied environmental impacts of grape production system and reported that grape production led to the release of 508.63 kg CO_2 t^{-1}.

Table 6

3.2. LCA of Horticultural Crops

In this section, results of environmental impacts are revealed based on ReCiPe2016 method of LCA for the mentioned horticultural crops production.

Table 7 shows effects of horticultural crop production on different damage categories. Amounts of human health damage category are computed as 0.01 DALY 10 t^{-1} for citrus, kiwifruit and watermelon and 0.05 and 0.02 DALY 10 t^{-1} for hazelnut and tea, respectively. Values of ecosystems damage category are computed as 1.73E-05, 1.37E-04, 2.36E-05, 6.09E-05, and 2.53E-05 for citrus, hazelnut, kiwifruit, tea and watermelon, respectively. Results indicate that the highest physical amount of resources damage category belongs to hazelnut with 717.33 USD2013 per 10 t yield. Moreover, the resource amounts for 10 t of citrus, kiwifruit, tea and watermelon are determined as 93.27, 128.68, 226.25, and 132.57 USD2013, respectively.

Table 7

Contributions of different inputs to the degradation rate for horticultural crop production are presented in Fig. 5. According to results, On-Orchard emissions and nitrogen fertilizers are two important factors with the highest contributions to the degradation related to environmental parameters in all crops. Analysis of human health reveal that the share of On-Orchard emissions is about 50% in all crops except tea, whose share is about 60%. Ecosystem category results illustrate that about 45%, 55%, 55%, 60%, and 50% emissions belong to citrus, hazelnut, kiwifruit, tea and watermelon, respectively. Moreover, the shares of nitrogen in human health and ecosystems are about 25%, 15%, 30%, 35%, and 40% for citrus, hazelnut, kiwifruit, tea and watermelon, respectively.

Fig. 5

As can be seen in Fig. 5, nitrogen and diesel fuel are the main hotspots of resource damage category in all crops. In hazelnut production, pesticides has the second rank, just after nitrogen in resource damage category. Details of the results indicate that the shares of On-Orchard emissions are about 35%, 25%, 50%, 85%, and 65% for citrus, hazelnut, kiwifruit, tea and watermelon, respectively.

Jefferies et al. [72] reported the use of LCA in tea production and showed that impact evaluation consequences of LCA for tea led to down-weight of water from Coonoor in consumer utilization step owing to higher water shortage. Sabzevari et al. [29] employed LCA analysis for hazelnut production. They showed that biocides were the main hotspot in eutrophication and agricultural machinery was the main hotspot in all impact categories. Mohammadi-Barsari et al. [30] studied carbon footmark for watermelon production and demonstrated that large percentages of GHG were generated by agricultural machinery and chemical fertilizer with 52.6% and 23.8% of entire GHG emissions, respectively. Kouchaki-Penchah et al. [34] employed LCA to ascertain environmental impacts in tea production. Nitrogen, diesel fuel and agricultural machinery were major hotspots in most impact categories according to consequences. Soheili-Fard et al. [36] studied the life cycle assessment of tea production in Iran. Their results showed that agricultural machinery and diesel fuel were the main hotspots in farm and factory, respectively.

3.3. CExD Analysis of Horticultural Crops

CExD results on energy forms for horticultural crop production are demonstrated in Table 8. Physical amounts of non-renewable fossil are the highest for all crops. Accordingly, quantities of non-renewable fossil are computed to be 11,114.46 MJ ha^{-1}, 76,471.72 MJ ha^{-1}, 15,229.94 MJ ha^{-1}, 30,778.69 MJ ha^{-1} and 15,633.80 MJ ha^{-1} for citrus, hazelnut, kiwifruit, tea and watermelon production, respectively. Mohseni et al. [37] reported that Renewable, water had the highest share in consumption than other energy resources in producing one ton of grape in Iran. Fig. 6 illustrates analysis of renewable and non-renewable resources utilized for the production of the mentioned horticultural crops based on each input share prospective. Based on the results, the most effective inputs in the consumption of energy forms are sorted in order from high to low as follows:

- Nitrogen, phosphate and potassium in citrus and kiwifruit production
- Nitrogen, fungicides and phosphate hazelnut production
- Nitrogen and phosphate in tea production
- Nitrogen, agricultural machinery and phosphate in watermelon production

Fig. 6

3.4. Selection of the Best Horticultural Crop

After having assessed damage categories and CExD analysis by using LCA technique for the production of horticultural crops (citrus, hazelnut, kiwifruit, tea, and watermelon) in Guilan Province of Iran and according to the analysis of results obtained from horticultural crops presented in this work, the best horticultural crop is selected as explained below.

3.4.1. Comparison of Endpoints among Horticultural Crops

Result comparison of weighted environmental impacts including human health, ecosystems, resources and total emissions of mentioned horticultural crop production are shown in Fig. 7. According to the results, total environmental impacts for hazelnut production are 840.87 Point (Pt), which generate the highest level of contamination amongst horticultural crops. Total environmental impacts for tea production are 400.21 Pt, which generates the second highest amount of pollutant, just following hazelnut production. Total environmental impacts for citrus production are 108.66 Pt, which is the least amount of contamination amongst all horticultural crops in this study. Therefore, after analyzing environmental effects of horticultural crops, citrus production is selected as the best horticultural crop.

Fig. 7

3.4.2. Comparison of Energy Forms among Horticultural Crops

Fig. 8 shows result comparison of CExD of the studied horticultural crops. According to the results of all horticultural crops, hazelnut production with 112283.31 MJ consumes more energy than other horticultural crops. Amongst all horticultural crops, the least amount of energy is 13455.84 MJ in citrus production. As such, in terms of CExD, citrus production is better than other horticultural crops.

Fig. 8

4. Discussion

4.1. Interpretation of Results

Based on the LCA results, On-Orchard emissions and nitrogen are the main effective inputs in environmental damage categories of all crops. Besides, one or two other inputs in some crops have significant shares in damages emissions. It should be noted that, despite similar patterns in the environmental damage distribution, the reasons behind the results are different with respect to the kind of crops. The detailed reasons are expanded as follows.

Citrus and kiwifruit: Urgent need to water for irrigation and using Rubin 2 inches water pump that is powered by diesel fuel cause the irregular usage of this fuel per t of yield. The consequence of this item not only brings high shares of On-Orchard emissions in human health and ecosystems but also an increased rate in resources damage category.

Hazelnut: The use of almost all effective inputs including diesel fuel, nitrogen, phosphate, pesticides and fungicides on the one hand and the low yield of hazelnut in northern Iran in comparison with the global standard on the other hand cause this product to become the most harmful horticulture crop in the studied area. Actually, the high rate of hazelnut in Iran makes a belief in orchardist that increasing inputs is equal to harvesting more yield. The lack of appropriate educational system, lack of input use pattern and supervision, lack of non-mechanized operations and lack of highly efficient varieties of hazelnut are the basic problems for the present environmental situation of this product.

Tea: The low price of nitrogen fertilizer and tea yield, utilization of manual method for fertilizing cause irregular usages of nitrogen fertilizers in this crop. Actually, applying mechanized methods and alternative sustainable cropping systems are not economical for orchardist in Guilan Province of Iran. Opening of imported gates for Indian tea and changing Iranian people's tastes to use them are the main effects for less demand of Iranian tea and finally, the low marginal price of tea. This issue not only brings low quality of Iranian tea from collective nitrate point of view, but also renders a high rate of environmental damages for this product.

Watermelon: Traditional agricultural systems of watermelon production are the main reason for the lowest diesel consumption in the production process. Accordingly, the highest share of On-Orchard emissions of watermelon belongs to a high consumption of nitrogen fertilizer. The lack of drainage systems and mechanized fertilizing operation for watermelon production is the main reason for applying irregular chemical fertilizers. Moreover, a high level of plant water requirement renders the irrigation the most important operation in watermelon production and consequently the increase of electricity use. This causes a significant share of electricity in resources damage category.

Based on CExD analysis, the distribution of energy forms reveals that chemical fertilizers and biocides are the main hotspots for horticultural cropping systems in Guilan Province of Iran. Actually, the existence of oil resources with a low price in Iran as the main country in extracting crude oil, their utilization in the production process of chemical fertilizers and biocides, and supplying electricity in power plants are the main reason for high rate of exergy consumption. On the other hand, the non-standard rate of these inputs causes more usage of non-renewable resources indirectly.

Generally, it can be said that the importance of citrus as a trading and strategic horticultural crop leads to applying an appropriate use of inputs with logical yield and finally, accomplishment of more exergoenvironmental friendly crop amongst all. On the other hand, unprofessional production of hazelnut with irregular input use and low yield cause inefficiency of this product from exergoenvironmental viewpoint.

4.2. Managerial Implications

With respect to above explanation, the solution can be divided into early and late return strategies to achieve more sustainability in horticultural crops:

I. Early return strategies:

- For the high rate of precipitation in the studied area, the establishment of water storage pools in appropriate positions can reduce the usage of water pumps, followed by diesel fuel and electricity specially in cirrus and kiwifruit production.
- Educational programs should be offered to orchardists for explanation of the advantages of appropriate input consumption. Although this item can be useful for all cropping systems, it is very necessary for hazelnut production.
- Soil texture testing should be performed to determine the required fertilizers to define standard input use pattern for all horticultural crops.
- Organic fertilizers should be used to reduce chemical fertilizers for enhancing soil and mitigating environmental pollutants and energy forms specially in tea and watermelon production.
- Efficient orchardists should be determined and then introduced as a pattern for demonstration to other units.

- Biological pest control should be applied to reduce biocide consumption, particularly for hazelnut crop.
- Appropriate schedules for maintenance of agricultural machinery should be determined to increase the efficiency.
- Mechanization level should be increased, especially in fertilizing operations of tea and watermelon productions.

II. Late return strategies:

- Plant breeding of hazelnut should be undertaken to obtain sustainable product with more yield.
- Appropriate policies for price control of chemical fertilizers and final products should be applied to balance demand and supply.
- Policies to use renewable energy resource such as tax exemption for orchardists should be encouraged.
- Old mechanized systems should be replaced with standard and efficient equipment, especially in water pumps. Low interest loans should be offered to orchardists on this.
- Input prices should be progressively increased with increasing inputs consumption, especially in diesel fuel and nitrogen.
- Import tariff should be increased especially for tea crop.

5. Conclusions

In this research, various damage categories of LCA are appraised and CExD is analyzed for different horticultural crops, including citrus, hazelnut, kiwifruit, tea and watermelon, in Guilan Province of Iran. According to results of the current work, shares of inputs and outputs vary in different horticultural crop productions. Amounts of inputs and outputs, orchard management practices, and input utilizations are significant causes for this dissimilarity. In LCA, three key indexes of environmental impacts, namely, human health, ecosystems and resources, are evaluated by ReCiPe2016 method for different horticultural crops. Results show that, among all studied horticultural crops, hazelnut and citrus productions have the highest and least amounts of emissions, respectively. In all examined horticultural crops, amounts of pollutants in On-Orchard emission and nitrogen fertilizer are very high. CExD results show that non-renewable, fossil has higher energy content than other energy forms in all investigated horticultural crops. The amount of energy forms in the production of hazelnut is more than those in other horticultural crops. Comparisons among horticultural crops show that, in total damage category, hazelnut production with total emissions of 840.87 Pt has the highest toxicity for living organisms, water and soil, while citrus production with total emissions of 108.66 Pt has the lowest toxicity index. Comparisons of total energy forms show that hazelnut production with 112283.31 MJ entails the highest amount of energy among different horticultural crops. Therefore, the general recommendations for horticultural crops are to select citrus production to mitigate environmental damages, to utilize more non-renewable energy, to apply organic fertilizers instead of chemical fertilizers, to employ modern methods and equipment for fertilizing and irrigation systems to reduce chemical fertilizers and diesel fuel in order to mitigate environmental pollutants and energy forms.

Detailed Response to Reviewers:

1. The text of the paper was examined in terms of the language structure of the English language and changes in the text were identified by tracked changes.

2. Thanks for your suggestion. We modified the Highlights according to your advice and added the main results. The changes in the text were identified by tracked changes as follows:

3. Thanks for your comment. The mentioned crops in this article were announced by Ministry of Jihad-e-Agriculture of Iran as horticultural crops. Moreover, in several papers, they were introduced as horticultural crops.

4. Thanks for your comment. With respect to all reviewers' suggestion, we removed the nomenclature table. Thus, we wrote the full name when it was mentioned in the first time after the "Introduction" and inserted the abbreviation in front of them. After that, we wrote only the abbreviation in the entire manuscript.

5. Thanks for your valuable suggestion. We modified the "Introduction" according to your advice and the changes were identified in the following track changes:

6. Thanks for your valuable suggestion. We added the mentioned references in … as the following tracked changes:

7. Thanks for your valuable comment. We modified the "Results and discussion" according to your advice and separated the results from the discussion to avoid any ambiguity. The changes were identified in the following tracked changes:

Highlights

- Horticultural crops are investigated from exergoenvironmental damages perspective by LCA.
- Hotspots of environmental burdens belong to On-Orchard emission and nitrogen.
- Hazelnut has the most total weighted damage category among horticultural crops.
- CExD results show that non-renewable, fossil had higher energy content in all crops.
- Citrus is exergoenvironmental friendly among horticultural crops.

Fig. 1. Geographical status of the investigated region in northern Iran.

Fig. 2. Horticultural production's system boundaries in northern Iran.

Fig. 3. Correlation between midpoints and endpoints based on ReCiPe2016 method of LCA.

Fig. 4. Configurations of CExD components to evaluate energy forms in horticultural crops.

Fig. 5. Share of each input to endpoints of horticultural crop production.

Fig. 6. Contributions of energy forms based on CExD analysis for horticultural crop production.

Fig. 7. Comparison of total weighted endpoints for horticultural crops.

Fig. 8. Comparison of total CExD for horticultural crops.

Table 1
List of samples studies undertaken on LCA and CExD in agricultural and horticultural crop production

Surveyed research	Surveyed location	Crop	LCA	Hotspot	CExD
Knudsen et al. [19]	Denmark	Orange	Partial coverage	Transport	No
Boulard et al [20]	France	Tomato	Partial coverage	Biocides	No
Page et al. [21]	Australia	Tomato	Greenhouse gas (GHG)	Transportation	No
Pishgar-Komleh et al. [22]	Iran (Golestan)	Cotton	GHG	Agricultural machinery and diesel fuel	No
Gunady et al. [23]	Australia	Strawberri	GHG	Electricity	No
Vázquez-Rowe et al. [24]	Spain	Grape	GHG	Diesel fuel and fertilizer	No
Torrellas et al. [25]	Spain	Tomato	Complete coverage	Chemical fertilisers	No
Vinyes et al. [26]	Spain	Peach	Complete coverage	Chemical fertilisers and p Biocides	No
Soode et al. [27]	Germany	Strawberry	Partial coverage	Electricity	No
Nikkhah et al. [28]	Iran (Guilan)	Kiwifruit	Partial coverage	Urea fertilizer	No
Sabzevari et al. [29]	Iran (Guilan)	Hazelnut	Complete coverage	Agricultural machinery	No
Mohammadi-Barsari et al. [30]	Iran (Kiashahr)	Watermelon	GHG	Agricultural machinery	No
Nabavi-Pelesaraei et al. [31]	Iran (Guilan)	Watermelon	GHG	Diesel fuel and Electricity	No
Masuda [32]	Japan	Wheat	Partial coverage	Nitrogen fertilizer	No
Nabavi-Pelesaraei et al. [33]	Iran (Guilan)	Watermelon	GHG	Chemical fertilizers	No
Kouchaki-Penchah et al. [34]	Iran (Guilan)	Tea	Complete coverage	Nitrogen, diesel fuel and agricultural machinery	No
Goossens et al. [35]	Belgium	Apple	Complete coverage	Chemical fertilizers and biocides	No
Soheili-Fard et al. [36]	Iran (Guilan)	Tea	Complete coverage	Agricultural machinery and diesel fuel	No
Mohseni et al. [37]	Iran (Arak)	Grape	Complete coverage	Poultry manure	Yes
Paramesh et al. [38]	India	Arecanut	Complete coverage	Dierct or On-Orchard emissions	No
Nabavi-Pelesaraei et al. [39]	Iran (Guilan)	Paddy	Complete coverage	Dierct or On-Farm emissions	Yes
Hosseinzadeh-Bandbafha et al. [40]	Iran (Guilan)	Peanut	GHG	Chemical fertilizer	No
Zarei et al. [41]	Iran (Fars)	Cucumber and tomato	Complete coverage	Electricity and nitrogen fertilizers	Yes
Kaab et al. [42]	Iran (Ahwaz)	Sugarcane	Complete coverage	Electricity, agricultural machinery and biocides	Yes
Grados and Schrevens [43]	Peru	Potato	Partial coverage	Agricultural machinery	No
Elhami et al. [44]	Iran (Kohgiluyeh)	Raisin	Complete coverage	Farmyard manure (FYM)	No
Liang et al. [45]	China	Winter wheat	Complete coverage	Chemical fertilizers	No
Ronga et al. [46]	Italy	Tomato	GHG	Pesticide and fungicide	No
Mostashari-Rad et al. [47]	Iran (Guilan)	Eggplant	GHG	Nitrogen	No
Hosseini-Fashami et al. [48]	Iran (Alborz)	Strawberry	Complete coverage	Dierct or On-Orchard emissions	Yes
Ronga et al. [49]	Italy	Tomato	GHG	Nitrogen	No
Ronga et al. [50]	Italy	Cardoon	GHG	Nitrogen	No
Saber et al. [51]	Iran (Mazandaran)	Rice	Complete coverage	Dierct or On-Farm emissions	Yes

Table 2
Details of sampling size computation

Crops	Number of statistical population [54]	Cochran's computation of sample size	Number of surveyed units
1. Citrus	388	193.29	195
2. Hazelnut	310	171.80	180
5. Kiwifruit	205	133.90	140
4. Tea	537	224.19	230
5. Watermelon	172	119.02	120

Table 3

Standard coefficients of emissions factors for combustion of diesel fuel in agricultural machinery

Emission	Amount (kg Megajoule (MJ)$^{-1}$ diesel)
A. Emissions to air	
Ammonia (NH_3)	4.44E-07
Benzene (C_6H_6)	1.62E-07
Benzo (a) pyrene	6.68E-10
Cadmium (Cd)	2.22E-10
Carbon dioxide (CO_2), fossil	0.07
Carbon monoxide (CO), fossil	1.30E-04
Chromium (Cr)	1.11E-09
Copper (Cu)	3.78E-08
Dinitrogen monoxide (N_2O)	2.67E-06
Heat, waste [a]	1.01
Methane (CH_4), fossil	2.87E-06
Nickel (Ni)	1.55E-09
Nitrogen oxides (NOx)	8.66E-04
Non-methane volatile organic compound (NMVOC)	4.77E-05
Polycyclic hydrocarbons (PAH)	7.29E-08
Particulates, < 2.5 micrometer (µm)	1.09E-04
Selenium (Se)	2.22E-10
Sulfur dioxide (SO_2)	2.24E-05
Zinc (Zn)	2.22E-08
B. Emissions to soil	
Cd	3.98E-09
Lead (Pb)	1.75E-08
Zn	1.07E-05

[a]. Emission is based on MJ

Table 4

Equivalent coefficients of On-Orchard emissions for computing applied inputs in horticultural production systems

Characteristic		Coefficient (Emission result)	Reference
A. Emissions of fertilizers			
1	$\left[\frac{kg\ N_2O - Nitrogen}{kg\ Nitrogen_{in\ fertilzers\ applied}}\right]$	0.01 (to air)	[59]
2	$\left[\frac{\text{kg NH}_3\text{ - }Nitrogen}{\text{kg }Nitrogen_{\text{in fertilizers applied}}}\right]$	0.1 (to air)	[59]
3	$\left[\frac{\text{kg N}_2\text{O - }Nitrogen}{\text{kg }Nitrogen_{\text{in atmospheric deposition}}}\right]$	0.001 (to air)	[59]
4	$\left[\frac{kg\ NO_3^- - Nitrogen}{\text{kg }Nitrogen_{\text{in fertilizers applied}}}\right]$	0.1 (to water)	[59]
5	$\left[\frac{\text{kg Phosphate emission}}{\text{kg Phosphate}_{\text{in fertilizers applied}}}\right]$	0.02 (to water)	[59]
6	$\left[\frac{\text{kg NO}_x}{\text{kg N}_2O_{\text{from fertilizers and soil}}}\right]$	0.21 (to air)	[59]
B. Conversion of emissions			
1	Coversion from kg CO_2 – Carbon to kg CO_2	$\left(\frac{44}{12}\right)$	[59]
2	Coversion from kg N_2O – Nitrigen to kg N_2O	$\left(\frac{44}{28}\right)$	[59]
3	Conversion from kg NH_3 - Nitrigen to kg NH_3	$\left(\frac{17}{14}\right)$	[59]
4	Conversion from kg Nitrate (NO_3) - Nitrigen to kg NO_3	$\left(\frac{62}{14}\right)$	[59]
5	Conversion from kg P_2O_5 to kg Phosphorus	$\left(\frac{62}{164}\right)$	[59]
C. Emissions from human labor			
1	$\left[\frac{\text{kg CO}_2}{\text{man - h Human labor}}\right]$	0.7 (to air)	[60]
D. Emissions from biocides			
1	$\left[\frac{\text{kg effective material}}{\text{kg biocides}}\right]$	Based on PestLCI 2.0 (to air)	[61]

2	$\left[\frac{\text{kg effective material}}{\text{kg biocides}}\right]$	Based on PestLCI 2.0 (to water)	[61]
3	$\left[\frac{\text{kg effective material}}{\text{kg biocides}}\right]$	0.85 (to soil)	[62]

Table 5
Coefficients of On-Orchard emissions of heavy metal to soil for applications of chemical fertilizers and FYM

Characteristic	Heavy metals						
	Cd	Cu	Zn	Pb	Ni	Cr	Mercury (Hg)
1 $\left[\frac{\text{Miligram (mg) Heavy metal}}{kg\ \ Nitrogen_{in\ \ fertilzer\ applied}}\right]$	6	26	203	5409	20.9	77.9	0.1
2 $\left[\frac{\text{mg Heavy metal}}{kg\ \ Phosphate\ _{in\ \ fertilzer\ applied}}\right]$	39.5	90.5	839	67	88.3	543	0.3
3 $\left[\frac{\text{mg Heavy metal}}{kg\ \ Potassium\ _{in\ \ fertilzer\ applied}}\right]$	0.1	4.8	6.2	0.8	2.5	5.8	0
4 $\left[\frac{\text{mg Heavy metal}}{kg\ \ Dry\ \ material\ \ of\ \ cow\ \ manure\ _{in\ \ fertilzer\ applied}}\right]$	452.3	1018	13.6	17.4	13.2	0.08	452.2

Table 6
LCI of horticultural products in Guilan Province of Iran per hectare

Item (unit)	Horticultural crops				
	Citrus	Hazelnut	Kiwifruit	Tea	Watermelon
A. Off-Orchard					
1. Agricultural machinery (kg)	20.17	9.44	33.82	12.46	52.37
2. Lubricating oil (kg)	4.15	1.89	5.16	2.28	6.59
3. Chemical fertilizers (kg)					
(a) Nitrogen	140.3	14.79	258.65	354.68	425.56
(b) Phosphate	99.21	18.94	110.79	66.35	125.85
(c) Potassium	290.12	25.93	104.35	-	112.56
4. FYM (kg)	1837	384.53	2325.53	350.9	386.69
5. Biocides (kg)					
(a) Pesticides	2.75	3.94	3.15	1.54	1.75
(b) Fungicides	3.14	4.52	3.62	1.78	2
6. Diesel fuel (kg)	90.82	8.18	98.71	24.67	54.75
7. Electricity (kWh)	135.7	-	338.35	-	260.11
B. On-Orchard					
1. Emissions by diesel fuel to air (kg)					
(a). NH_3	2.64E-03	2.38E-04	2.84E-03	7.18E-04	1.59E-03
(b). C_6H_6	9.64E-04	8.68E-05	1.04E-03	2.62E-04	5.81E-04
(c). Benzo (a) pyrene	3.97E-06	3.58E-07	4.27E-06	1.08E-06	2.39E-06
(d). Cd	1.32E-06	1.19E-07	1.42E-06	3.59E-07	7.97E-07
(e). CO_2, fossil	412.22	37.13	443.23	111.97	248.49
(f). CO, fossil	0.78	0.07	0.83	0.21	0.47
(g). Cr	6.61E-06	5.95E-07	7.10E-06	1.79E-06	3.98E-06
(h). Cu	2.25E-04	2.02E-05	2.41E-04	6.10E-05	1.35E-04
(i). N_2O	0.02	1.43E-03	0.02	4.31E-03	0.01
(j). Heat waste (Based on MJ)	6001.46	540.51	6452.86	1630.13	3617.74
(k). CH_4, fossil	0.02	1.54E-03	0.02	4.64E-03	0.01
(l). Ni	9.24E-06	8.33E-07	9.94E-06	2.51E-06	5.57E-06
(m). NOx	5.15	0.46	5.54	1.4	3.11
(n). NMVOC	0.28	0.03	0.3	0.08	0.17
(o). PAH	4.33E-04	3.90E-05	4.66E-04	1.18E-04	2.61E-04
(p). Particulates, < 2.5 um	0.65	0.06	0.7	0.18	0.39
(q). Se	1.32E-06	1.19E-07	1.42E-06	3.59E-07	7.97E-07
(r). SO_2	0.13	0.01	0.14	0.04	0.08
(s). Zn	1.32E-04	1.19E-05	1.42E-04	3.59E-05	7.97E-05
2. Emissions by diesel fuel to soil (kg)					
(a). Cd	2.36E-05	2.13E-06	2.54E-05	6.42E-06	1.43E-05
(b). Pb	1.04E-04	9.36E-06	1.12E-04	2.82E-05	6.27E-05
(c). Zn	0.06	0.01	0.07	0.02	0.04
3. Emissions by fertilizers to air (kg)					
(a). N_2O	2.78	0.37	4.80	5.70	6.81
(b). NH_3 by FYM	8.92	2.11	11.30	1.93	1.88
(c). NH_3 by chemical fertilizers	17.04	1.80	31.41	43.07	51.68
4. Emission by atmospheric deposition of fertilizers to air (kg)					
(a). N_2O by chemical fertilizers	0.22	0.02	0.41	0.56	0.67
(b). N_2O by FYM	0.12	0.03	0.15	0.02	0.02
5. Emissions by fertilizers to water (kg)					
(a). Nitrate	23.52	3.12	40.54	48.18	57.57
(b). Phosphate	2.77	0.47	3.18	1.46	2.87
6. Emission by N_2O of fertilizers and soil to air (kg)					

(a). NOx	0.53	0.09	1.12	1.32	1.58
7. Emission by heavy metals of fertilizers to soil (mg)					
(a). Cd	6376.78	888.90	7947.73	4794.03	7869.67
(b). Cu	419077.38	37159.39	530030.32	47109.98	108258.76
(c). Zn	1206164.43	97694.30	1529326.28	199436.69	422674.35
(d). Pb	787622.17	82335.57	1434194.32	1923864.85	2314979.37
(e). Ni	39219.64	3392.42	49378.64	14499.98	25929.67
(f). Cr	82593.59	12608.59	101307.01	64589.98	105530.10
(f). Hg	163.21	13.15	210.27	60.84	105.45
8. Emission by human labor to air (kg)					
(a). CO_2	315.78	122.37	1012.24	4632.52	499.14
9. Emissions by biocides to air (kg)					
(a). Benomyl	0.07	0.10	0.08	0.04	0.04
(b). Captan	0.1	0.15	0.12	0.06	0.07
(c). Thiophanate-methyl	0.05	0.07	0.06	0.03	0.03
(d). Chlorothalonil	0.06	0.09	0.07	0.03	0.04
(e). Thiram	0.1	0.14	0.11	0.06	0.06
(f). Chloropicrin	0.04	0.05	0.04	0.02	0.02
(g). Parathion	0.1	0.15	0.12	0.06	0.06
(h). Carbofuran	0.07	0.1	0.08	0.04	0.04
10. Emissions by biocides to water (kg)					
(a). Benomyl	0.04	0.05	0.04	0.02	0.02
(b). Captan	0.05	0.07	0.06	0.03	0.03
(c). Thiophanate-methyl	0.03	0.04	0.03	0.01	0.02
(d). Chlorothalonil	0.03	0.04	0.03	0.02	0.02
(e). Thiram	0.05	0.07	0.06	0.03	0.03
(f). Chloropicrin	0.02	0.03	0.02	0.01	0.01
(g). Parathion	0.05	0.07	0.06	0.03	0.03
(h). Carbofuran	0.03	0.05	0.04	0.02	0.02
11. Emissions by biocides to soil (kg)					
(a). Benomyl	0.6	0.85	0.69	0.34	0.38
(b). Captan	0.88	1.26	1.01	0.49	0.56
(c). Thiophanate-methyl	0.43	0.62	0.5	0.24	0.27
(d). Chlorothalonil	0.51	0.73	0.59	0.29	0.33
(e). Thiram	0.83	1.19	0.95	0.47	0.53
(f). Chloropicrin	0.3	0.43	0.35	0.17	0.19
(g). Parathion	0.87	1.24	0.99	0.49	0.55
(h). Carbofuran	0.59	0.85	0.68	0.33	0.38
C. Yield					
1. Citrus (kg)	22273.81	-	-	-	-
2. Hazelnut (kg)	-	450.20	-	-	-
3. Kiwifruit (kg)	-	-	22862.60	-	-
4. Tea (kg)	-	-	-	10524.34	-
5. Watermelon (kg)	-	-	-	-	27350.25

Table 7
Results of endpoints for producing 10 t of horticultural crops in Guilan Province of Iran

Endpoint	Unit	Amount				
		Citrus	Hazelnut	Kiwifruit	Tea	Watermelon
Human health	DALY [a]	0.01	0.05	0.01	0.02	0.01
Ecosystems	species.yr [b]	1.73E-05	1.37E-04	2.36E-05	6.09E-05	2.53E-05
Resources	USD2013	93.27	717.33	128.68	226.25	132.57

a DALY: Disability adjusted life years. A damage of 1 is tantamount to: lack of 1 life year of 1 individual, or 1 person travails 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.

Table 8
Energy form results of CExD analysis for horticultural crop production in Guilan Province of Iran

Energy form	Unit	Amount				
		Citrus	Hazelnut	Kiwifruit	Tea	Watermelon
Non-renewable, fossil	MJ 10 t^{-1}	11942.41	99658.18	16289.02	29245.51	17238.61
Renewable, kinetic	MJ 10 t^{-1}	44.54	542.89	57.39	116.86	66.99
Renewable, potential	MJ 10 t^{-1}	280.94	3159.38	370.77	670.62	417.22
Non-renewable, primary	MJ 10 t^{-1}	324.04	1542.85	215.76	363.74	250.81
Non-renewable, metals	MJ 10 t^{-1}	404.04	3481.99	619.52	1491.78	801.94
Non-renewable, minerals	MJ 10 t^{-1}	459.87	3898.02	572.80	1112.53	639.80