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Title:

Multi-objective optimization of energy use and environmental emissions for walnut production using imperialist competitive algorithm

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Abstract

Although the agricultural sector is an important source of bioenergy production, this production can be considered sustainable when energy consumed and environmental emissions are optimal. As such, the assessment of energy flow, environmental emissions of walnut orchards in Alborz province of Iran and their simultaneous optimization by multi-objective imperialist competitive algorithm are the main goals of this investigation. Input-output energy analysis, IMPACT 2002+ method of life cycle assessment, and multi-objective imperialist competitive algorithm are used in the energy-environmental evaluation for optimization in this study. Results ascertain that energy uses of the entire output and input are computed to be 31015 and 27200 MJ ha^{-1}, respectively and that gasoline with 40% is the dominated consumer of energy. Moreover, energy use efficiency is 0.88, which indicates energy inefficiency in walnut production. Environmental results shows that On-Orchard emissions with a share more than 50% in ecosystem quality, human health, and climate changes and gasoline in resources category are the main hotspots. Multi-objective optimization illustrates that the reduction in total energy is 19316 MJ ha^{-1} (about 62%) and gasoline with 58% is the most energy saving input among all. On the other hand, the total weighted emission decreases by about 1.47 Pt (about 40%). Generally, results reveal that timely maintenance can help orchardist attain close to optimal condition. Furthermore, the application of imperialist competitive algorithm not only can offer optimum pattern of walnut production, but also be extended to the world for different crops.

Keywords: Agriculture, Energy use efficiency, IMPACT 2002+, Imperialist competitive algorithm, Life cycle assessment, Metaheuristic algorithm

Nomenclature

C_2H_4O	Acetaldehyde
C_3H_4O	Acrolein
C_3H_6	Propene
C_4H_6	Butadiene
C_6H_6	Benzene
C_7H_8	Toluene
C_8H_{10}	Xylene
Cd	Cadmium
CH_2O	Formaldehyde
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
DALY	Disability adjusted life years
DEA	Data envelopment analysis
EP	Energy productivity
EUE	Energy use efficiency
FU	Functional unit
FYM	Farmyard manure
h	Hour
ha	Hectare
Hg	Mercury
ICA	Imperialist competitive algorithm
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometer
km^2	Square kilometer
kWh	Kilowatt hour
l	Liter
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
m	Meter
mg	Milligram
MJ	Mega joule
MOGA	Multi-objective genetic algorithm
MOICA	Multi-objective imperialist competitive algorithm
N_2O	Dinitrogen monoxide
NE	Net energy

NH_3	Ammonia
Ni	Nickel
NMVOC	Non-methane volatile organic compound
NO_3^-	Nitrate
NOx	Nitrogen oxides
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PDF*m^2*yr [b]	Potentially disappeared fraction
Pt	Point
SE	Specific energy
Se	Selenium
SO	Sulfur monoxide
SO_2	Sulfur dioxide
SPSS	Statistical package for the social sciences
t	Ton
U.S.LCI	Life cycle inventory of United States
VOC	Volatile organic compounds
Zn	Zinc
µm	Micrometer

1. Introduction

Energy is applied in all parts of the world and in all aspects of human life, and consequently facilitates human civilizations, ecosystems and life [1]. In response to population growth, the consumption of energy in agriculture section has been raised for supplying better living condition [2]. Agricultural and horticultural production system is one of the main energy consumer and energy producer and its energy consumption is related to input application and the generated energy is related to the yield [3]. Accordingly, the relationship between energy and agriculture as well as environmental impacts of using the finite sources of fossil fuels as non-renewable resources, have to be changed dramatically [4].

Iran is categorized the third after China and the USA in the world for walnut production [5]. Walnut, along with almond and pistachio, has covered around 800,000 ha (about 28.5 %) of orchards in Iran. Moreover, high energy content of walnut yield is one of the main reason for concentrating this crop for more sustainable energy source not only in Iran but also in the world

[6]. On the other hand, energy efficiency and sustainable agricultural production are closely related due to fossil fuel conservation, economic savings and pollution reduction [7]. Besides, sustainability clearly becomes one of the biggest issues the agriculture sector faces nowadays [8]. Under such circumstances, different research works have been conducted to determine the amounts of energy input and output during the production along with environmental impacts during the products' life cycle, which have gained growing attention in agricultural management [9]. Life cycle assessment (LCA), being a proper environmental management method, is often used to examine environmental aspects of a product over its lifetime [10]. In addition to quantifying energy consumption, LCA concept can be a suitable measure for assessing environmental matters pertinent to the production of agricultural product types.

Generally, increasing input energy has direct relationship with increasing output energy and environmental effects. Whilst energy efficiency enhancement is very useful to mitigate effects of environmental burdens in the agricultural sector, irregular reduction of input energy can reduce yield [11]. In other words, the unavailability of correlation and impacts of simultaneous and conflicting objectives is the main reason in using metaheuristic algorithms for multi-objective optimization [12]. It is clear that due to certain and various limitations, instead of a particular solution to achieve the desired goal, a set of nuances should be considered and designed. It is possible to solve continuous problems through a new algorithm (namely, imperialist competitive algorithm (ICA)) without considering the gradient to the function [13]. There are several main benefits of ICA method, namely, neighborhood movement can be performed easily, there is less emphasis on dependability of primary solutions and the computation period can be remarkably cut down. Nonetheless, the opposing goals in multi-objective design problem cannot be addressed simultaneously [14]. Moreover, if ICA is used for high-dimensional functions that have complicated multimodal forms, there might be a flaw so that it is being trapped in local optimum solutions. Thus, it is suggested to apply multi-objective imperialist competitive algorithm (MOICA) for handling these solutions. In fact, in the stage of assimilation, an attraction and repulsion concept is introduced, which aims to develop algorithm performances in order to gain universe optimal position [15].

Various researches have quantified energy analysis, environmental impacts and their optimization in the production process of different agricultural production systems and Table 1 summarizes several of these studies.

Table 1

In Table 1, literature review indicates that in preliminary studies, the relationship between input and output energy (yield) was the main subject of these studies. Over the time, researchers have concluded that the enhancement of yield would be possible by increasing input energy, but the point to consider was the increase in environmental emissions due to increased energy consumption in agricultural production, which was contrary to the principles of sustainable agriculture. Therefore, in the next step, the researchers studied the environmental emissions from agricultural products along with energy studies, which often considered solely emissions of greenhouse gases. In the next step, with the development of environmental assessment methods, LCA indicators, which were more complete and comprehensive in environmental studies of agricultural products, replaced greenhouse gas emissions. In most of these studies, only the energy use and emission pattern were evaluated. After having investigated some study results, researchers concluded that assessing energy and environmental emissions and providing only a few recommended methods alone for attaining sustainable production was not effective. Therefore, optimization and determination of the optimal model for energy inputs were investigated in the next step. Most studies in this field, even in recent years, have only optimized the energy consumption using local methods such as DEA by determining the optimum consumption of each input with benchmarking efficient units, and then estimated the emission reduction in the production of various agricultural products by the new model.

Despite the value of these studies, two major issues remain unresolved. Firstly, single-approach optimization cannot introduce the ideal optimal point in product production. This means that optimization is performed with the approach of minimizing energy consumption as long as the product performance is maintained. However, if a separate function of input energies and emissions are plotted, different points will definitely be determined as the optimal points for each input. Secondly, the consumption of individual inputs in all local optimum units may not be the real optimal in the world. The results of previous studies only show a potential of decreasing percentage of total energy consumption by approaching the local optimum. While the present study, by providing the optimal consumption for each input (according to the minimum and maximum required amounts of input to produce walnut), includes both the optimization of environmental emissions and energy consumption, and the ability to generalize the method to create a production system elsewhere in the world. In previous studies, only maintaining maximum yield in the region was considered and no attention was paid to the product's physiological need for any input. This may render these optimal models not implementable from an environmental perspective and also may not lead to sustainable crop production from agricultural perspective. However, the offered model of this study not only can clearly determine the amount of consumption of each input, but also include the physiological needs of each input and the environmental consequences of their consumption, which clearly shows the difference between the results of this study and other previous studies. Therefore, according to these explanations, the research issue in this study is to find global optimal points in order to optimize these multi-objectives in walnut production, considering the logical limitations for each input. Solving this problem requires not only agricultural knowledge to analyze the amount of input required, but also engineering knowledge in mathematical optimization of problems. Because many solutions may be found for different objective functions, one requires multi-objective optimization in choosing the global optimal.

It should be noted that not only the comprehensive multi-objective optimization approach is an important novelty in the present study, but also the use of ICA as a metaheuristic algorithm is another novelty in this study. The results of this study, considering that it has a general energy-environmental approach, can be applied as an ideal consumption pattern in walnut production to all orchardists around the world. Nevertheless, they can also attain local optimization if necessary by changing the amount of input restrictions according to the conditions of their region. Besides, the applied method in this study can be used for other agricultural products in other regions of the world in performing multi-objective optimization.

Based on the above explanation, the objectives of the present research work include input-output energy analysis, energy indices assessment, determining environmental life cycle emissions, performing MOICA to optimize energy and environmental emissions of walnut production simultaneously and offering early and late return solutions to improve walnut cultivation system in the studied site.

2. Materials and methods

2.1. Study site and data

Information are gathered from orchards in Alborz province. This province is in latitude from 35° 28′ to 36° 30′ North and longitude from 50° 10′ to 51° 30′ East and covers an area of 5833 km^2. It is located at the southern area of Caspian Sea, in foothills of Alborz Mountains [6], and is situated 35 km west of Tehran, capital of Iran as shown in Fig. 1.

Fig. 1

For more information and determination of the required standards for data collection, which are firstly based on reports of the Ministry of Jihad-e-Agriculture of Iran [6], topological specifications for walnut production are collected, which are shown in Table 2.

Table 2

Initial data are collected randomly for each type of agricultural input parameters (grain size, fertilizer, biocides, etc.), energy channels, applied equipment and machinery, farmland cultivated land, walnut fields, etc., from 48 walnut producers. In this study, Cochran [44] method is employed to compute sampling size. Data are collected by face to face questionnaires and a sample is indicated in the "Supplementary material".

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

where d shows the deviation of the permissible error rate from the mean population (equal to 0.05), p represents the computed rough proportion of a feature of population (equal to 0.5), q equals to 1-p (equal to 0.5), z denotes the confidence coefficients (equal to 1.96, representing 95% the level of confidence), N represents the statistics society' total size and n shows the required sample size.

2.2. Input-Output energy in walnut production

Walnut production's input energy resources are agricultural machinery, chemical fertilizers, human labor, biocides, diesel fuel, gasoline, electricity, and farmyard manure (FYM) in this region; while walnut fruit is considered as the output energy source. Solar energy, under both heat or radiation, are not investigated since they are determined to be free subsidy for the economic and energetic assessment of agricultural production systems [45]. The output and input energy equivalent are applied to quantify the energy values as outlined in Table 3.

Table 3

The energy productivity (EP), energy input-output ratio energy use efficiency (EUE), net energy (NE) and specific energy (SE) are estimated by applying the fruit yield (kg ha^{-1}) and entire outputs and inputs energy equivalent per unit (MJ ha^{-1}) , involving the formulas that are outlined in Table 4 [56]:

Table 4

2.3. LCA

LCA includes goal statement, input and output identification, and a system for assessing environmental effects and their interpretation. Guidelines for assessing environmental impacts of crops based on LCA method are provided by ISO 14040 [57].

2.3.1. Scope, goal and definition statement

A significant procedure in defining scope and goals is to determine the boundary of the studied system. LCA results cannot be determined in case the system boundaries have not been properly determined [58]. Environmental indicators are computed for one ton of walnut produced as a FU. It should be noted that walnut kernel is important as an economical product in the production of this crop and it determines the FU. System boundary of walnut production in the research work is determined in Fig. 2.

Fig. 2

The LCA assumptions in this study include, firstly, the orchards are all established in the same condition for exploitation and agricultural operations. Secondly, environmental conditions, such as the characteristics of water and soil, etc., are almost the same for everyone. Thirdly, the system boundary starts from the beginning of the preparation of an orchard at the beginning of the working season and ends with the walnut harvest and finally, increasing the amount of input will increase emissions and not only will not increase yield, but according to the diminishing return's law, we will also face a decrease in yield.

2.3.2. LCI

All resources and quantities needed to produce walnut as well as all quantities of pollutants released to the environment through the use of different types of inputs are considered based on a reference unit [59]. It is split into two datasets, namely, Off-Orchard and On-Orchard emissions, for the walnut production's life cycle as explained below.

2.3.2.1. Off-Orchard emissions

In the current study, the application of biocides, agricultural machinery, diesel fuel, fertilizers, gasoline, and electricity are regarded as system inputs. The system' output is symbolic. Inputs are used as an indirect release in the walnut production cycle.

2.3.2.2. On-Orchard emissions

Generally, On-Orchard emissions are transmitted to air, water and soil. Environmental degradation in relation to air includes greenhouse effect, acid rain, and the depletion of the ozone layer. Emissions to air by microorganisms or using chemicals cause pollution of a river, stream, ocean, aquifer, lake, or other water bodies and degrade the quality of water and turn it into toxic form to the environment or humans. Moreover, emissions to soil degrade the chemical, biological, and physical decline in the quality of soil, which can be the reduction of the fertility of soil along with structural condition, organic matter' loss, remarkable changes in acidity, salinity, or alkalinity, erosion, excessive flooding, and the adverse impacts of pollutants as well as toxic chemicals.

The release of polluting gases in walnut production is mainly due to the use of agricultural machinery together with tractors in field operations such as fertilization and spraying. In this study, the first part of On-Orchard emissions includes the emissions from combustion of gasoline and diesel fuel in agricultural machinery. For computation of On-Orchard emissions relate to these fuels, their energy equivalents are considered as a base. Moreover, values of distribution factors for diesel fuel combusted in agricultural machinery and gasoline are extracted from EcoInvent$^{®}$3.6 [60] and U.S.LCI database [61], respectively as outlined in Table 5.

Table 5

Apart from emissions to water and air, chemical fertilizer is consumed to compensate for the loss of soil organic matter of walnut. Moreover, emissions to soil in walnut production include chemical fertilizer application for enhancing the soil resulting in direct emissions with heavy metals and employment of human labor for fertilizing, spraying, harvesting, etc. The related application of input in walnut production is computed by multiplying the amount of input to its equivalent coefficients, as introduced by IPCC [62], Mousavi-Avval et al. [63], and Durlinger et al. [64]. These coefficients of inputs are shown in Fig. 3.

Fig. 3

In this study, PestLCI 2.0 model is used to evaluate On-Orchard emissions of biocides application related to air and water. The model [65] is intended for use in the second step of LCA to estimate the emissions of pesticides from agricultural farms to environment. In fact, PestLCI 2.0 is the updated version of PestLCI 1.0, which incorporates improved trends to model the fate of pesticides; modelling updated involved processes; extending the model's geographical area [66]. The model is briefly described here and further explanation was given by Dijkman et al. [65]. The model estimates the emissions of each pesticide via determining the distribution of primary and secondary pesticides through the 'field box', in which the model boundaries are defined. It includes the field where the pesticides are used, air above the farm up to 100 m, and up to 1 m depth of soil. In fact, all components within the 'field box', such as air, water, crop, and soil, are determined to be a technosphere part. As a result of crossing the 'field box' borders, the pesticides become emissions to the ecosphere [67]. The schematic diagram of PestLCI 2.0 model is demonstrated in Fig. 4.

Fig. 4

It should be noted the PestLCI 2.0 model cannot analyze On-Orchard emissions to soil related to biocides. So, the standard coefficient that is offered by Margni et al. [68] is used for computation of emissions to soil of biocides as follows:

$$\text{On-Orchard emissions of biocides to soil} = \text{Biocides effective rate} \times 0.85 \qquad (2)$$

2.3.3. LCIA

The third stage of LCA is LCIA. LCIA collects data on raw material extraction and material release in relation to the product life cycle [57]. IMPACT 2002+, CML method, EPS2000, and Eco-indicator 99, etc. [69] are typical methods of LCIA. In this study, IMPACT 2002+ is used. The study' purpose is the interpretation of inputs and outputs of the walnut system. It includes four stages: (i) selection and classification of impact categories ; (ii) characterization; (iii) normalization; and (iv) weighting [70].

2.3.3.1. IMPACT 2002+ method

In the classification stage, each quantity released to the environment as well as the resources used in the product life cycle are attributed to the relevant environmental effects [71]. IMPACT 2002+ model is adopted for LCA in producing one t of walnut in different scenarios. This method allows for the analysis of environmental emissions under four endpoints as well as fifteen midpoint impact categories [72] and their relationships are shown in Fig. 5.

Fig. 5

2.3.3.2. Weighting

Weighting is the final step in LCIA. Weighting can be considered as multiplying the normalised results of impact categories with a weighting factor, which indicates the importance of the desired impact categories. So, the weighted results which have similar unit can be added up to make one single score for a scenario or product's environmental impacts. In other words, weighting applies a value judgment to the LCA results. A weighting factor shows the potential emission to each impact group. The higher is the factor, the greater is the potential of the negative group effects of the environment. For LCA interpretation stage, the classification of emitted effects is based on individual resources, climate change, ecosystem quality and human health [73].

2.3.4. Sensitivity analysis

Sensitivity analysis is considered as a study of how dubiety in the output of a mathematical system or model (numeral or in other ways), dividing to various origins of dubiety in its inputs [74]. In this study, modifying ±10% of fossil fuels (diesel and gasoline) and chemical fertilizers (nitrogen, phosphate, and potassium) is considered for evaluating sensitivity analysis for four environmental categories of IMPACT 2002+. In other words, fossil fuels (diesel and gasoline) and chemical fertilizers (nitrogen, phosphate, and potassium) are independent variables; while four environmental endpoints are dependent variables.

2.4. Multi-objective optimization

2.4.1. Problem statement

In the current study, for the first time, the multi-objective output energy and total environmental emission problem under input energy identity is studied for walnut production. An important point of this research is the existence of contradictory goals. Two main objectives are maximizing output energy and minimizing total environmental emissions based on input energy in walnut production. The objective functions are ascertained as follows [33]:

$$F_{\max/\min} = \sum_{i=1}^{j} C_i X_i + e_i \tag{3}$$

where $F_{max/min}$ represents objective function to be minimized or maximized, C_i shows the model coefficient, and Xi denotes the input variable. In order to solve an optimization problem, MATLAB toolbox only points to the minimized objective function. Consequently, the maximized objective functions must be multiplied by (-1).

In the current study, whereas output energy should be maximized, total environmental emissions should be minimized. So, the governing equations are depicted as follows:

$$OE = (-1)\times \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + \alpha_5 X_5 + \alpha_6 X_6 + \alpha_7 X_7 + \alpha_8 X_8 + \alpha_9 X_9 + \alpha_{10} X_{10} + e_i \tag{4}$$

$$TED = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + e_i \tag{5}$$

where X_1 is human labor, X_2 is agricultural machinery, X_3 is diesel fuel, X_4 is gasoline, X_5 is nitrogen, X_6 is energy equivalent of phosphate, X_7 is potassium, X_8 is FYM, X_9 is biocides, and X_{10} is electricity. It can be observed that all independent variables are expressed in terms of energy equivalent based on MJ. Besides, *OE* and *TED* are output energy based on MJ and total environmental emissions based on Pt in walnut production, respectively as dependent variables. After description of all the functions, each function' limitations are described for optimization process. As such, each independent variable's maximum and minimum energy consumption are determined as upper and lower scope, respectively as follows:

$$\textit{Minimum rate of energy use} \leq X_1, X_2, \ldots, X_{10} \leq \textit{Maximum rate of energy use} \qquad (6)$$

A variety of acceptable values for each variable shows that the finding of an optimum point for each input energy cannot be performed solely by simple computations.

2.4.2. Development of MOICA

An optimization problem comprises of minimizing or maximizing a function through choosing input values systematically within variable limit as well as computing the function value. Several algorithms are available as optimizing mathematical models [75]. Among them, meta-heuristic algorithms can be useful for solving the problem. As a quantification method, ICA is applied to solve optimization difficulties of various types among all meta-heuristic algorithms. This technique is usually used for single-objective optimization, but in recent years, a developed and modified algorithm, namely, MOICA, was introduced by researches based on ICA to solve multi-objective optimization [12]. This method is used in this study. The development process of ICA and MOICA is explained as follows.

The empires are created in the first step of ICA. Each of the imperialist directly takes some colonies based on its power as depicted in Fig. 6. Stronger imperialists have more colonies and weaker imperialists have less colonies. The process of assimilation begins after having initialized the empires.

Fig. 6

Fig. 7 represents the model involving countries, which go through their resembling imperialists. In this process, a probability exists that each of the colonies can gain a better position than their imperialist and, accordingly, can reach the imperialist state. This process is accordingly resumed by a new one in charge of empire; hence, the total colonies go through it.

Fig. 7

Each empire is given a whole power agreement with both the imperialist and their colonies, after applying the assimilation policy; however, colonies effects are negligible [76]. Moreover, the total power is computed by Eq. (7).

$$T.Cn = Cost\ (imperialist_n) + \mathcal{E}\ mean\ \{cost\ (colonies\ of\ empire_n)\} \tag{7}$$

where $T.Cn$ shows the nth empire' whole cost and $\mathcal{E}$ denotes a positive small number. The little amounts of $\mathcal{E}$ causes the empire's total power to be only specified by the imperialist and its enhancement will extend the colonies' role in specifying the empire's total power. In most implementations, the amount of 0.1 for $\mathcal{E}$ has shown great results.

A pernicious challenge begins among almost all of the empires during the imperialistic competition process, in which all of them tend to take each other' colonies. The weaker empires fight to survive desperately, while the more powerful ones develop their territories and broaden their own powers. ICA basically models the imperialistic competition through getting the weakest colony out of other empires with a specific competition among the rest of them (Fig. 8). The empire's possession probability is in agreement with its own power and expansion. At the time that all the empire's countries are lost in the imperialistic competition, it generally falls. Finally, there exists just an empire controlling all other countries. Almost all countries involving the imperialist have the same merits and positions. This shows the optimization problem's ultimate solution.

Fig. 8

As mentioned above, the paper's main objective is to obtain a solution for multi-objective problem applying MOICA method. In this regard, a set of prevailing points is obtained by using this method, which are to obtain minimum total environmental emissions along with maximum output energy. MOICA will generate several solutions. As such, a third condition is needed to determine the best generation. In this study, the minimum rate of total energy consumption by independent variables is considered for the determination of optimal unit in walnut production. A flowchart to apply the MOICA method on multi-objective energy-environmental problem is demonstrated in Fig. 9.

Fig. 9

Excel 2019 spreadsheet is applied for analyzing the energy use. LCA is conducted by SimaPro V9.0.0 software. Besides, Matlab (R2020a) software package is employed in developing MOICA and SPSS 25 is used in modelling among outputs and inputs to describe the fitness functions.

3. Results

3.1. Energy analysis of walnut production

Input and output amounts as well as their energy equivalents for walnut production process are outlined in Table 6. These findings show that human labor and agricultural machinery are applied at about 522 h and 3 kg per ha, respectively. A great deal of machine power in the orchards are applied in fertilizing and spraying processes. Analysis of fuel consumption reveals that average diesel fuel and gasoline requirements for operating, fertilizing, spraying and water pumping are about 120 and 269 L ha^{-1}, respectively. In Table 6, the total energy consumption for producing walnut and the computed energy output are around 31015 and 27200 MJ ha^{-1}, respectively.

Table 6

Fig. 10 presents the energy percentage distributions related to inputs. Most part of the total input energy is consumed by gasoline (40.18%). The contribution of diesel fuel is 21%. Nitrogen fertilizers has the third place with 13.43%.

Fig. 10

EUE, SE EP, and NE of walnut production are outlined in Table 7. EUE is considered as 0.88. Based on Ministry of Jihad-e-Agriculture of Iran [6], EUE of oil crops such as walnut and hazelnut should be more than 1 because energy contents of these harvested crops are very high. Obviously, their total energy consumption should be less than the generated energy from energy balance point of view. Thus, in the region, the energy consumption in walnut production is inefficient. EP, SE and NE are about 0.03 kg MJ^{-1}, 29.82 MJ kg^{-1}, and -3815.13 MJ ha^{-1}, respectively. The negative NE ratio is an evidence that energy is not generally used effectively in walnut production, and hence high efficiency is not obtained for energy usage in the surveyed region.

Table 7

3.2. LCA results of walnut

3.2.1. LCI analysis

In this study, LCI is categorized into two main sections including inputs and outputs of walnut cultivation systems (Off-Orchard emissions), and On-Orchard emissions. LCI of walnut production is presented in Table 8. All inputs in the production process equal to input energies, except human labor, are considered as On-Orchard emissions and their rates for 1 ha of walnut production are inserted into Table 8. On-Orchard emissions related to different input consumptions are computed for 1 ha of walnut production system in the region.

Table 8

3.2.2. Environmental emissions of walnut production

According to IMPACT 2002+ method, there are 15 midpoints for quantifying environmental burdens. In fact, each impact's rate is important on the surveyed emissions. The results of emission category, however, are basically intended to give more insight in analyzing along with policy making. As such, four impact categories are addressed for walnut cultivation system, and the results are outlined in Table 9.

Table 9

Results indicate that emissions of human health, ecosystem quality, climate change and resources indicators are 0.005 DALY, 35498 PDF*m^2*yr, 2365 kg CO_2 $_{eq.}$, and 28872 MJ primary per 1 t of walnut kernel in Alborz province of Iran, respectively.

The contribution of various inputs to the walnut production' degradation rate is presented in Fig. 11. Based on the results, On-Orchard emissions and nitrogen fertilizers are two main elements having the highest contribution to the degradation in relation to environmental effects. For walnut production in Alborz province of Iran, the contributions of On-Orchard emissions related to ecosystem quality, human health, and climate change are about 90%, 65%, and 32%, respectively. Contributions of nitrogen fertilizers emissions in walnut production are 12% for human health and 22% for climate change. As can be seen in Fig. 11, gasoline has the highest contribution of resources category with about 30%; followed by diesel fuel with about 20%.

Fig. 11

Fig. 12 shows changes to the weighting of environmental emissions. It can be seen that two emission categories, namely, ecosystem quality and human health, have the greatest environmental emissions in walnut production. Moreover, most emissions are related to On-Orchard emissions and nitrogen fertilizers.

Fig. 12

3.2.3. Sensitivity analysis of environmental emissions

Fig. 13 displays the sensitivity analysis for four environmental emissions based on effects of fossil fuels and chemical fertilizers. Fig. 13 is divided into four sections and each part belongs to an endpoint. In each section, the vertical line in the center is the average of the related emissions. In other words, the emissions are computed again by ten percent increase or decrease (±10%) of fossil fuels and chemical fertilizers and decreasing and increasing rates are highlighted by green and red, respectively. Results reveal that, in all environmental emissions (expect resources), chemical fertilizers have the highest sensitivity on environmental categories. As can be seen in part (d) of Fig. 13, the highest sensitivity on resources category belongs to fossil fuels.

Fig. 13

3.3. Optimized energy use and environmental emissions by MOICA

The objective functions are fitted by applying linear regression for outputs and inputs based on Eqs. (8) and (9) as follows:

$$OE = -.0.66_1 X_1 - 0.47X_2 - 0.07X_3 - 0.001X_4 - 0.07_5 X_5 - 0.17X_6 + 0.05X_7 - 0.09X_8 - 0.03X_9 - 0.04X_{10} + e_i \tag{8}$$

$$TED = -0.43X_1 - 0.07X_2 + 0.23X_3 + 0.32X_4 + 0.21X_5 - 0.04_6 X_6 + 0.03X_7 + 0.1X_8 + 0.07X_9 + 0.05X_{10} + e_i \tag{9}$$

MOICA generates 100 solutions in order to enhance energy output and simultaneously decrease total environmental emissions in walnut production. However, the focus is on decreasing energy use in walnut production. Accordingly, the input energy's optimal rate attains the highest output energy, the lowest total weighted emissions and the lowest total energy requirement as the best empire are presented in Table 10.

Table 10

Energy saving along with its percentage of MOICA application are presented in Table 10. Results reveal the optimal energy requirement is equal to 11698.18 MJ ha^{-1}; whilst the output energy is fixed and equal to average (27199.55 MJ ha^{-1}). In other words, the best solution can be reduced by 19316.49 MJ ha^{-1} in total energy use of walnut production, which implies it saves 62.28% of total input energy without walnut yield reduction. The last column of Table 10 indicates each input's change percentage in comparison with the original value. Moreover, the largest difference between optimal and present condition in inputs belongs to gasoline and biocides with 90.63% and 73.69%, which can save energy by about 11293 and 233 MJ ha^{-1}, respectively. Moreover, electricity has the lowest change with 23.03%, which reveals that the difference between optimum and present consumptions in electricity is not significant. Although diesel fuel has a 63.20% difference between present and optimum conditions, about 4261 MJ ha^{-1} can be saved by changing diesel fuel consumption pattern to optimum rate.

The different sources' contributions from the total input energy saving are demonstrated in Fig. 14. Our findings show that the largest total saving energy's contribution is 58.47% for gasoline, followed by diesel fuel (22.06%). Moreover, the shares of agricultural machinery, phosphate, potassium, FYM and biocides are low, indicating that they have been applied properly by most orchards from energy perspective.

Fig. 14

The walnut production's energy indices improvements are shown in Table 11. After the optimization by MOICA, EUE is computed as 2.33, showing an improvement of 11,616%. Besides, EP, SE and NE in optimal condition are 0.09 kg MJ^{-1}, 11.25 MJ kg^{-1}, and 15501.37 MJ ha^{-1}, respectively. These rates indicate that MOICA can modify EP, SE and NE by about 116.15%, 60.45% and 506.31%, respectively.

Table 11

After having optimized the energy consumption in walnut production by using MOICA, environmental emissions are recomputed, and the computation results are outlined in Table 12. Based on the results, ecosystem quality, climate change, human health, and resources in optimal condition can be saved by about 13366.97 PDF*m^2*yr, 1061.50 kg CO_2 eq., 0.002

DALY (Disability adjusted life years), and 16002.43 MJ primary, respectively. Moreover, Table 12 shows that the highest improvement between categories in comparison with the original values belongs to resources with 55.43%.

Table 12

Fig. 15 displays the shares of different categories in total weighted emission reduction by MOICA. The greatest contribution to the total weighted emission reduction is provided by ecosystem quality with 66.22% and followed by human health (19.35%). Moreover, the contributions of climate change and resources are about 7.28% and 7.15%, respectively.

Fig. 15

4. Discussion

4.1. Interpretation of results

4.1.1. Before MOICA

As mentioned above, the total energy use in walnut system is around 31015 MJ ha^{-1} and gasoline and diesel fuel have the greatest proportion in energy consumption. Moreover, nitrogen and electricity are also significant energy consumers in next places. Previous studies reported that the total input energy about were 19488, 35235, 10906, 39812, and 83782 MJ ha^{-1} in walnut production of Iran [77], almond production of Chaharmahal-Va-Bakhtiari province, Iran [27], walnut production of Turkey [31], almond production of Turkey [41], and citrus production of Adana province, Turkey [78], respectively. Furthermore, in other researches in Hamedan province of Iran [77] and in Turkey [31], nitrogen fertilizer was reported as most energy consuming in walnut production. The result comparison reveals that the amount of energy consumption for this product is relatively higher than other products in Iran and also compared to other oil products in other countries. This comparison indicates that in recent years, fuel consumption has increased compared to fertilizers in walnut production. Of course, this interpretation alone cannot determine the energy consumption' efficiency in the production of crops. To this end, the results of energy indicators should also be considered.

Energy indices analysis of walnut production reveals that walnut production is not efficient from energy prospective because EUE is less than 1 (0.88). When EUE is less than 1, it indicates that the total input energy is greater than output energy. In other words, the production process of walnut not only increases the total energy usage in the nature but also reduces the energy resource of world. Furthermore, as mentioned earlier, low EUE rate indicates energy inefficiency for agricultural products anywhere in the world. However, due to the oily nature of the walnut crop and the higher energy content of the harvested crop compared to many crops and horticultural products, this index should show a higher rate. Previous studies reported that EUE rates for maize [79] in Netherlands, apple [45] and walnut [77] in Iran, soybean [45] in Italy, kiwifruit [54] in Iran, walnut [31] and almond [41] in Turkey are 2, 1.16, 2.9, 6.2, 1.17, 0.66, and 2.02, respectively. Comparing energy indices of walnut system in Alborz province of Iran with its production in other places as well as the production of other crops also indicate the inefficiency of energy consumption in the production of walnut product, which renders the need for optimization more obvious. As indicated in the attained results of environmental analysis, On-Orchard emissions has the main effect on environmental emissions. In fact, research of On-Orchard emissions showed that direct emissions from gasoline combustion and diesel fuel used in agricultural machinery caused high rates of On-Orchard emissions in walnut production. It should not be forgotten that gasoline and diesel production process in Iranian refineries is the main cause of environmental emissions caused by resources.

In another study, Cambria and Pierangeli [80] examined LCA of walnut trees production in Italy. Their results also revealed that fertilizers and fuel for primary tillage had the highest environmental impacts. Results of another research in Greece [81] about LCA in three horticultural crops including apple, almond and pistachio revealed that fertilizers and fuels in filed management had the highest share in production process emissions. In a study about LCA in conventional and organic production of apple in China, fertilizers and diesel were introduced as main hotspots by Zhu et al. [82]. In similar results with the present study, Hosseini-Fashami et al. [47] pointed out that On-Farm emissions, diesel fuel and nitrogen fertilizers were most effective in environmental effects of strawberry production in Iran.

The results of sensitivity analysis show that environmental emissions are more sensitive to changes in the use of chemical fertilizers. Of course, this sensitivity in the resources category is more affected by fuel. This is due to the strong dependence of this index on the background emissions from the fossil fuel production process in refineries and On-Orchard emissions have no effect on it.

However, all interpretations not only in this study, but also in studies in other parts of the world and on other products, are largely focused on excessive applications of chemical fertilizers and fossil fuels. In the first step, agricultural management should address the reasons for these irregular consumption.

Generally, in walnut production, these reasons include the use of horticultural tillers for primary tillage and transportation of FYM in orchards with low efficiency in fuel consumption, old mechanism application in agricultural machinery including sprayers and fertilizers that cause irregular use of fuels, biocides and chemical fertilizers such as nitrogen, use of inefficient gasoline engine in biocides sprayers, lack of timely maintenance in agricultural machinery including horticultural tillers, sprayers, fertilizers and water pumps, use of water pumps with low efficiency with irregular rate of gasoline and diesel fuel for irrigation, use of chainsaw for pruning of extra branches with high rate of gasoline, lack of determination of standard pattern for inputs energy, small area of orchards that causes lack of economic justification for buying agricultural machinery in the studied area.

The low cost of chemical fertilizers and fuel, and the lack of incentive and punishment policies for producers with optimal consumption, as well as the lack of orchardist's education, even internationally, have led to the belief that more chemical fertilizers equals higher yields. This issue is one of the important reasons for fossil fuels and chemical fertilizers' excessive consumption not only in Iran but also in many parts of the world.

Since the world moves to conserve energy resources, the production of crops with negative efficiency is not logical. As such, there are two ways to resolve this problem. The first one is increasing walnut yield and the second one is decreasing input energy. Although the increase in walnut kernel has much utility from output energy and economic benefits viewpoint for orchardists but there are two main problems for achieving this purpose. The first one is biological limitation, which does not allow increasing yield from a determined amount. The second one is more required energy for increasing inputs. In another way, the reduction of input energy is possible by modification of the production system, but the main point is fixing walnut yield with a reduction of energy resources. Thus, energy optimization is a vital program for future production of this horticultural crop.

4.1.2. After MOICA

MOICA creates an optimized input energy model by finding an energy-environmental-friendly condition that requires the results to be analyzed according to each approach. In energy aspect, MOICA results indicate that gasoline and diesel fuel have positive effects with more than 80% total energy saving. About 60% of this amount belongs to gasoline and 20% to diesel. As shown in Table 10, the consumption of gasoline in the optimum mode is reduced by 90% and diesel consumption by 63% compared to the present mode, and this reduction takes place without reducing the yield of walnuts. In environmental aspects, the highest difference between the present and optimum conditions in environmental emission category belongs to resources. It is because this category is dependent on gasoline and diesel fuel more than other categories and as shown in the results, gasoline and diesel fuel have the greatest shares in total saving by MOICA. On the other hand, MOICA indicates that ecosystem quality has the highest share in total weighted emission reduction. This result is not unexpected because most share of total weighted emissions belongs to ecosystem quality. On-Orchard emissions related to using gasoline and diesel fuel have most effect on this category in the present scenario. Thus, with respect to the reduction of gasoline and diesel fuel amounts in the optimum condition by MOICA, the ecosystem quality is largely reduced out of total weighted environmental emissions in walnut system.

Banaeian et al. [16] found that the DEA application for single-objective optimization of input energy in walnut production could save about 7745 MJ ha-1 of the whole input energy in case farmers followed the input package suggested by efficient units. They reported that the largest part of energy savings appertained to nitrogen with 69%. They also reported that EUE of walnut production was able to improve by about 27.5% using DEA optimization [16]. Besides, Nabavi-Pelesaraei et al. [33] reported that genetic algorithm utilization for multi-objective optimization could reduce the global warming potential by about 70%.

Almost all researches regarding energy optimization and environmental impacts in crops were either local or single-purpose, as explained in detail above in the literature review. Of course, they have been able to be somewhat effective in improving the system and the process of input consumption, but none of them has provided a definite and final solution with a comprehensive view. Few previous studies studied multi-objective optimization, yet most of them used genetic algorithm; while MOICA has many advantages on multi-objective optimization over other algorithms. The first advantage is the novelty of the basic idea of the algorithm, which as the first optimization algorithm based upon a socio-political process has the ability to optimize evenly and even higher in comparison with other optimization algorithms in solving a variety of optimization problems. The second advantage is the speed of finding the optimal answer.

A remarkable thing about most evolutionary optimization methods is that these methods are usually derived from biological evolution and modeling of natural phenomena, and usually aspects of evolution for which there is no known model are marginalized in research. In fact, MOICA's main motivation is to find an answer to the question of whether other aspects of human evolution can be used as a source of inspiration for an optimization algorithm. Given the applications of ICA, it can be said that human and behavioral factors that logically cannot be considered mathematically in optimization algorithms in other evolutionary algorithms, such as genetics, have been fully considered in solving the optimization problem.

As mentioned, the optimal consumption points of each input is the point between the minimum and maximum input consumption in the study area, which is obtained by MOICA in the Pareto principle according to the objective functions defined. In other words, walnut yield average is attained by orchardists with a much lower rate of gasoline and diesel fuel consumption. Actually, increasing gasoline and diesel consumption not only does not increase yield, but also does not reduce walnut yield based on diminishing return's law. Therefore, the hypothesis that consuming less fossil fuels may reduce yield is completely wrong. The same argument can be used to justify the improvement of all energy indicators, including EUE, because the optimal rate indicates that in much less consumption, more yield and less environmental emissions are attained. One of the benefits of MOICA is that it sets a reasonable limit on input consumption. This limitation not only does not address the results locally, but also generalizes the optimization results globally by adhering to defined standards for the minimum amount of input required. Accordingly, considering the input use pattern of optimal units (less input consumption without less production) is a necessary item to determine fossil fuel saving as much as the computed optimum rate without disrupting the walnut horticultural system, which will be described in the next section. It should be noted that nitrogen fertilizer with a much lower percentage of fuels can save energy using MOICA. The lack of significant differences in the minimum and maximum amounts of chemical fertilizers indicates that the dependence of walnut producers on chemical fertilizers is very high and there is not much difference in terms of chemical fertilizer consumption between the optimal and present units. This shows a high sensitivity of orchards to the use of chemical fertilizers, as in the sensitivity analysis, the high effect of this input on environmental indicators is discussed. Therefore, if the saving of chemical fertilizers is considered by policymakers, they should make fundamental changes in the horticultural systems, which requires a global reform and definition of the international structure.

4.2. Managerial implications

After expression of results, the presentation of managerial solutions is necessary because a comprehensive study should consider the early and late return strategies for improvement of the systems. The walnut production and its optimization by MOICA are not exempted from this subject. As mentioned in the previous section, the optimization of fossil fuels and chemical fertilizers inputs is the most important part of applied management in horticultural systems. Their amount in gasoline up to about 90% and diesel fuel up to about 63% can be reduced compared to the conventional consumption. The reports of the Ministry of Jihad-e-Agriculture of Iran [6] on "Study of agricultural inputs management in the world" as well as the study of units whose fuel consumption and chemical fertilizers are close to the optimal level, showed that hard working conditions of agricultural machinery in orchards could lead to fuel consumption up to between 50% to 60% over the standard. Therefore, timely maintenance, including timely change of engine oil, adjusting wheel air, checking the health of wheels, timely replacement of oil and air filters, checking valves and periodic inspections of the refueling system can reduce fuel consumption (in the same period of use from agricultural machinery) up to 30% in gasoline and machines and up to 20% in diesel machines [6]. In other words, the failure to comply with any of these causes a loss of useful energy and increases the required indicated power and therefore the engine must consume more fuel to supply it. Proper and timely pruning methods reduce the use of chainsaw by 20% and consequently gasoline consumption by 13%. Besides, the experience of agricultural machinery operators can be very effective in reducing fuel consumption. Proper training of operators by relevant organizations and consequently the basic use of agricultural machinery such as avoiding stressful driving, timely shifting of gears, cause less pressure and improve fuel efficiency so that the consumption in the gasoline and diesel machine can be reduced by about 27% and 15% [6]. On the other hand, the combination of biological control with chemical methods in the fight against insects and fungi, in addition to reducing about 90% of agrochemicals, by eliminating spraying operations up to about 20% can reduce gasoline consumption in gasoline sprayers and 28% in diesel sprayers [6]. Since the Ministry of Jihad-e-Agriculture is in charge of supplying and distributing chemical fertilizers for walnut orchardists in the studied area, conducting soil texture experiments and determining the required fertilizer and granting the required fertilizers' amount can be one of the most effective solutions in proper use of chemical fertilizers by up to 33%. In other parts of the world, NGOs and syndicates can take on this task. Although all these cases can be attained internationally without reducing crop yield as quick-return solutions to achieve optimal and sustainable production, but the development of management strategies to promote and educate these cases is also important and necessary in the development of these methods. The adoption of policies such as the elimination of fossil fuel subsidies, as well as the imposition of restrictions on over-refueling or excessive use of chemical fertilizers by a scientific observer approved by government agencies or NGOs, can be one of early return solutions in horticultural production.

Although early return solutions can make tangible improvements in a short period, internalizing a sustainable production system also requires late return strategies. These strategies can include some cases such as increasing agricultural mechanization level, use of renewable energy sources such as solar systems to supply the required energy for different operations that use gasoline and diesel fuels, planting resistant varieties of walnut to avoid chemical control of insects and fungus, integration of ownership levels for small-scale walnut orchards, and monitoring orchardists' behavior in input energy consumption and determining penalty policies for inefficient units.

4.3. Limitations

This study has several limitations. The first limitation is the lack of data for transporting inputs from the factory to the orchard. In fact, the supply and purchase of inputs from different marketing units and the variety of vehicles in transportation render them to be ignored due to lack of access to this information in LCA. However, there was a theory that the type of transportation system and its efficiency or inefficiency could not be taken into account by the orchardists and the horticultural system. The second limitation is the lack of experiments to determine the amount of chemical fertilizers required, which lead to the minimum and maximum consumption as a limitation in optimization with MOICA, while experiments can shorten this range and provide more accurate results. Finally, changes in weather conditions in some areas may change the policy of applying the input in the orchard, so there may be uncertainty in some data. Therefore our results are affected by these limitations.

5. Conclusions

Energy-life cycle assessment of walnut production is evaluated for multi-objective energy optimization and environmental emissions for walnut system in Alborz province of Iran. Input-output analysis is considered with four environmental categories as variables. In this study, the boundary system covers inputs entry to the orchard till the harvesting process and the functional unit is considered as 1 ton of walnut. The main findings of this study are total input and output energies of about 31015 and 27200 MJ ha^{-1}, respectively. Energy use efficiency rate is about 0.88, which reveals an inefficient energy balance. In environmental aspect, On-Orchard emissions are important factor in ecosystem quality, climate change, and human health categories. These emissions are mostly related to fossil fuels and chemical fertilizers. Moreover, in resources category, gasoline and diesel fuel are the most contributing inputs. The best generation computed by multi-objective imperialist competitive algorithm indicates savings of 19316.49 MJ ha^{-1} (62% reduction in comparison with the present condition) and 1.47 Pt (40% of total weighted emissions). Fossil fuels including gasoline and diesel fuel are most energy-environmental effective in walnut production. So, they have the highest potential for reduction by multi-objective optimization. Applying timely maintenance, true education systems for orchardists, adopting appropriate policies can help orchardist attain close to optimum condition from energy-environmental point of view.

The results indicate that multi-objective imperialist competitive algorithm, as a new approach in meta-heuristic algorithms, can modify the horticultural production system especially in walnut by offering comprehensive global pattern. It should be noted that the proposed optimal model covers all aspects and goals, and its comprehensiveness is such that it can be used and exploited not only in the study area but also in all parts of the world, and this distinguishes this study from all previous studies. Of course, this research can be continued by studying other indices such as eco-efficiency and planting sustainability using optimum pattern of this study in an orchard, avoiding limitation about soil texture experiment and determination of accurate requirement rate of chemical fertilizers. The research method of this study can be used by other researchers elsewhere in the world to evaluate the optimum condition of other agricultural systems. Moreover, integrating knowledge about precision agriculture especially in variable rate technology and evaluating optimal route for agricultural operations with multi-objective imperialist competitive algorithm can present better optimization pattern with more details to orchardists. Definitely, these new patterns can furnish clearer guideline to produce sustainable products.

Highlights

- Energy and life cycle assessment of walnut are computed by IMPACT 2002+.
- MOICA is used to optimize output energy and total weighted damages.
- Gasoline and On-Orchard emissions are the most effective factors in energy and LCA.
- MOICA can save total energy and damages by about 19316 MJ ha^{-1} and 1.47 Pt.
- Gasoline and ecosystem quality have most potential in saving by MOICA.

Table 1
Summary of researches carried out on energy, environmental analysis and their optimization in agri-food sector.

Previous study	Geographical position	Crop	Energy analysis	Environmental analysis	LCA method	Optimization approach		Optimization technique
						Single-objective	Multi-objective	
Banaeian et al. [16]	Iran (Hamedan)	Walnut	☑	☒	☒	☑	☒	DEA
Gundogmus [17]	Turkey	Walnut	☑	☒	☒	☒	☒	☒
Mohammadi et al. [18]	Iran (Golestan)	Soybean	☑	☑	CML2	☑	☒	DEA
Moya et al. 2013 [19]	Cuba	Sugarcane	☑	☑	ReCiPe2008	☒	☒	☒
Nabavi-Pelesaraei et al. [20]	Iran (Guilan)	Orange	☑	☑	Greenhouse gas	☑	☒	DEA
Romero-Gámez et al. [21]	Spain	Tomato	☒	☑	ReCiPe2008	☒	☒	☒
Palmieri et al. [22]	Italy	Rapeseed	☒	☑	ReCiPe2008	☒	☒	☒
Kendall et al. [23]	United States	Almond	☑	☑	Greenhouse gas	☒	☒	☒
Ebrahimi and Salehi [24]	Iran (Isfahan)	Mushroom	☑	☑	Greenhouse gas	☑	☒	DEA
Mohammadi et al. [25]	Iran (Golestan)	Paddy	☑	☑	CML2	☑	☒	DEA
Proietti et al. [26]	Italy	Walnut	☒	☑	Greenhouse gas	☒	☒	☒
Beigi et al. [27]	Iran (Chaharmahal)	Almond	☑	☒	☒	☒	☒	☒
Boone et al. [28]	Belgium	Maize	☒	☑	ReCiPe2008	☒	☒	☒
Nabavi-Pelesaraei et al. [29]	Iran (Guilan)	Orange	☑	☑	Greenhouse gas	☒	☑	MOGA
Bacenetti et al. [30]	Europe	Agricultural crops	☑	☑	Greenhouse gas	☒	☒	☒
Baran et al. [31]	Turkey	Walnut	☑	☒	☒	☒	☒	☒
Mousavi-Avval et al. [32]	Iran (Golestan)	Canola	☑	☑	CML2	☒	☑	MOGA
Nabavi-Pelesaraei et al. [33]	Iran (Guilan)	Paddy	☑	☑	CML2	☒	☑	MOGA
Paramesh et al. [34]	India	Arecanut	☑	☑	CML2	☑	☒	DEA
Kaab et al. [35]	Iran (Khuzestan)	Sugarcane	☑	☑	CML2	☒	☑	MOGA
Álvarez-Rodríguez et al. [36]	Spain	Groceries	☑	☑	CML2	☑	☒	DEA
Nabavi-Pelesaraei et al. [11]	Iran (Guilan)	Rice	☑	☑	CML2	☒	☑	MOGA
Wang et al. [37]	China	Wolfberry	☑	☑	Greenhouse gas	☒	☒	☒
Grados and Schrevens [38]	Peru	Potato	☑	☑	CML2	☑	☒	DEA
Breen et al. [39]	Ireland	Dairy farms	☑	☑	Greenhouse gas	☒	☑	MOGA
Saber et al. [40]	Iran (Mazandaran)	Paddy	☒	☑	IMPACT 2002+	☒	☒	☒
Baran et al. [41]	Turkey	Almond	☑	☑	Greenhouse gas	☒	☒	☒
Ghasemi-Mobtaker et al. [2]	Iran (Hamedan)	Barley	☑	☑	ReCiPe2016	☒	☒	☒
Fan et al. [42]	China	Rice Paddy	☑	☑	Greenhouse gas	☒	☒	☒
Mostashari-Rad et al. [43]	Iran (Guilan)	Horticultural crops	☑	☑	ReCiPe2016	☒	☒	☒
Present study	**Iran (Alborz)**	**Walnut**	☑	☑	**IMPACT 2002+**	☒	☑	**MOICA**

Table 2

Specification of walnut production in Alborz province of Iran.

Item	Specification
Soil	Well-drained loamy bottomlands with medium texture (at least 3 feet deep)
Slope	Less than 15 percent
Nitrogen	0.25 to 0.3%
Phosphate	60 to 80 pounds per acre
Calcium	3000 to 4000 pounds per acre
Potassium	225 to 275 pounds per acre
Magnesium	375 to 600 pounds per acre
Organic matter	2 to 3.5%
pH	6.5 TO 7.2
Optimum condition	Full sun protected from wind and extreme temperature variations
Sensitive to	Prolonged flooding (3 to 4 days of standing water)
Tractors (sweeper & blower)	John Deere 3020
Tractors (shaker)	Hesston 780
Tractors (harvester)	John Deere 4020
Best harvest conditions	4 inches in height grass, smooth soil surface, not any dead branches and a minimal rise through the tree' row

Table 3
Standard coefficients to compute energy content of outputs and inputs in walnut production.

Item	Unit	Energy equivalent (MJ unit^{-1})	Reference
A. Inputs			
1. Human labor	h	1.96	[46]
2. Agricultural machinery	kg based on economic life	142.7	[47]
3. Diesel fuel	L	56.31	[48]
4. Gasoline	L	46.3	[49]
5. Chemical fertilizers	kg		
(a). Nitrogen		66.14	[50]
(b). Phosphate		12.44	[51]
(c). Potassium		11.15	[52]
6. FYM	kg	0.3	[53]
7. Biocides	kg	120	[54]
8. Electricity	kWh	11.93	[55]
B. Output			
1. Walnut	kg	26.15	[16]

Table 4
Energy indices in cropping system of walnut production.

Index	Unit	Equation
1. EUE	-	$\frac{\text{Output energy (MJ ha}^{-1}\text{)}}{\text{Total input energy (MJ ha}^{-1}\text{)}}$
2. EP	kg MJ^{-1}	$\frac{\text{Walnut yield (kg ha}^{-1}\text{)}}{\text{Total input energy (MJ ha}^{-1}\text{)}}$
3. SE	MJ kg^{-1}	$\frac{\text{Total input energy (MJ ha}^{-1}\text{)}}{\text{Walnut yield (kg ha}^{-1}\text{)}}$
4. NE	MJ	$\text{Output energy (MJ ha}^{-1}\text{) - Total input energy (MJ ha}^{-1}\text{)}$

Table 5
Emission coefficients related to diesel fuel and gasoline combustion in machinery.

Emission	Amount (kg MJ^{-1} diesel)
A. Emissions of diesel fuel combustion to air	
NH_3	4.44E-07
C_6H_6	1.62E-07
Benzo (a) pyrene	6.68E-10
Cd	2.22E-10
CO_2, fossil	0.07
CO, fossil	1.30E-04
Cr	1.11E-09
Cu	3.78E-08
N_2O	2.67E-06
Heat, waste (MJ)	1.01
CH_4, fossil	2.87E-06
Ni	1.55E-09
NOx	8.66E-04
NMVOC	4.77E-05
PAH	7.29E-08
Particulates, < 2.5 um	1.09E-04
Se	2.22E-10
SO_2	2.24E-05
Zn	2.22E-08
B. Emissions of diesel fuel combustion to soil	
Cd	3.98E-09
Pb	1.75E-08
Zn	1.07E-05
C. Emissions of gasoline combustion to air	
C_4H_6	5.86E-07
C_2H_4O	1.15E-05
C_3H_4O	1.39E-06
C_6H_6	1.40E-05
CO_2	2.09
CO	0.14
CH_2O	1.77E-05
CH_4	9.21E-04
N_2O	6.10E-05
NOx	0.03
PAH	2.52E-06
Particulates, > 2.5 µm, and < 10 µm	2.65E-04
C_3H_6	3.86E-05
C_7H_8	6.13E-06
SO	5.01E-04
VOC	2.84E-03
C_8H_{10}	4.27E-06

Table 6

Inputs and outputs' physical amount along with their energy equivalents for walnut system in Alborz province, Iran.

Item (unit)	Unit ha^{-1}	Energy consumption ($MJ\ ha^{-1}$)	Standard deviation ($MJ\ ha^{-1}$)	Uncertainty percentage (%)
A. Inputs				
1. Human labor (h)	521.56	1022.25	298.87	29.24
2. Agricultural machinery (kg)	2.60	370.55	123.42	33.31
3. Diesel fuel (L)	119.74	6742.78	949.99	14.09
4. Gasoline (L)	269.13	12460.76	1843.79	14.80
5. Chemical fertilizers (kg)				
(a). Nitrogen	62.96	4164.30	287.84	6.91
(b). Phosphate	72.46	901.46	49	5.44
(c). Potassium	130.70	1457.29	179.93	12.35
6. FYM (kg)	1655.08	496.53	110.87	22.33
7. Biocides (kg)	2.63	315.75	39.54	12.52
8. Electricity (kWh)	258.42	3083	216.53	7.02
Total input energy (MJ)	-	31014.68	2903.92	9.36
B. Output				
1. Walnut (kg)	1040.14	27199.55	3340.33	12.28

Table 7
Energy indices assessment for walnut system in Alborz province, Iran.

Index	Unit	Value
1. EUE	-	0.88
2. EP	kg MJ^{-1}	0.03
3. SE	MJ kg^{-1}	29.82
4. NE	MJ	-3815.13

Table 8

LCI report of walnut production of Alborz province, Iran based upon 1 ha.

Item	Unit	Amount
A. Off-Orchard emissions		
1. Agricultural machinery	kg	2.6
2. Chemical fertilizers	kg	
(a). Nitrogen		62.96
(b). Phosphate		72.46
(c). Potassium		130.7
3. FYM	kg	1655.08
4. Biocides	kg	
(a). Pesticides		1.71
(b). Fungicides		0.92
5. Diesel fuel	kg	102.98
6. Gasoline	kg	183.01
7. Electricity	kWh	258.42
B. On-Orchard emissions		
1. Emissions by diesel fuel burning to air		
(a). NH_3	kg	0.003
(b). C_6H_6	kg	1.09E-03
(c). Benzo (a) pyrene	kg	4.50E-06
(d). Cd	kg	1.50E-06
(e). CO_2, fossil	kg	467.39
(f). CO, fossil	kg	0.88
(g). Cr	kg	7.49E-06
(h). Cu	kg	2.55E-04
(i). N_2O	kg	0.02
(j). Heat waste	MJ	6804.64
(k). CH_4, fossil	kg	0.02
(l). Ni	kg	1.05E-05
(m). NOx	kg	5.84
(n). NMVOC	kg	0.32
(o). PAH	kg	4.91E-04
(p). Particulates, < 2.5 um	kg	0.74
(q). Se	kg	1.50E-06
(r). SO_2	kg	0.15
(s). Zn	kg	1.50E-04
2. Emissions by diesel fuel burning to soil		
(a). Cd	kg	2.68E-05
(b). Pb	kg	1.18E-04
(c). Zn	kg	0.07
3. Emissions by gasoline burning to air		
(a). C_4H_6	kg	1.58E-07
(b). C_2H_4O	kg	3.09E-06
(c). C_3H_4O	kg	3.73E-07
(d). C_6H_6	kg	3.76E-06
(e). CO_2	kg	0.56
(f). CO	kg	0.04
(g). CH_2O	kg	4.76E-06
(h). CH_4	kg	2.48E-04
(i). N_2O	kg	1.64E-05
(j). NOx	MJ	0.01
(k). PAH	kg	6.77E-07

(l). Particulates, > 2.5 um, and < 10um	kg	7.14E-05
(m). C_3H_6	kg	1.04E-05
(n). C_7H_8	kg	1.65E-06
(o). SO	kg	1.35E-04
(p). VOC	kg	7.63E-04
(q). C_8H_{10}	kg	1.15E-06
3. Emissions by fertilizers to air		
(a). N_2O	kg	1.58
(b). NH_3 derived from pure nitrogen in chemical fertilizers	kg	9.08
(c). NH_3 derived from pure nitrogen in FYM	kg	7.65
4. Emission by atmospheric deposition of fertilizers to air		
(a). N_2O derived from pure nitrogen in chemical fertilizers	kg	0.1
(b). N_2O derived from pure nitrogen in FYM		0.12
5. Emissions by fertilizers to water		
(a). NO_3^-	kg	13.33
(b). PO_4^{3-}	kg	1.59
6. Emission by N_2O of fertilizers and soil to air		
(a). NOx	kg	0.38
7. Emission by heavy metals of fertilizers to soil		
(a). Cd	mg	3465.99
(b). Cu	mg	159195.53
(c). Zn	mg	412874.38
(d). Pb	mg	350026.26
(e). Ni	mg	13835.09
(f). Cr	mg	49408.36
(g). Hg	mg	53.81
8. Emission by human labor to air		
(a). CO_2	kg	365.09
9. Emissions by biocides to air		
(a). Ethion	kg	0.01
(b). Copper oxychloride	kg	0.04
(c). Diazinon	kg	0.07
(d). Dimethoate	kg	0.02
(e). Cypermethrin	kg	0.02
(f). Captan	kg	0.05
(g). Carbaryl	kg	0.05
(h). Malathion	kg	0.01
10. Emissions by biocides to water		
(a). Ethion	kg	0.01
(b). Copper oxychloride	kg	0.02
(c). Diazinon	kg	0.03
(d). Dimethoate	kg	0.01
(e). Cypermethrin	kg	0.01
(f). Captan	kg	0.03
(g). Carbaryl	kg	0.03
(h). Malathion	kg	0.004
11. Emissions by biocides to soil		
(a). Ethion	kg	0.12
(b). Copper oxychloride	kg	0.35
(c). Diazinon	kg	0.56
(d). Dimethoate	kg	0.13
(e). Cypermethrin	kg	0.14
(f). Captan	kg	0.43
(g). Carbaryl	kg	0.44

(h). Malathion	kg	0.06
C. Output		
1. Walnut yield	kg	1040.14

Table 9
Emission rate of endpoints based on 1 t of walnut production in the studied area.

Endpoint	Unit	Quantity
Human health	DALY [a]	0.005
Ecosystem quality	PDF*m^2*yr [b]	35498.08
Climate change	kg $CO_{2\ eq.}$	2364.60
Resources	MJ primary	28872.21

[a] DALY: An emission of 1 is equivalent to: lack of 1 life year of 1 personal, or 1 person suffers 4 years from an inability with a weight of 0.25.

[b] PDF*m^2*year: An emission of 1 is equivalent to disappearing of all species from 1 m^2 throughout 1 year, or vanishment of 10% of species from 1 m^2 throughout 10 years, or vanishment of 10% of species from 10 m^2 throughout 1 year.

Table 10

Assessment of optimum and saved energies in walnut production after MOICA optimization.

Input energy	Computed optimum energy (MJ ha^{-1})	Saved energy (MJ ha^{-1})	Saved energy (%)
1. Human labor	288.75	733.5	71.75
2. Agricultural machinery	247.40	123.15	33.23
3. Diesel fuel	2481.29	4261.49	63.20
4. Gasoline	1167.36	11293.4	90.63
5. Chemical fertilizers			
(a). Nitrogen	3183.02	981.28	23.56
(b). Phosphate	562.27	339.19	37.63
(c). Potassium	969.29	488	33.49
6. FYM	342.79	153.74	30.96
7. Biocides	83.07	232.68	73.69
8. Electricity	2372.94	710.06	23.03
Total input energy	11698.18	19316.49	62.28

Table 11
Energy indices improvement by MOICA application in walnut production.

Energy index (unit)	Value after optimization	Difference (%) [a]
1. EUE	2.33	116.16
2. EP (kg MJ^{-1})	0.09	116.15
3. SE (MJ kg^{-1})	11.25	-60.45
4. NE (MJ)	15501.37	-506.31

[a] [(Optimum quantity- Present quantity) / Present quantity] × 100

Table 12

Assessment of environmental emissions and saved amounts in walnut production after MOICA optimization.

Endpoint (unit)	Optimum rate of emission category	Saved amount	Saved emission category (%)
Human health (DALY)	0.003	0.002	40.77
Ecosystem quality (PDF*m^2*yr)	22131.11	13366.97	37.66
Climate change (kg $CO_{2\ eq.}$)	1303.10	1061.50	44.89
Resources (MJ primary)	12869.78	16002.43	55.43