Renewable Agriculture and Food Systems

cambridge.org/raf

Sustainability assessment and optimization of legumes production systems: energy, greenhouse gas emission and ecological footprint analysis

Nahid Aghili Nategh[1], Narges Banaeian[2], Alireza Gholamshahi[1] and Mohammad Nosrati[1]

[1]Department of Agricultural Machinery Engineering, Sonqor Agriculture Faculty, Razi University, Kermanshah, Iran and [2]Department of Agricultural Mechanization Engineering, Faculty of Agricultural Sciences, University of Guilan, Guilan, Rasht, Iran

Research Paper

Cite this article: Aghili Nategh N, Banaeian N, Gholamshahi A, Nosrati M (2021). Sustainability assessment and optimization of legumes production systems: energy, greenhouse gas emission and ecological footprint analysis. *Renewable Agriculture and Food Systems* **36**, 576–586. https://doi.org/10.1017/S1742170521000193

Received: 22 November 2020
Revised: 30 January 2021
Accepted: 15 March 2021
First published online: 4 June 2021

Key words:
Chickpea; EFA; energy; lentil; MOGA; optimization

Author for correspondence:
Nahid Aghili Nategh,
E-mail: n.aghili@razi.ac.ir;
Narges Banaeian,
E-mail: banaeian@guilan.ac.ir

Abstract

This study examined energy, greenhouse gas emission and ecological footprint analysis (EFA) of chickpea and lentil cultivation with different mechanization production systems. In lentil production, except for tillage operations, other operations are performed manually and the remaining straw is burned in the field; while in chickpea production, most of the agricultural operations are mechanized and residues are collected, baled and transferred to the warehouse for animal feed. In this paper, for the first time, some of the sustainability indicators are investigated and compared in two different legume production systems. Energy productivity and net energy for chickpea and lentil production were calculated at 0.036, 0.161 and 2373 and 5900 MJ per hectare, respectively. The CO_2 emission and ecological carbon footprint were 173 kg CO_{2-eq} and 0.15 global hectare for lentil and 484 and 0.87 for chickpea production. Totally, due to excessive consumption of diesel fuel and lack of proper management, the social cost of emission from straw baling in chickpea production (27.65 dollars per hectare) was higher than burning straw in lentil production (8.77). Multi-objective genetic algorithm results showed the potential of minimizing diesel fuel and fertilizer consumption and no chemical for chickpea production. Overall audition results of two different production systems revealed that traditional lentil production is more sustainable. Therefore, implementations of modern agricultural practices alone are not enough to achieve sustainability in agricultural production systems.

Introduction

Chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* medik) are annual grain legumes that emanated from west Asia and are widely consumed in human daily food. Chickpeas and lentils are the most important legumes that grow in marginal areas and saline soils (Rao *et al*., 2002). The high protein content (25–25%) of chickpea and lentil makes it widely used in human and animal diets (Yousefi and Damghani, 2012). The cultivation area of lentil in Iran is 140,000 ha, which ranked the sixth most cultivated area in the world. Total chickpea production in Iran is 200,000 tons/year from a cropping area of 56,000 ha (Anonymous, 2010). Based on the Food and Agriculture Organization (FAO) statistics (FAO, 2008), Iran was the seventh largest producer of chickpea after India, Australia, Pakistan, Turkey, Myanmar and Ethiopia, respectively.

Due to the increasing population, energy consumption in agriculture has been increased. Energy analysis studies commonly answer questions about how energy efficiency is and how energy affects the environment. Also, environmental awareness of people increased the demand for the environmentally friendly product that caused agro-scientists to give more attention to cleaner production (Khoshnevisan *et al*., 2015). Many types of research in Table 1 have investigated the energy input–output auditing in different agricultural products from 2004 in different countries. The primary studies on the pattern of energy consumption in the agricultural sector began in 2008 in Iran. Gradually, Artificial Intelligence and new indices entered in the analysis of agricultural systems to find how to achieve sustainable agriculture (Banaeian *et al*., 2020).

Ecological footprint analysis (EFA) is a scientifically reviewed tool that measures life-supporting natural capital (Tusher *et al*., 2020). The role of the EFA as a sustainability indicator has been widely acknowledged (Kissinger and Gottlieb, 2012). The global hectare (gha) is a measurement unit for the EFA that is defined as 'the annual productivity of one hectare of biologically productive land or sea with world-average productivity' (GFN, 2009).

© The Author(s), 2021. Published by Cambridge University Press

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 1. A summary of the previous research done on energy and environmental management

Surveyed study	Geographical scale	Crop	Optimization method of energy consumption	Studied environmental impacts	Ecological footprint analysis
Ozkan *et al.* (2004)	Turkey	Citrus	No	No	No
Rathke and Diepenbrock (2006)	Germany	Oilseed rape	No	No	No
Uzunoz *et al.* (2008)	Turkey	Sunflower seed	No	No	No
Nassiri and Singh (2009)	India	Rice	DEA[a]	No	No
Banaeian *et al.* (2010)	Iran	Walnut	DEA	No	No
Mousavi-Avval *et al.* (2011)	Iran	Canola	DEA	No	No
Qasemi-Kordkheili and Nabavi-Pelesarae (2014)	Iran	Nectarine	DEA	Yes	No
Shamshirband *et al.* (2015)	Iran	Watermelon	MOGA	Yes	No
Baran and Gokdogan (2016)	Turkey	Sugar beet	No	No	No
Elhami *et al.* (2016)	Iran	Chickpea	DEA and MOGA	Yes	No
Elhami *et al.* (2017)	Iran	Lentil	No	Yes	No
Firouzi *et al.* (2017)	Iran	Bean	No	Yes	No
Borsato *et al.* (2018)	Italy	Main agricultural products	No	Yes	No
Nabavi-Pelesaraei *et al.* (2019)	Iran	Rice	DEA and MOGA	Yes	No
Ilahi *et al.* (2019)	Pakistan	Wheat	DEA	Yes	No

[a]Data envelopment analysis.

Commonly, CO_2 emissions are the largest origin of global greenhouse gas (GHG) emissions in the world. Iran as a non-industrial country has always been included among the most polluting countries regarding CO_2 emission and the agriculture section is the most blameful (Taghavifar and Mardani, 2015). In this regard, the assessment tools for the prediction of optimum energy consumption in agriculture section have been investigated in different researches.

Genetic algorithm (GA) is generally applied to generate high-quality solutions to optimization and search problems. Aghili nategh *et al.* (2020) used a multi-objective genetic algorithm (MOGA) optimization to consider economic, energy and environmental indices at the same time. Cellura *et al.* (2013) used GA optimization to determine solutions for the multi-output systems.

For the first time, this paper aims to discuss relevant legumes cultivation with different mechanization production systems in Sonqor and compare the indicators of sustainability in two different lentil and chickpea production systems. Although energy consumption in chickpea and lentil production is investigated separately by Elhami *et al.* (2016, 2017) in Isfahan province of Iran, the current paper is a comparative study that investigates some of the environmental indicators that lead to sustainability and also discuss straw management and social costs for different scenarios.

Other contributions of this paper are applying MOGA optimization procedure to compare the results and find the best combination of energy, CO_2 emissions and ecological footprint parameters for lentil and chickpea production. That is why in this study, energy, CO_2 emission and EFA analyses of lentil and chickpea were performed, common indices calculated and compared by ANOVA test. Consequently, regression models were extended to estimate output energy, EFA and CO_2 emissions. Finally, MOGA was used to forecast how much the input energy has the potential to decrease.

Methodology

This research was conducted in Sonqor town in Kermanshah province in the west of Iran, located between 47 degrees and 36 min east longitudes and 49 degrees and 36 min north latitudes, and its altitude is 1681 m above sea level. The area under cultivation of chickpea and lentil in Sonqor is about 25,000 hectares. The sample size was calculated based on a simple random sampling method (Zangeneh *et al.*, 2010). Fifty-two fields after preliminary evaluation were selected and data collected by using a face-to-face questionnaire method in 2018 work season (Fig. 1).

Nitrogen is used as a chemical fertilizer in chickpea production. Pyramide and bentazone are selective contact post-emergence herbicides, which are applied in chickpea production and control weeds and unwanted plants. Lentil production is completely organic with no chemicals and fertilizer. Mechanization process in lentil production limited just to the application of moldboard, while in chickpea production it used moldboard, disk, row planter and combine (Table 2).

Energy and CO_2 emission

To investigate and analyze energy consumption optimization in a production system, it is necessary to compute the input–output, and then convert all inputs and outputs consumed in agricultural activity to energy, and CO_2 emission by multiplication of related coefficients. Table 3 shows the energy and CO_2 coefficients in legumes production.

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

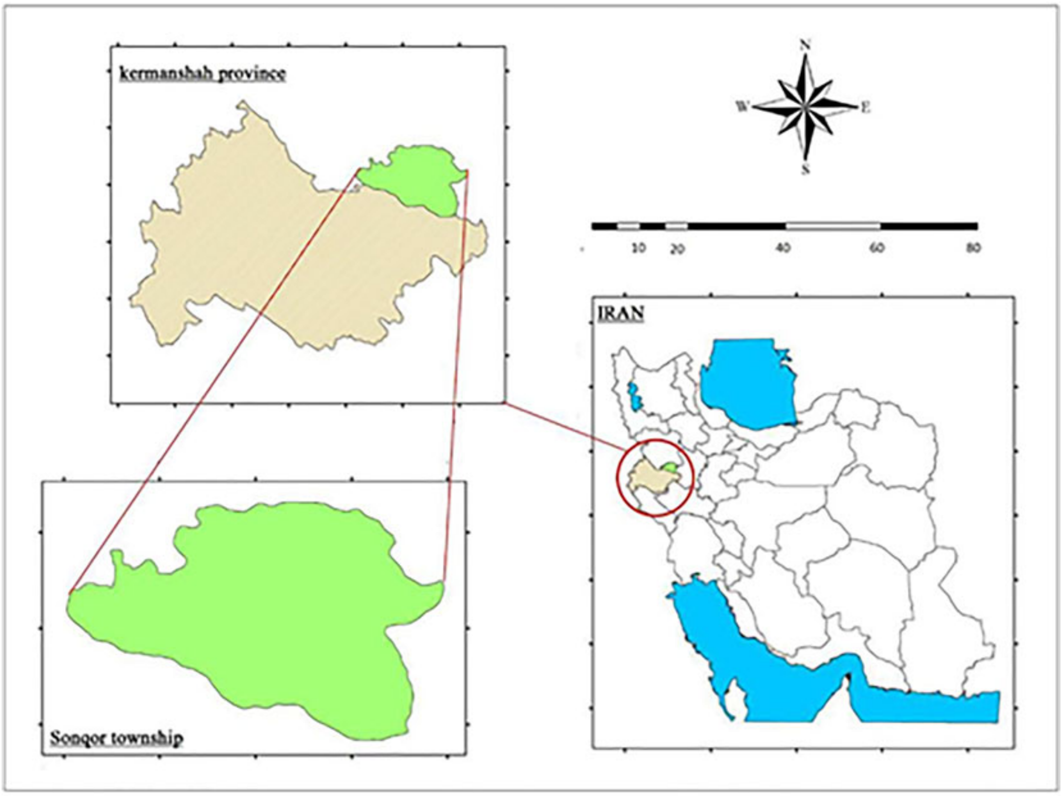

Fig. 1. Location of the studied area in western Iran.

Table 2. Different legumes production systems and straw management in Sonqor

Status	Moldboard ploughing	Disk ploughing	Row planter	Chemicals	Harvester	Straw management
Chickpea production						Animal feed
Lentil production						Burning straw

Fx1 Mechanized, Fx2 semi-mechanized, Fx3 manual.

Ecological footprint

The model of ecological footprint for sustainability assessment of the agricultural environment has been provided by Kissinger and Gottlieb (2012) and Solís-Guzmán *et al.* (2013). A simplified equation based on energy consumption and location-based approach for the calculation of the legumes production footprint following this approach is displayed below:

$$EF_t = \sum_{i=1}^{n} EF_i = \left(\frac{E_i \times T}{C_0}\right) \quad (1)$$

$$E_i = F_i \times \mathrm{EQF} \times 1000 \quad (2)$$

$$T = \left(\frac{P_c}{E_c \times O_C \times K}\right) \quad (3)$$

where each of the considered factors would be: EF_t is the ecological footprint index (gha), E_c is the capability of energy generation by one gram of coal (20 KJ), E_i is the energy of the ith factor (KJ), C_0 is the capability of one hectare farm for carbon absorption (ton) [1.8 ton for Iran (Gharakhlou *et al.*, 2009), F_i is the energy of ith factor, EQF is the equivalence factor of the ith factor for converting productive land to global hectare (Anielski and Wilson, 2010), P_c is the percent of the carbon in coal (g) (0.85%)], O_c is the percent of coal-derived from plants (g) (0.314%), the constant coefficient for converting gram to tone (1,000,000) (Solís-Guzmán *et al.*, 2013).

Straw management and social costs

There is a major difference in straw management of legumes in the Sonqor region (Table 1). In chickpea production, straw is harvested, baled and transferred to storehouses, then is used for animal feed in winter. While farmers who produce lentil burn crop residue in the field.

The social cost of the emission is estimated by using a standard coefficient. The table shows the cost of environmental emissions (\$/kg of CO_2eq.) and other emission indices (Table 4).

Multi-objective genetic algorithm

GA is an adaptive heuristic search algorithm that belongs to the larger category of evolutionary algorithms and generates solutions

Table 3. Energy and CO_2 emission coefficients in the legumes production system

Inputs	Unit	Energy equivalent (MJ Unit^{-1})	References	Unit	Emission factor (kg CO_2-eq Unit^{-1})	References
Legumes (seed and output)	kg	23.8	(Mohammadi *et al.*, 2014)	kg	0.433	(Haq, 2014)
Legumes straw	kg	18.29	(Mohammadi *et al.*, 2014)	kg	–	–
Human labor	h	1.96	(Hosseinzadeh-Bandbafha *et al.*, 2018)	h	0.7	(Houshyar *et al.*, 2017)
Machinery	kg	64.8	(Banaeian *et al.*, 2011)	MJ	0.071	(Nabavi-Pelesaraei *et al.*, 2016)
Diesel fuel	Liter	56.31	(Banaeian and Zangeneh, 2011)	Liter	2.761	(Nabavi-Pelesaraei *et al.*, 2016)
Fertilizer (N)	kg	66.14	(Banaeian *et al.*, 2011)	kg	1.3	(Nabavi-Pelesaraei *et al.*, 2016)
Herbicide	Liter	238	(Zangeneh *et al.*, 2010)	MJ	0.069	(Audsley *et al.*, 2009)

Table 4. Emission-cost coefficients for background emission indices in the production system

		Emission index							
	Unit	CO_2	N_2O	CH_4	PM 10	NO_x	SO_2	CO	NH_3
Emission equivalent for diesel consumption	(g/MJ)	4195.095	0.161	0.173	6.025	59.688	1.357	8.466	0
Emission equivalent for burning straw	(kg/ton)	1460	0.79	0.74	3.7	3.1	0.7	34.7	0
Social cost for emission index	($/kg)	0.01	4.58	0.21	4.3	0.6	1.825	0.187	2.83

optimizing problems. The MOGA is available for all types of input parameters and can handle multiple goals. The problem of optimization in the production of chickpeas and lentils was done by considering energy output, ecological footprint and CO_2 emission as three objective functions according to Aghili nategh *et al.* (2020).

Minimum and maximum values for energy inputs are mentioned based on data confirmed in the Sonqor (Table 5).

Assuming the output energy (F), benefit to cost ratio (G) and GHG emissions (H) as a function of energy inputs the following equations to obtain mathematical models for inputs and outputs were developed:

$$\begin{aligned} F_{\text{chickpea}} &= (\propto_1 X_1 + \propto_2 X_2 + \propto_3 X_3 + \propto_4 X_4 + \propto_5 X_5 + \propto_6 X_6 + u_F) \\ F_{\text{lentil}} &= (\propto_1 X_1 + \propto_2 X_2 + \propto_3 X_3 + \propto_4 X_4 + u_F) \end{aligned} \quad (4)$$

$$\begin{aligned} G_{\text{chickpea}} &= (\beta X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + u_G) \\ G_{\text{lentil}} &= (\beta X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + u_G) \end{aligned} \quad (5)$$

$$\begin{aligned} H_{\text{chickpea}} &= (\gamma_1 X_1 + \gamma_2 X_2 + \gamma_3 X_3 + \gamma_4 X_4 + \gamma_5 X_5 + \gamma_6 X_6 + u_H) \\ H_{\text{lentil}} &= (\gamma_1 X_1 + \gamma_2 X_2 + \gamma_3 X_3 + \gamma_4 X_4 u_H) \end{aligned} \quad (6)$$

where energy inputs were including machinery (X_1), human labor (X_2), diesel (X_3), seed (X_4), fertilizers (X_5), chemical (X_6). The criteria for stopping the MOGA method was considered as Aghili nategh *et al.* (2020). The data analysis was done with the Excel 2013 spreadsheet, SPSS 16.0 and MATLAB software 2015a.

Result

Input/output analysis

The results of Table 6 showed that chickpea production due to mechanized cultivation consumed higher energy in machinery and diesel fuel. Traditional harvesting operation in lentil production requires 147.52 h of human labor per hectare, while mechanized harvesting in chickpea production consumed just 24.9. One of the main advantages of lentil production is to support organic farming. No chemical fertilizer (urea) and herbicides are applied in lentil production. Therefore, lentil production has no chemical energy consumption too.

Energy, ecological footprint and CO_2

Emission analysis

Table 7 shows the share of major inputs of lentil and chickpea production systems in total energy consumption, ecological footprint and CO_2 emission. Chemical fertilizer (urea), herbicide and machinery were the most energy-consuming inputs in chickpea production, while the results in lentil production were different from an organic production system (no fertilizer and chemicals). Seed and fuel consumption was the most energy-consuming inputs in lentil production. Chickpea and lentil production consumed 11,611 and 2080 MJ energy per hectare, respectively. Applying more machines and fertilizer and chemicals

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 5. Lower and upper bounds for the optimization problem of lentil and chickpea

Input parameters	The lower bound (MJ ha^{-1})	The upper bound (MJ ha^{-1})
	Lentil production	
1. Machinery	176.17	704.68
2. Seed	101.66	584.37
3. Labor	3.99	3989.21
4. Diesel	236.67	1656.69
	Chickpea production	
1. Machinery	236.68	5924.70
2. Fertilizer	58.21	888.32
3. Seed	27.081	8469.97
4. Labor	515.97	5675.67
5. Diesel	997.94	18,908.42
6. Chemical	0	5077.33

consumption in semi-mechanized chickpea production has increased the energy consumption per hectare of chickpea.

CO_2 emission in chickpea and lentil production was 484 and 173 kg CO_{2-eq}, respectively; the most effective inputs in CO_2 emission were machinery and fertilizer in chickpea production and human labor in lentil production. Of course, there is a disagreement among researchers here, some publications disregard human calculus (Khoshnevisan *et al.*, 2013; Mobtaker *et al.*, 2013; Nabavi-Pelesaraei *et al.*, 2016), but some researchers believe that human activity should also be considered in computation (Houshyar *et al.*, 2017). In any case, with the increasing agricultural mechanization, human-induced emissions reduced. As in chickpea cultivation, human-induced emissions have decreased; instead, emissions from machine use have increased several times. The machine is an input that produces a lot of carbon emissions, according to increasing mechanized farms so it is advisable to reduce carbon dioxide and resource utilization by serious repair and maintenance of the farm machinery and also remanufacture them after the machine's useful life (Yang *et al.*, 2019).

The ecological carbon footprint of legumes reported about 0.15 and 0.87 global hectares for lentil and chickpea production, respectively. Therefore, the environmental aspects of lentil production are more stable. According to Gharakhlou *et al.* (2009) capability of one hectare of Iranian farm for carbon, absorption is 1.8 ton, and according to this study, during the process of lentil and chickpea production, 0.27 and 1.56-ton carbon produce. This implies that during the process of lentil and chickpea production, 1.53 and 0.24-ton carbon will absorb. So from the ecological viewpoint, both legumes are environmentally sustainable and there is no need for productive land to offset the decline in biological capacity.

Energy use efficiency, energy productivity and net energy of chickpea and lentil are shown in Table 8. Energy use efficiency in both legume production is more than 1, indicating that energy consumption in chickpea and lentil production in the surveyed region is efficient; in other words, energy production (output energy) was greater than energy consumption (input energy). Mishra *et al.* (2017) observed energy use efficiency of 2.29 and 2.59 in the traditional and partially mechanized farming system of lentil production in India, respectively. Energy productivity and net energy for chickpea and lentil production were calculated at 0.036, 0.161 and 2373 and 5900 MJ per hectare, respectively. Yousefi and Damghani (2012) reported the energy use efficiency, energy productivity and net energy of 3.04, 0.13 kg/MJ and 9836 MJ/ha, respectively, for chickpea production in Kangavar region of Kermanshah province of Iran.

Table 6. Inputs and outputs in three different scenarios of the legumes production system

Inputs/amount		Unit	Chickpea	Lentil
Seed		kg/ha	35.86	36.9
Machinery	Moldboard	h/ha	5.2	1.02
	Disk		1.83	–
	Row planter		1.1	–
	Sprayer		7	–
	Tractor		14.08	4.56
Diesel	Moldboard	Liter/ha	2.38	9.73
	Disk		1.47	–
	Planting		7.5	–
	Spraying		1.9	–
	Harvesting		0.7	–
	Baling		4.2	–
Human labor	Moldboard	h/ha	5.2	1.02
	Disk		1.88	–
	Planting		10.5	1.03
	Fertilizer		7.10	–
	Herbicide		17.96	–
	Harvesting		24.9	147.52
	Baling		15	–
Herbicide	Pyramide	Liter/ha	2.89	–
	Bentazone		3.54	–
Fertilizer (N)		kg/ha	93	–
Outputs				
Yield		kg/ha	433	335
Straw			433	111.6

Energy indices in lentil production are more than chickpea, which shows that lentil production is more energy-efficient. Koocheki *et al.* (2011) showed similar results of energy use efficiency as 1.79 and 1.21 for lentil and chickpea production, respectively.

The distribution of input energy in legume production according to renewable and non-renewable energy forms is presented in Table 8. The share of renewable energy in lentil production is 56%, while due to the application of fertilizers and chemicals in chickpea production, the share of renewable energy forms decreased to 8%.

Straw management and social costs analysis

The main difference between lentil and chickpea production systems was straw management. Burning is one way to dispose of the

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 7. Energy, ecological footprint and CO_2 emission in the legumes production system of Sonqor

Inputs	Chickpea			Lentil		
	Input energy (MJ)	Ecological footprint (gha)	CO_2 emission (kg CO_2-eq)	Energy (MJ)	Ecological footprint (gha)	CO_2 emission (kg CO_2-eq)
Seed	853.47	0.0642	15.53	878.22	0.066	15.97
Machinery	1892.81	0.1423	134.39	361.58	0.0272	25.67
Diesel	1022.03	0.0768	50.11	547.9	0.0412	26.86
Human labor	161.78	0.0122	57.78	293.16	0.022	104.7
Herbicide	1530.34	0.1151	105.59	0	0	0
Fertilizer (N)	6151.02	0.4625	120.9	0	0	0
Total	11,611.45	0.8731	484.3	2080.86	0.1564	173.2

Table 8. Energy input–output ratio in legume production of Sonqor

	Energy use efficiency	Energy productivity	Net energy	Renewable energy[a]	Non-renewable energy[b]
Chickpea	1.200	0.036	2373.437	992.9499 (8%)	10,819.86 (92%)
Lentil	3.846	0.161	5900.292	1165.594 (56%)	907.1127 (44%)

[a]Includes human labor, farmyard manure, water for irrigation.
[b]Includes diesel fuel, electricity, chemicals, chemical fertilizer, machinery.

Table 9. Pollutant gases in straw management of one hectare of legumes production

Production	Treatment	CO_2	N_2O	CH_4	PM 10	NO_x	SO_2	CO	NH_3
Chickpea	Diesel consumption for baling straw (kg/ton)	992.1	0.038	0.041	1.425	14.11	0.321	1.997	0
Lentil	Burning straw (kg/MJ)	162.9	0.088	0.082	0.413	0.346	0.078	3.87	0

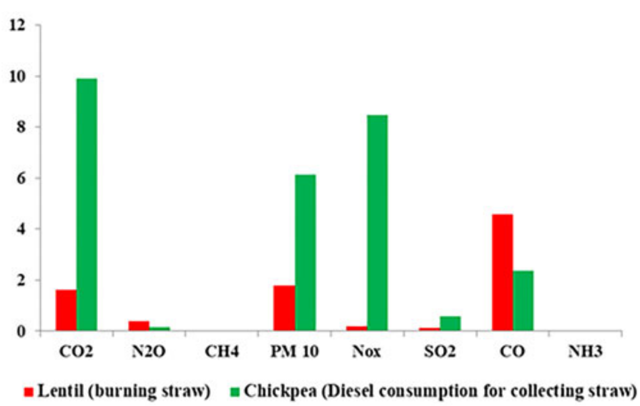

Fig. 2. Social costs ($/kg) of straw management in different legume production of lentil and chickpea in Sonqor.

straw left after harvest which lentil producers selected. But in this region, chickpea producers are faced with more straw and prefer to collect, bale and use it for animal feed. Legumes crop residue is a rich source of animal feed.

Open-field burning of straw has become the key factor hampering sustainable management in intensive cultivation systems and also burning brings losses in nutrients (Nguyen *et al.*, 2016). Therefore, limiting crop residue burning in the field is a recommended option to ensure more environmental-friendly legumes farming systems in the region.

Table 9 shows the details of pollutant emissions from two different scenarios in straw management of lentil (burning) and chickpea (baling) production. The results revealed that lentil farms that burnt crop residue in the field generate significantly less GHG emissions than chickpea farms. Social costs are calculated by multiplying the coefficients of the emission index in Table 4 by the amount of emissions in Table 9. CO_2 emission cost from diesel consumption for baling straw in chickpea production is $9.921, while in straw burning of lentil production is $1.629 (Fig. 2). The social cost of emission from straw baling in chickpea production was 27.65 dollars per hectare while burning straw in lentil production was 8.77. This means that the straw collection which seems the rational scenario is not properly managed and extreme fuel consumption has imposed higher social costs. For example, fuel consumption reduction can be possible by avoiding unused machine capacity, timely maintenance, machine adjustments, etc., and also the distance from the warehouse to the farm should be reduced as much as possible.

Optimization results

According to Equations (4), (5) and (6), the objective functions are fitted by linear correlation analysis among inputs and output for chickpea and lentil production. Therefore, three regression

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 10. Coefficient of independent variables for objective functions

Crop type	Dependent variables	Independent variables					
		Machinery	Human labor	Diesel fuel	Seed	Fertilizers	Chemicals
Chickpea							
	OE[a]	0.339	−2.177	0.261	19.097	0.054	−0.279
	GHG	0.002	0.675	0.093	0.034	0.037	0.005
	EFP[b]	7.4E-05	7.4E-05	7.4E-05	7.4E-05	7.4E-05	7.4E-05
Lentil							
	OE	−3.753	−2.035	−0.932	6.274	–	–
	GHG	0.001	0.411	0.056	0.021	–	–
	EFP	7.5E-05	7.5E-05	7.5E-05	7.5E-05	–	–

[a]Output energy.
[b]Ecological footprint.

Table 11. Multi-objective genetic algorithm results for chickpea production

Generation number	Optimum energy use (MJ ha^{-1})						Output energy	ecological footprint	CO_2 emission
	Machinery	Human labor	Diesel fuel	Seed	Fertilizer	Chemical			
1	**236.68**	**58.21**	**27.08**	**515.97**	**997.94**	**0.00**	**7825.53**	**0.14**	**97.06**
2	2794.70	98.53	4119.80	5627.77	2282.60	308.57	107,276.93	1.13	733.69
3	1124.62	85.42	457.46	5618.21	1399.07	246.80	105,570.10	0.66	348.70
4	1606.86	80.14	2866.06	5626.47	1758.54	157.36	106,575.84	0.89	582.37
5	2831.29	90.58	3584.03	5626.79	1700.25	351.76	107,104.54	1.05	657.36
6	2915.71	100.61	4547.04	5628.73	2960.32	243.37	107,498.18	1.21	799.75
7	2772.82	78.79	3267.87	5627.34	3341.37	201.40	107,169.25	1.13	680.13
8	2904.29	104.00	1846.81	5627.45	1605.27	363.11	106,651.26	0.92	502.22
9	2748.82	97.20	3085.99	5626.13	1947.53	224.51	106,968.47	1.01	623.99
10	1383.91	88.06	882.02	5622.43	1692.26	233.53	105,863.28	0.73	401.30
11	266.16	59.00	56.06	4510.17	1017.31	17.99	84,114.63	0.44	238.42
12	240.40	58.35	29.49	3973.94	1000.95	6.07	73,862.43	0.39	216.36
13	2961.21	119.95	4964.83	5628.76	6142.65	415.19	107,705.29	1.50	970.69
14	2961.21	119.95	4964.83	5628.76	6142.65	415.19	107,705.27	1.50	970.69
15	253.77	58.86	88.88	2685.87	1010.14	16.25	49,280.79	0.30	178.37
16	238.29	58.64	34.97	1777.71	999.84	0.00	31,922.69	0.23	141.51
17	250.98	59.76	35.18	4992.24	1034.68	44.30	93,302.08	0.47	254.32
18	243.07	58.70	32.34	1924.52	1001.08	6.20	34,725.53	0.24	146.44
19	244.86	58.71	31.27	1347.19	1001.07	7.10	23,700.27	0.20	126.52
20	2843.44	100.85	3972.98	5627.77	1687.98	335.55	107,210.38	1.08	699.83
21	274.23	59.12	40.99	3608.61	1056.01	12.15	66,899.90	0.37	207.54
22	2920.61	109.19	4749.17	5628.76	4536.43	307.67	107,601.77	1.35	883.15
23	2946.24	91.36	4510.78	5627.37	2017.36	200.84	107,453.99	1.14	754.93
24	2961.21	119.95	4964.83	5628.76	6142.65	415.19	107,705.29	1.50	970.69
25	257.43	60.63	82.12	5106.30	1096.80	63.70	95,490.66	0.49	265.60
26	250.93	59.25	33.12	2964.42	1023.58	11.55	54,585.84	0.32	183.50

(*Continued*)

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 11. (*Continued.*)

Generation number	Optimum energy use (MJ ha^{-1})								
	Machinery	Human labor	Diesel fuel	Seed	Fertilizer	Chemical	Output energy	ecological footprint	CO_2 emission
27	2951.96	98.72	4852.47	5627.62	2681.47	385.55	107,518.25	1.23	817.23
28	246.08	62.93	121.73	3428.71	1018.44	30.46	63,460.40	0.36	210.06
29	253.98	58.88	41.21	4657.91	1005.51	11.61	86,929.41	0.45	241.54
30	860.71	65.60	85.41	5399.27	1103.60	66.04	101,280.09	0.56	280.84
31	2934.21	97.72	4571.40	5628.70	4307.29	363.43	107,555.72	1.32	850.77
32	2836.33	86.75	2538.83	5626.97	1747.60	323.66	106,855.78	0.97	559.59
33	1826.33	91.13	471.63	5618.23	1709.84	224.44	105,823.04	0.73	366.74
34	1518.68	72.31	2382.53	5622.65	1367.23	152.45	106,343.97	0.82	517.43
35	2838.49	94.60	4133.78	5627.62	1745.56	359.20	107,257.87	1.09	712.76
36	238.58	58.25	63.00	762.12	1003.55	9.91	12,533.73	0.16	109.14
37	262.30	69.45	39.67	2422.13	1086.05	2.52	44,219.04	0.29	174.65
38	237.71	58.64	29.46	3116.15	999.94	0.56	57,481.14	0.33	187.00
39	2937.21	103.14	4622.04	5628.74	3349.05	269.06	107,533.48	1.25	823.02
40	238.68	62.22	50.55	2280.36	1019.73	36.09	41,509.18	0.27	163.58
41	380.46	60.53	38.39	969.89	1035.47	24.33	16,535.99	0.19	117.09
42	271.19	59.56	42.76	3816.33	1014.57	9.38	70,863.67	0.39	213.58
43	2849.26	101.90	2311.93	5627.51	1937.37	333.96	106,785.73	0.97	555.94
44	2923.64	106.43	4686.63	5628.76	4398.09	324.77	107,580.13	1.34	870.46
45	2831.29	90.58	3584.03	5626.79	1700.26	351.76	107,104.54	1.05	657.36
46	1407.81	71.39	1719.81	5623.27	1581.19	154.50	106,158.36	0.78	463.18
47	242.50	59.34	27.99	856.88	1005.11	15.13	14,331.82	0.16	109.98
48	255.91	59.28	45.99	3688.20	1024.61	32.27	68,407.15	0.38	209.75

models for both legume crops are developed by SPSS software and coefficients are shown in Table 10 for chickpea and lentil, respectively. Data include machinery, human labor, diesel fuel, seed, fertilizer and chemicals as input and output energy, CO_2 emission and carbon footprint as output.

MATLAB software is applied to accomplish the optimized recipe with MOGA. MOGA results generated 70 and 18 Pareto optimal solutions that achieved as optimum solutions for chickpea and lentil production, some of them are shown in Tables 11 and 12, respectively. Numbers 1 and 12 for chickpea and lentil were characterized as the best generation based on the criteria found in Nabavi-Pelesaraei *et al.* (2017). Total output energy, ecological footprint and CO_2 emission for these generations were about 7825.53 MJ ha^{-1}, 0.14 gha and 97.06 ton CO_2eq. ha^{-1} and 4550.26 MJ ha^{-1}, 0.04 gha and 47.15ton CO_2eq. ha^{-1} for chickpea and lentil production respectively.

According to the results of MOGA optimization, the optimum energy requirement for each input was identified while energy output maximized and CO_2 and ecological footprint minimized. Table 13 shows that diesel fuel has the greatest potential to save input energy in both lentils (99.27) and chickpea (97.39) production, which confirms the results of straw management too. Therefore, the results of this study emphasize excessive consumption and lack of proper management of diesel fuel as a major source of non-renewable energy. Other inputs that have a high potential to reduce energy content in chickpea production are chemical fertilizers and pesticides. MOGA results support minimizing fertilizer consumption and reducing chemicals to zero for chickpea production (Fig. 3).

Optimization results show that seed input has less energy-saving potential in the production of lentil and chickpea (Fig. 3), which means that seed input has been properly applied. On the other hand, the results of Table 10 confirm that seed energy is the most effective energy input on output energy (yield).

Conclusion

The implementation of ecological agricultural practices can contribute to more sustainable production systems. For the first time, this paper investigates and compares some sustainability aspects in two common lentil and chickpea production in the Kermanshah region of Sonqor. Another contribution of this paper is applying MOGA optimization procedure to compare the results and discover the best combination of energy, CO_2 emissions and ecological footprint parameters of lentil and chickpea production with two different cultivation systems. Lentil production is traditionally cultivated while chickpea is semi-mechanized. While in the straw management sector,

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Table 12. Multi-objective genetic algorithm results for lentil production

Generation number	Optimum energy use (MJ ha^{-1})						
	Machinery fuel	Human labor	Diesel	Seed	CO_2 emission	Output energy	Ecological footprint
1	176.17	101.66	3.99	236.67	47.15	4550.26	0.04
2	181.68	106.06	16.67	1326.55	72.48	11,370.15	0.12
3	184.91	123.03	3015.55	1570.26	253.66	15,646.91	0.37
4	185.09	121.29	2384.36	1569.26	217.33	15,055.37	0.32
5	179.82	104.18	10.39	473.05	53.50	6020.38	0.06
6	185.63	122.98	3015.71	1570.24	253.64	15,644.38	0.37
7	179.05	122.62	77.38	273.63	60.67	4797.06	0.05
8	183.48	118.98	864.56	1551.01	130.30	13,535.43	0.21
9	184.90	124.09	3015.08	1569.01	254.04	15,636.53	0.37
10	179.99	119.86	859.73	1491.48	129.14	13,168.72	0.20
11	184.51	116.36	357.69	1563.23	100.90	13,141.23	0.17
12	**176.17**	**101.66**	**3.99**	**236.67**	**47.15**	**4550.26**	**0.04**
13	183.82	121.44	1995.55	1560.78	195.29	14,644.37	0.29
14	176.48	107.83	13.46	555.02	56.88	6542.69	0.06
15	180.04	119.53	233.87	1070.90	84.91	9947.41	0.12
16	182.06	118.40	1252.44	1541.30	151.72	13,842.45	0.23
17	179.26	116.73	79.47	739.99	68.13	7736.03	0.08
18	184.56	123.00	1311.59	1558.21	157.31	13,984.91	0.24

Table 13. Optimum energy requirement and saving for chickpea and lentil production based on MOGA

Input parameters	Optimum energy requirement (MJ ha^{-1})	Saving energy (MJ ha^{-1})	Saving energy (%)
Lentil production			
1. Machinery	176.17	184.18	51.11
2. Seed	236.67	636.85	72.90
3. Labor	101.66	190.41	65.19
4. Diesel	3.99	542.77	99.27
Chickpea production			
1. Machinery	236.68	1675.82	87.62
2. Fertilizer	997.94	5312.82	84.18
3. Seed	515.97	309.65	37.50
4. Labor	58.21	109.11	65.21
5. Diesel	27.08	1011.20	97.39
6. Chemical	0	1558.29	100

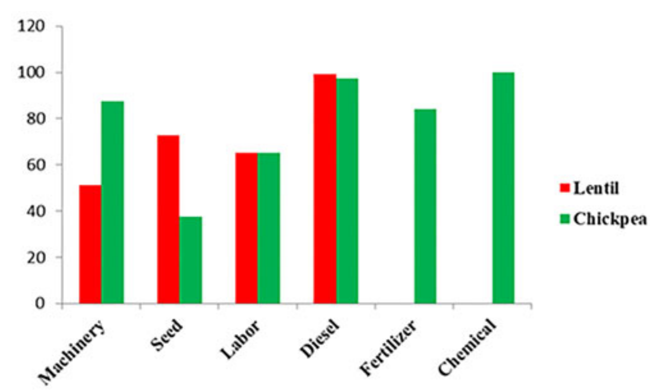

Fig. 3. Comparison between chickpea and lentil production for inputs energy savings.

chickpea residues will be burnt and lentil residues are collected for animal feed.

Results revealed that machines, fertilizers and chemicals are extensively consumed per hectare in semi-mechanized chickpea production which leads to higher energy consumption, ecological and carbon footprint indices. Energy use efficiency, energy productivity and net energy in lentil production are higher than chickpea, which shows that traditional lentil production is more energy-efficient.

Assessment of social costs in two scenarios of straw management (burning straw *vs* bale and collection) showed that traditional lentil cultivation paid less social costs by burning straw. While chickpea semi-mechanized production pays much more for baling and collecting due to excessive fuel consumption. Optimization results of energy use in legume production according to the reduction of CO_2 and ecological footprint and maximizing energy output will lead to more economic benefits and achieving social and environmental sustainability. Energy consumption, GHG emission and ecological footprint can be saved if all farmers operate according to the suggested value.

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Optimization results also showed that fuel input has the greatest potential for energy savings. While seed inputs were the most effective inputs on the output energy and managed perfectly well than other inputs and showed the least potential for energy savings.

The overall comparison of legume cultivation in the Sonqor region shows that the traditional lentil production system has more sustainable conditions than semi-mechanized chickpea cultivation. The results of this study have demonstrated that modern agricultural practices are not enough to achieve sustainability. The important point is that farmers lack effective knowledge of management. With the advancement of technology, farmers need to increase their awareness simultaneously. Department of Extension and Development of Agricultural Ministry transmit the knowledge and should establish a better relationship and social networks with local farmers so that the concepts convey correctly. Also, wrong government policies such as fuel, fertilizers and chemical subsidies have exacerbated unwise input consumption problems. Due to the outcomes of this study, optimization investigations can be extended to identify weaknesses and inefficient resources and drive the agricultural systems to sustainability. According to Banaeian *et al.* (2020), it is suggested that in future, sustainability studies and other sustainability indicators, such as economic and social indicators, examine and optimize along with environmental indicators.

References

Aghili nategh N, Banaeian N, Gholamshahi A and Nosrati M (2020) Optimization of energy, economic and environmental indices in sunflower cultivation-a comparative analysis. *Environmental Progress & Sustainable Energy* **40**, e13505.

Anielski M and Wilson J (2010) Environmental footprinting for agriculture in Alberta: literature review and analysis. Retrieved from Alberta, Canada.

Anonymous (2010) Iran agriculture statistics. Retrieved from Tehran – Iran.

Audsley E, Stacey K, Parsons DJ and Williams AG (2009) Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Retrieved from Cranfield, Bedford.

Banaeian N and Zangeneh M (2011) Study on energy efficiency in corn production of Iran. *Energy* **36**, 5394–5402.

Banaeian N, Zangeneh M and Omid M (2010) Energy use efficiency for walnut producers using data envelopment analysis (DEA). *Australian Journal of Crop Science* **4**, 359–362.

Banaeian N, Omid M and Ahmadi H (2011) Energy and economic analysis of greenhouse strawberry production in Tehran province of Iran. *Energy Conversion and Management* **52**, 1020–1025.

Banaeian N, Zangeneh M and Clark S (2020) Trends and future directions in crop energy analyses: a focus on Iran. *Sustainability* **12**, 10002.

Baran MF and Gokdogan O (2016) Determination of energy balance of sugar beet production in Turkey: a case study of Kırklareli Province. *Energy Efficiency* **9**, 487–494.

Borsato E, Tarolli P and Marinello F (2018) Sustainable patterns of main agricultural products combining different footprint parameters. *Journal of Cleaner Production* **179**, 357–367.

Cellura M, Longo S, Marsala G, Mistretta M and Pucci M (2013) The use of genetic algorithms to solve the allocation problems in the life cycle inventory. In Cavallaro F (ed.), *Assessment and Simulation Tools for Sustainable Energy Systems: Theory and Applications, Green Energy and Technology*. London: Springer, pp. 267–284.

Elhami B, Akram A and Khanali M (2016) Optimization of energy consumption and environmental impacts of chickpea production using data envelopment analysis (DEA) and multi objective genetic algorithm (MOGA) approaches. *Information Processing in Agriculture* **3**, 190–205.

Elhami B, Khanali M and Akram A (2017) Combined application of artificial neural networks and life cycle assessment in lentil farming in Iran. *Information Processing in Agriculture* **4**, 18–32.

FAO, Food and Agriculture Organization of the United Nations (2008) Livestock's long shadow-environmental issues and options. Retrieved from 2020.

Firouzi S, Nikkhah A and Rosentrater KA (2017) An integrated analysis of non-renewable energy use, GHG emissions, carbon efficiency of groundnut sole cropping and groundnut-bean intercropping agro-ecosystems. *Environmental Progress & Sustainable Energy* **36**, 1832–1839.

GFN, Global Footprint Network (2009) Available at www.footprintnetwork.org/en/index.php/GFN.

Gharakhlou M, Abdi N and Shahraki Z (2009) Analysis of the level of urban sustainability in informal settlements of Sanandaj (Persian). *Human Geography Research* **42**, 1–16.

Haq ME (2014) Carbon footprint of selected cereal and legume crops cultivated in the old Brahmaputra floodplain soil. (master), Bangladesh agricultural university Mymensingh, Bangladesh.

Hosseinzadeh-Bandbafha H, Nabavi-Pelesaraei A, Khanali M, Ghahderijani M and Chau K-W (2018) Application of data envelopment analysis approach for optimization of energy use and reduction of greenhouse gas emission in peanut production of Iran. *Journal of Cleaner Production* **172** (Suppl C), 1327–1335.

Houshyar E, Mahmoodi-Eshkaftaki M and Azadi H (2017) Impacts of technological change on energy use efficiency and GHG mitigation of pomegranate: application of dynamic data envelopment analysis models. *Journal of Cleaner Production* **162**(Suppl C), 1180–1191.

Ilahi S, Wu Y, Raza MA, Wei W, Imran M and Bayasgalankhuu L (2019) Optimization approach for improving energy efficiency and evaluation of greenhouse gas emission of wheat crop using data envelopment analysis. *Sustainability* **11**, 1–15. doi: 10.3390/su11123409.

Khoshnevisan B, Rafiee S, Omid M and Mousazadeh H (2013) Reduction of CO2 emission by improving energy use efficiency of greenhouse cucumber production using DEA approach. *Energy* **55**(Suppl C), 676–682.

Khoshnevisan B, Bolandnazar E, Shamshirband S, Shariati HM, Anuar NB and Mat Kiah ML (2015) Decreasing environmental impacts of cropping systems using life cycle assessment (LCA) and multi-objective genetic algorithm. *Journal of Cleaner Production* **86**, 67–77.

Kissinger M and Gottlieb D (2012) From global to place oriented hectares—the case of Israel's wheat ecological footprint and its implications for sustainable resource supply. *Ecological Indicators* **16**, 51–57.

Koocheki A, Ghorbani R, Mondani F, Alizade Y and Moradi R (2011) Pulses production systems in term of energy use efficiency and economical analysis in Iran. *International Journal of Energy Economics and Policy* **1**, 95–106.

Mishra PK, Tripathi A, Tripathi H and Moses SC (2017) Energy inputs in production of lentil crop under different types of farming systems. *International Journal of Current Microbiology and Applied Sciences* **6**, 971–977.

Mobtaker HG, Taki M, Salehi M and Shahamat EZ (2013) Application of nonparametric method to improve energy productivity and CO2 emission for barley production in Iran. *Agricultural Engineering International: CIGR Journal* **15**, 84–93.

Mohammadi A, Rafiee S, Jafari A, Keyhani A, Mousavi-Avval SH and Nonhebel S (2014) Energy use efficiency and greenhouse gas emissions of farming systems in north Iran. *Renewable and Sustainable Energy Reviews* **30**(Suppl C), 724–733.

Mousavi-Avval SH, Rafiee S, Jafari A and Mohammadi A (2011) Improving energy use efficiency of canola production using data envelopment analysis (DEA) approach. *Energy* **36**, 2765–2772.

Nabavi-Pelesaraei A, Hosseinzadeh-Bandbafha H, Qasemi-Kordkheili P, Kouchaki-Penchah H and Riahi-Dorcheh F (2016) Applying optimization techniques to improve of energy efficiency and GHG (greenhouse gas) emissions of wheat production. *Energy* **103**, 672–678.

Nabavi-Pelesaraei A, Rafiee S, Mohtasebi SS, Hosseinzadeh-Bandbafha H and Chau K-W (2017) Energy consumption enhancement and environmental life cycle assessment in paddy production using optimization techniques. *Journal of Cleaner Production* **162**(Suppl C), 571–586.

Nabavi-Pelesaraei A, Rafiee S, Mohtasebi SS, Hosseinzadeh-Bandbafha H and Chau K-W (2019) Comprehensive model of energy, environmental impacts and economic in rice milling factories by coupling adaptive neuro-fuzzy inference system and life cycle assessment. *Journal of Cleaner Production* **217**, 742–756.

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press

Nassiri SM and Singh S (2009) Study on energy use efficiency for paddy crop using data envelopment analysis (DEA) technique. *Applied Energy* **86**, 1320–1325.

Nguyen HV, Nguyen CD, Tran TV, Hau HD, Nguyen NT and Gummert M (2016) Energy efficiency, greenhouse gas emissions, and cost of rice straw collection in the Mekong river delta of Vietnam. *Field Crops Research* **198**, 16–22.

Ozkan B, Akcaoz H and Karadeniz F (2004) Energy requirement and economic analysis of citrus production in Turkey. *Energy Conversion and Management* **45**, 1821–1830.

Qasemi-Kordkheili P and Nabavi-Pelesarae A (2014) Optimization of energy required and potential of greenhouse gas emissions reductions for nectarine production using data envelopment analysis approach. *International Journal of Energy, Environment and Economics* **5**, 207–218.

Rao DLN, Giller KE, Yeo AR and Flowers TJ (2002) The effects of salinity and sodicity upon nodulation and nitrogen fixation in chickpea (*Cicer arietinum* L.). *Annals of Botany* **89**, 563–570.

Rathke G and Diepenbrock W (2006) Energy balance of winter oilseed rape (*Brassica napus* L.) cropping as related to nitrogen supply and preceding crop. *European Journal of Agronomy* **24**, 35–44.

Shamshirband S, Khoshnevisan B, Yousefi M, Bolandnazar E, Anuar NB, Abdul Wahab AW and Khan SUR (2015) A multi-objective evolutionary algorithm for energy management of agricultural systems—a case study in Iran. *Renewable and Sustainable Energy Reviews* **44**, 457–465.

Solís-Guzmán J, Marrero M and Ramírez-de-Arellano A (2013) Methodology for determining the ecological footprint of the construction of residential buildings in Andalusia (Spain). *Ecological Indicators* **25**, 239–249.

Taghavifar H and Mardani A (2015) Energy consumption analysis of wheat production in West Azarbayjan utilizing life cycle assessment (LCA). *Renewable Energy* **74**(Suppl C), 208–213.

Tusher TR, Pondit T, Hasan M, Latif MB and Binyamin M (2020) Impacts of resource consumption and waste generation on environment and subsequent effects on human health: a study based on ecological footprint analysis. In Singh R, Srinagesh B and Anand S (eds), *Urban Health Risk and Resilience in Asian Cities. Advances in Geographical and Environmental Sciences*. Singapore: Springer, pp. 179–203.

Uzunoz M, Akcay Y and Esengun K (2008) Energy input-output analysis of sunflower seed (*Helianthus annuus* L.) oil in Turkey. *Energy Sources, Part B: Economics, Planning, and Policy* **3**, 215–223.

Yang Y, Yuan G, Zhuang Q and Tian G (2019) Multi objective low-carbon disassembly line balancing for agricultural machinery using MDFOA and Fuzzy AHP. *Journal of Cleaner Production* **233**, 1465–1474.

Yousefi M and Damghani AM (2012) Evaluation of energy flow and indicators of chickpea under rainfed condition in Iran. *International Journal of Farming and Allied Sciences* **1**, 57–61.

Zangeneh M, Omid M and Akram A (2010) A comparative study on energy use and cost analysis of potato production under different farming technologies in Hamadan province of Iran. *Energy* **35**, 2927–2933.

https://doi.org/10.1017/S1742170521000193 Published online by Cambridge University Press