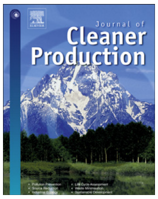
Journal of Cleaner Production 263 (2020) 121529

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Exergoenvironmental-Life cycle cost analysis for conventional, low external input and organic systems of rice paddy production

Zahra Saber [a, 1], Mohammadali Esmaeili [a, *], Hemmatollah Pirdashti [a, **], Ali Motevali [b], Ashkan Nabavi-Pelesaraei [c, d, 1, 2, 3, 4]

[a] *Department of Agronomy and Plant Breeding, Sari Agricultural Sciences and Natural Resources University, Sari, Iran*
[b] *Department of Mechanics of Biosystem Engineering, Sari Agricultural Sciences and Natural Resources University, Sari, Iran*
[c] *Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran*
[d] *Coordination Affairs Expert, Management of Fruit and Vegetables Organizations, Tehran Municipality, Tehran, Iran*

ARTICLE INFO

Article history:
Received 22 January 2020
Received in revised form
31 March 2020
Accepted 3 April 2020
Available online 11 April 2020

Handling editor: Jin Yang

Keywords:
Emission cost
Environmental damage
Exergy
Paddy
Sustainability

ABSTRACT

Climate change, increasing energy demand, and fossil fuel constraints have led to many plights regarding sustainable food and agricultural production. The purpose of this paper is to assess of exergoenvironmental aspects across different paddy production systems, including conventional (CS), low external input (LEI), and organic systems (OS) in Iran. Also, life cycle cost (LCC) and the emissions costs have been considered as a novelty for these scenarios. Data were collected through interviews from 213 paddy producers. Environmental life cycle damages were assessed by IMPACT 2002+ based on 1 ton of paddy yield as the functional unit. The findings revealed that diesel fuel followed by nitrogen had the most substantial role in the resource damage category of CS and LEI, while most values of OS belonged to diesel fuel followed by electricity. Furthermore, On-Farm emissions claimed almost the largest share among the other impacts categories in the surveyed systems. The cumulative exergy demand (CExD) analysis indicated that Non-renewable, fossil fuel was the main energy consumer. In this regard, diesel fuel was the most substantial part of energy forms for all three systems reducing the total CExD. The economic analysis showed that the lowest LCC was associated with OS; accordingly, the highest net profit belonged to OS, followed by CS. Overall, it can be concluded that the advantage of the OS scenario is evident for long-term management and planning in different environmental-exergy-economic indices of production systems.

1. Introduction

Rice (*Oryza sativa* L.), as the main crop, has become a particular material for the majority of people; it is most cultivated and renowned agricultural crop across the world (He et al., 2018). According to FAO (2018), approximately 759.6 million tons of paddy and 503.9 million tons of white rice were produced around the world in 2017. In Iran, rice is so essential that people consume it as part of their main meal at least once a day (Nabavi-Pelesaraei et al., 2018). Estimations indicate that around 2,386,492 t of paddy with a mean yield of 42,862 kg ha^{-1} are annually produced in rice planting farms of Iran (FAO, 2018). According to the annual report of the Ministry of Jihad-e-Agriculture of Iran (2019), northern Iran is the producer of 42% of the whole rice production, with 214300 ha of rice planting fields across the country. In agricultural systems, the major use of inputs in the form of diesel fuels, pesticides, agrochemicals, and the use of Non-renewable energies in production systems contributes to environmental problems including climate change and global warming (Mousavi and Falahatkar, 2019). Thus, nowadays, either deciding between continuing the use of technologies based on chemical inputs or returning to traditional, environmentally friendly methods for sustainable development and production is a major concern (Shabanzadeh-Khoshrody et al., 2016; Li et al., 2019). Organic culture, as a sustainable system of production, forgoes usage

---

* Corresponding author.
** Corresponding author.
E-mail addresses: z.saber@stu.sanru.ac.ir (Z. Saber), m.esmaeili6@sanru.ac.ir (M. Esmaeili), h.pirdashti@sanru.ac.ir (H. Pirdashti), ashkan.nabavi@ut.ac.ir, ashkan.nabavi@yahoo.com (A. Nabavi-Pelesaraei).
[1] These authors contributed equally.
[2] https://www.researchgate.net/profile/Ashkan_Nabavi-Pelesaraei.
[3] http://orcid.org/0000-0003-2823-6616.
[4] https://scholar.google.com/citations?user=JQNGIlIAAAAJ&hl=en.

https://doi.org/10.1016/j.jclepro.2020.121529

Nomenclature

\$	Dollar
Bq	Becquerel
C-14	Carbon-14
C_2H_3Cl	Vinyl chloride
C_2H_4	Ethylene
Cd	Cadmium
CExD	Cumulative exergy demand
CFC-11	Trichlorofluoromethane
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
CS	Conventional system
Cu	Copper
DALY	Disability adjusted life years
FU	Functional unit
FYM	Farmyard manure
g	Gram
GHG	Greenhouse gas
GWP	Global warming potential
h	hour
ha	Hectare
HC	Hydro carbons
Hg	Mercury
ISO	International Organization for Standardization
kg	Kilogram
kWh	Kilowatt hour
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEI	Low external input
m^2	Square meter
mg	Milligram
MJ	Mega joule
N_2O	Dinitrogen monoxide
NH_3	Ammonia
Ni	Nickel
NMVOC	Non-methane volatile organic compound
NO_3	Nitrate
NOx	Nitrogen oxides
OS	Organic system
PAH	Polycyclic hydrocarbons
Pb	Lead
PDF	Potentially Disappeared Fraction
PM	Particulate matter
Pt	Point
Se	Selenium
SO_2	Sulfur dioxide
SPM	Suspended particulate matter
t	ton
TEG	Triethylene glycol
yr	Year
Zn	Zink
µm	Micrometer

of synthetic or any chemical pesticides and fertilizers, minimizes soil, air, and water pollution and improves the health of the animal, plant and human communities (Scialabba and Mller-Lindenlauf, 2010), which is completely different from CS. A wide range of inputs is employed in CS, while the use of external input is limited in LEI systems. Various methods have been proposed on environmental performances related to agricultural activities, among which LCA is mostly employed. As a standard method aiming for holistic evaluation of the environmental resources and impacts, LCA measures the process of each product's entire life cycle; in other words, LCA analyzes the possible environmental impacts of any products during their life time (ISO, 2006).

The energy parameter is the second side of the agricultural production's triangle which is directly interwoven with environmental pollution. Thus, the energy forms in farming activity should be evaluated for the production processes. Among all methods, CExD is an important and allegedly the major analytic tool in this regard. CExD indicates the entire renewable and Non-renewable primary exergy consumption values to generate a product (Nabavi-Pelesaraei et al., 2018), and tries to find solutions an effective way to lower degradation (Peters et al., 2014). Although the examination of LCA and CExD is critical, these methods would not explain the economic implication of the production process.

As LCA does not involve any analysis of costs (Balaguera et al., 2018), while the cost analysis is an essential criterion for making significant decisions, the total cost of a product or system flows and processes is calculated using a tool for LCCA (Smol et al., 2018). Indeed, LCCA as a useful tool is used to assess the long-term cost issues of projects (Verhoeven et al., 2018), with the combination of LCA and LCCA considered as a new approach to determining green supply chain. Numerous studies are focusing on LCA, CExD, and LCCA methods, as demonstrated in Table 1.

Although previous studies showed the serious attempts to improve different agri-industrial production, especially for rice, the focus of studies has mostly been on only one method among the three. The results of LCA, CExD, and LCCA would provide us with a deeper understanding of emissions, energetic parameters, and economic values through comparing different system scenarios. Further, in most studies, LCC was limited to variable and fixed cost, while the consideration of emissions cost is a novelty of this study. Accordingly, the existence of a difference between rice paddy production systems in the Mazandaran province of Iran regarding LCA, CExD, and LCCA was considered as statement of the problem in the present study. The divisions of agricultural production systems to CS, LEI, and OS, less input use, and more net profit of organic due to the high price of OS in comparison with two other methods, have been determined as research assumptions. Note that most cases in the past research have only concentrated on CS and OS systems. This study intends to address a system that is the middle of the two mentioned systems, namely, the LEI supply system as a novelty.

According to the above description, the following constitute the aims of the present study:

- ➢ Defining three scenarios of rice paddy production, including CS, LEI, and OS in Mazandaran province, Iran.
- ➢ Evaluating environmental damages of each mentioned scenario.
- ➢ Assessing energy forms calculated by CExD in paddy production systems of Mazandaran province, Iran.
- ➢ Estimating total production costs along with considering emissions costs to investigate LCC, comprehensively.
- ➢ Choosing the best scenario with an energy-environment-economic perspective.

Table 1
A literature review of different studies about LCA, CExD, and LCCA of agricultural production or dependent industrial.

Investigated research	Geographical area	Studied section	Surveyed item
Wang et al. (2007)	North China Plain	Agriculture	LCA
Hokazono et al. (2009)	Japan	Agriculture	LCA
Singh and Grover (2011)	Punjab	Agriculture	Economic indices
Hokazono and Hayashi (2012)	Japan	Agriculture	LCA
Kralisch et al. (2012)	Germany	Agriculture	LCA + Economic indices
Fallahpour et al. (2012)	Iran	Agriculture	LCA
Ghahderijani et al. (2013)	Iran	Agriculture	GHG
Bacenetti et al. (2013)	Italy	Agriculture	LCA
Moya et al. (2013)	Cuba	Agriculture	LCA + CExD
Brodt et al. (2014)	California	Agriculture	GHG
Fusi et al. (2014)	Italy	Agriculture	Partial LCA
Hayashi et al. (2014)	Japan	Agriculture	LCA
Niero et al. (2015)	Denmark	Agriculture	LCA
Hokazono and Hayashi (2015)	Japan	Agriculture	LCA
Bacenetti et al. (2016)	Italy	Agriculture	LCA
Hayashi et al. (2016)	Japan	Agriculture	GHG
Kouchaki-Penchah et al. (2016)	Iran	Agriculture	LCA + CExD
Morrissey (2017)	United States	Agriculture	LCA
Yodkhum et al. (2017)	Thailand	Agriculture	GHG
Mousavi-Avval et al. (2017b)	Iran	Agriculture	LCA
Rivera et al. (2017)	Denmark and Italy	Agriculture	LCA
Coltro et al. (2017)	Southern Brazil	Agriculture	Partial LCA
Dijkman et al. (2017)	Denmark	Agriculture	Partial LCA
Sakolwitayanon et al. (2018)	Thailand	Agriculture	No
Soam et al. (2018)	India	Agriculture	LCA
He et al. (2018)	China	Agriculture	LCA
Hosseinzadeh-Bandbafha et al. (2018)	Iran	Agriculture	GHG
Gharaei et al. (2019a)	Iran	Agriculture + Industrial	LCCA
Nabavi-Pelesaraei et al. (2019a)	Iran	Agriculture + Industrial	LCA + CExD + Emissions social cost
Hoseini Shekarabi et al., 2019	Iran	Agriculture + Industrial	LCCA
Nabavi-Pelesaraei et al. (2019b)	Iran	Agriculture + Industrial	LCA + CExD + Emissions social cost
Gharaei et al. (2019c)	Iran	Agriculture + Industrial	Green supply chain + LCCA
Motevali et al. (2019)	Iran	Agriculture	LCA
Gharaei et al. (2019d)	Iran	Agriculture + Industrial	Supply chain + LCCA
Mostashari-Rad et al. (2019)	Iran	Agriculture	GHG
Gharaei et al. (2019b)	Iran	Agriculture + Industrial	Green supply chain + LCCA
Kaab et al. (2019)	Iran	Agriculture	LCA + CExD

2. Materials and methods

2.1. Surveyed region description and sampling design

To evaluate the environmental-exergy-economic perspective, this research was conducted in Mazandaran province, Iran. Mazandaran is located in the South Coast of the Caspian Sea at the latitude between 35°47′and 36° 35′N and the longitude between 50°34′and 56° 14′ E (Ministry of Jihad-e-Agriculture of Iran, 2019). The study area's location is depicted in Fig. 1.

Due to its unique geographic location, ample supply of water (around 631 mm), fertile lands, and high relative humidity of this area, Mazandaran is considered as one of the most important paddy producers in Iran. Tarom Hashemi cu. is regarded as the main paddy cultivation planted in the wet season, whose quality and aroma are highly valued all over the country (Motevali et al., 2019).

Concerning the large number of rice paddy producers in the studied region, the sampling method was essential for saving time and cost. Thus, the Cochran's sample size method was chosen as a standard method in this study whose formula is (Cochran, 1977):

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

where, z represents the coefficient of reliability denoting confidence level of 95% (equaling 1.96), n denotes the entailed size of the sample, N shows the paddy fields number of per target population, q is 1-p equaling 0.5, p represents the attribute's computed ratio in the population (equaling 0.5), and the allowable error ratio deviation from the mean of the population is considered as d equaling 0.05.

The total number of farmers was evaluated about 475 units. So, the sample size was obtained about 212.5 by Eq. (1). A total of 213 rice paddy producers were considered for completing the data required in the present study.

Some sort of primary data were randomly collected from each paddy field, consisting of all agricultural inputs (biocides, chemical fertilizers, etc.), land occupation, paddy yield, and machinery used.

2.2. LCA methodology

According to ISO (2006) norms 14040, LCA is comprised of four main levels: (a) goal and scope, identifying the purpose, system boundaries and FU as the main aims of (a); (b) LCI, involving a precise collection of whole inputs (materials and energies) along with outputs (air, soil, and water emissions); (c) LCIA, whose purpose is to quantify the relative matter of the environmental burdens recognized in LCI by identifying their impact on particular environmental consequences, and (d) interpreting the results.

2.2.1. Goals, FU, and system boundary

To define the goals is the first step of LCA (Guinée, 2001; Soheili-Fard and Kouchaki-Penchah, 2015; Nabavi-Pelesaraei et al., 2019). In this research work, three scenarios were defined for evaluating LCA environmental damages, including CS, LEI, and OS, whose comparison was one of the main objectives. The specifications of the mentioned scenarios are outlined in Table 2.

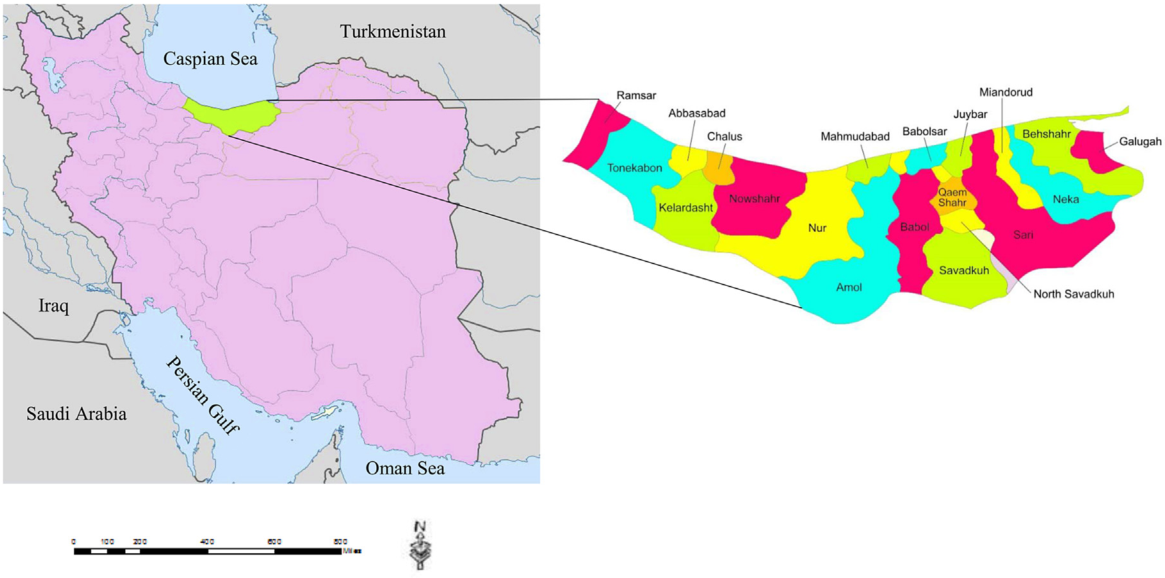


Fig. 1. Geographical status of Mazandaran province in Northern Iran.

Table 2
The specification of surveyed scenarios of paddy production in the Mazandaran province of Iran.

Item	Scenarios		
	CS	LEI	OS
Agriculture operation period	1 April - 30 July	1 April - 30 July	1 April - 30 July
Irrigation type	Flooded paddy cultivation practice	Flooded paddy cultivation practice	Flooded paddy cultivation practice
Transport (paddy and fertilizers)	Trailer	Trailer	Trailer
Tractor (primary and secondary tillage)	Massey Ferguson 299 and Kubota	Massey Ferguson 285 and Kubota	Massey Ferguson 285
Puddling by rotary harrow	Badeleh and Hadi companies	Badeleh and Hadi companies	Badeleh and Hadi companies
Transplanting type	By human labor	By human labor	By human labor
Weeding, diseases, and insect control (sprayer)	By backpack sprayer	By backpack sprayer	Manual weeding
Harvesting	Direct with combine	Direct with combine	Direct with combine
Combine harvester	Combine 780 TT	Combine 4LZ20	Combine 4LZ20

FU, as a vital concept in LCA, refers to a reference unit for inventory data (Kylili et al., 2016; Soheili-Fard et al., 2018; Farahani et al., 2019). In other words, based on the ISO 14040 standard, it is considered as the reference unit by which the performance of the production system would be quantified (ISO, 2006). In this research, the FU was considered as one t of paddy. As illustrated in Fig. 2, the system boundary in the present research work is the farm gate.

2.2.2. LCI

LCI, as the second step of LCA, involves the total input and output collection for each unit of FU throughout the life cycle (ISO, 2006). To accomplish LCI, two datasets are employed: the dataset from the foreground and background systems (Nabavi-Pelesaraei et al., 2017). The first category of data includes all emissions from input's consumption in paddy fields (such as different fuels, chemical fertilizers, chemical pesticides, and electricity gleaned from direct inquiries), while the second consists of emissions related to the consumable input production. The first On-Farm emission's category is related to diesel fuel combustion causing emissions. There are determined coefficients of emissions per unit of energy consumption in diesel-fuel burning processes, as presented in Table 3 (Kouchaki-Penchah et al., 2017).

The second category of On-Farm emissions is relevant to both fertilizers and FYM into the air and water. Based on previous studies, standard coefficients were selected to compute On-Farm emissions of fertilizers whose comprehensive explanation is presented in Table 4.

In most studies, the emissions of fertilizers were limited to the items mentioned in Table 4. In this research, on the other hand, the heavy metal emissions derived from fertilizers to soil and emissions of residue burning to air were also considered to obtain greater accuracy in calculating On-Farm emissions whose relevant coefficients are indicated in Table 5 based on Durlinger et al. (2015) and Mousavi-Avval et al. (2017a) research.

Other than the categories mentioned above, there are two On-Farm categories, with the first being related to CO_2 emissions derived from human labor activity to the air (Hosseini-Fashami et al., 2019), and the second the emissions of active materials of biocides into air and soil (Margni et al., 2002). The calculation methods of these emissions are given in Eqs. (2)–(4).

$$CEH = THA \times 0.7 \tag{2}$$

$$BEMEA = BEM \times 0.1 \tag{3}$$

$$BEMES = BEM \times 0.85 \tag{4}$$

where, *CEH* is CO_2 emissions derived from human labor activity based on kg CO_2, TAH is the total human activity based on h, *BEMEA* is emissions of biocides effective materials into the air based on kg of effective material, *BEMES* is emissions of biocides effective

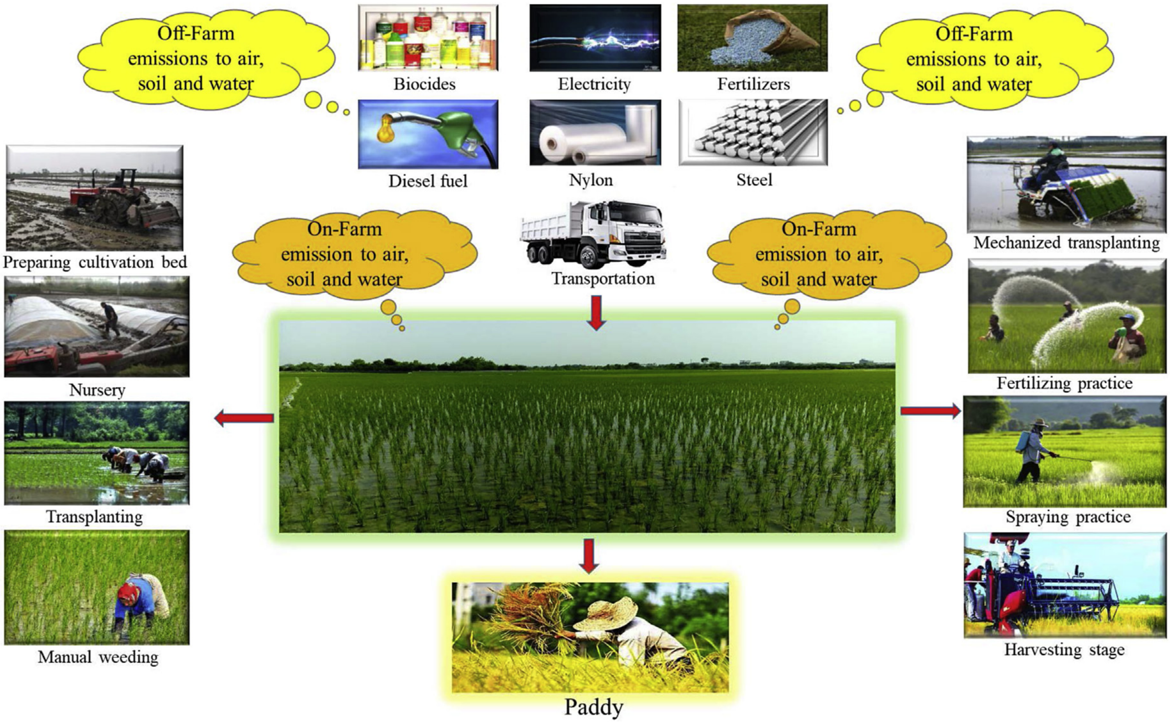


Fig. 2. The defined LCA system boundary for planting scenarios of paddy in Mazandaran province, Iran.

Table 3
Emissions equivalent of the EcoInvent database for burning diesel fuel based on 1 MJ produced energy.

Emission	Amount (g MJ^{-1} diesel)
CO_2	74.5
SO_2	2.41E-02
CH_4	3.08E-03
Benzene	1.74E-04
Cd	2.39E-07
Cr	1.19E-06
Cu	4.06E-05
N_2O	2.86E-03
Ni	1.67E-06
Zn	2.39E-05
Benzo (a) pyrene	7.16E-07
NH_3	4.77E-04
Se	2.39E-07
PAH	7.85E-05
HC, as NMVOC	6.80E-02
NOx	1.06
CO	1.50E-01
Particulates (b2.5 μm)	1.07E-01

materials into the soil based on kg of effective material, and *BEM* denotes the effective materials of biocides based on kg.

2.2.3. LCIA

Impact assessment analyzes all outputs and inputs of the paddy system consisting of classifications, normalization, and weighting steps. The first stage is mandatory, while the last two stages are optional.

Various methodologies, including EcoPoints (Frischknecht et al., 2007), EPS2000 method (Steen, 1999), EDIP2003 (Hauschild and Potting, 2005), EDIP97 ′ (Frischknecht et al., 2007), CML 2001 (Frischknecht et al., 2007), ReCiPe 2008 (Goedkoop et al., 2009), environmental indicators 99 (Goedkoop and Spriemsma, 2001) can be used to develop these stages. Among all, IMPACT 2002+ has been employed in this study, as it is often used in LCA (Jolliet et al., 2003). This methodology is an impact assessment methodology developed at the Swiss Federal Technology Institute (Hischier et al., 2015). It links all the types of LCI results via 15 intermediate classes to human health, climate change, ecosystem quality, and resource reduction, as four categories of damage (Jolliet et al., 2003). Human toxicity, ionizing radiation, ozone layer depletion, and respiratory effects, are factors that affect the human health category (Jolliet et al., 2003). Terrestrial acidification, ecotoxicity, land occupation, and terrestrial nitrification, all contribute to damages to the ecosystem quality (Goedkoop and Spriemsma, 2001). Global warming also contributes to developing the detrimental effects of

Table 4
On-Farm emissions related to FYM and chemical fertilizers consumption in the agricultural production system (IPCC, 2006).

Emission	Cause	Unit	Coefficient	Under the influence environment
1. N_2O	Pure nitrogen in total chemical fertilizers and FYM	kg N_2O	0.01	Air
2. NH_3	Pure nitrogen in FYM	kg NH_3	0.2	Air
3. NH_3	Pure nitrogen in chemical fertilizers	kg NH_3	0.1	Air
4. N_2O	Atmospheric deposition of nitrogen in chemical fertilizers	kg N_2O	0.001	Air
5. N_2O	Atmospheric deposition of nitrogen in FYM	kg N_2O	0.003	Air
6. NO_3^-	Pure nitrogen in total chemical fertilizers and FYM	kg NO_3^-	0.1	Water
7. Phosphate	Pure phosphate in total chemical fertilizers and FYM	kg phosphate	0.02	Water
8. NOx	N_2O in fertilizers and soil	kg NOx	0.21	Air

Table 5
Standard coefficients of emissions related to heavy metals of chemical of fertilizers and residue burning process of paddy production scenarios.

Item	Heavy metals emissions to soil							Residue burning emissions to air			
	Cd	Cu	Zn	Pb	Ni	Cr	Hg	CH_4	CO	N_2O	NOx
1. Unit	mg	mg	mg	mg	mg	mg	mg	kg	kg	kg	kg
2. The coefficient for 1 kg of nitrogen fertilizer	6	26	203	5409	20.9	77.9	0.1	–	–	–	–
3. The coefficient for 1 kg of phosphate fertilizer	39.5	90.5	839	67	88.3	543	0.3	–	–	–	–
4. The coefficient for 1 kg of potassium fertilizer	0.1	4.8	6.2	0.8	2.5	5.8	0	–	–	–	–
5. The coefficient for 1 kg of FYM (poultry)	1.5	99	469	16.2	19.05	8.7	0.085	–	–	–	–
6. The coefficient for 1 kg of residue burning	–	–	–	–	–	–	–	0.005	0.06	0.007	0.121

Table 6
Explanation of midpoints and their relationship with endpoints in the IMPACT 2002+ method of LCA.

Midpoint	Unit	Definition	Impact indicator	Damage category
Carcinogens	kg C_2H_3Cl eq.	Toxic effects of chemicals on humans	Cancer, respiratory diseases	Human health
Non-Carcinogens	kg C2H$_3$Cl eq.	Chronic toxicological effects on human health	Cancer, respiratory diseases	Human health
Respiratory inorganics	kg PM2.5 eq.	Suspended tiny particles originated from anthropogenic processes	Increase in various sized particles suspended on-air (PM0.1, PM2.5, PM10)	Human health
Ionizing radiation	Bq C-14 eq.	Type of radiation composed of particles with appropriate energy to liberate an electron from a molecule or atom	Radiation effects (illnesses, cancer, health decline)	Human health
Ozone layer depletion	kg CFC-11 eq.	Diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone-depleting substances	Increase of ultraviolet UV-B radiation and skin illnesses	Human health/Ecosystem quality
Respiratory organics	kg C_2H_4 eq.	Type of smog produced from the effect of sunlight, heat, and NOx	Increase in the summer smog	Human health/Ecosystem quality
Aquatic ecotoxicity	kg TEG water	Toxic effects of agrochemicals on the ecosystem	Biodiversity loss and Species extinction	Ecosystem quality
Terrestrial ecotoxicity	kg TEG soil	Toxic effects of agrochemicals on the ecosystem	Biodiversity loss and Species extinction	Ecosystem quality
Terrestrial acid/nutria	kg SO_2 eq.	Diminution of the pH in response to the acidifying effects of anthropogenic emissions	Increase of the acidity in the soil	Ecosystem quality
Land occupation	m$_2$org.arable	Impact on the land due to agriculture, resource extractions, and anthropogenic settlement	Decrease in the content of dry organic matter, soil loss, etc.	Ecosystem quality
Aquatic acidification	kg SO_2 eq.	Reduction of the pH due to the acidifying effects	Increase of the acidity in water	Ecosystem quality
Aquatic Eutrophication	kg phosphate P-lim	Accumulation of nutrients in aquatic systems	Enhance of phosphorus and nitrogen concentrations, Formation of biomass (algae)	Ecosystem quality
Global warming	kg CO_2 eq.	Alteration of global temperature caused by greenhouse gases	Disturbances in global temperature and climatic phenomenon	Climate change
Non-renewable energy	MJ primary	Reduction of the availability of the non-biological resources due to their unsustainable use	Decrease in resources	Resources
Mineral extraction	MJ surplus	Reduction of the availability of the non-biological resources due to their unsustainable use	Decrease in resources	Resources

climate change. Further, Non-renewable energy consumption and mineral extraction are two midpoint categories affecting the resources category (Goedkoop and Spriemsma, 2001). Table 6 describes each midpoint with a relevant midpoint for the IMPACT 2002+ method of LCA.

2.2.4. *Life cycle interpretation*

This section examines the environmental damage results for presenting logical exegesis for each scenario and determining the best and worst scenarios in the rice paddy production systems.

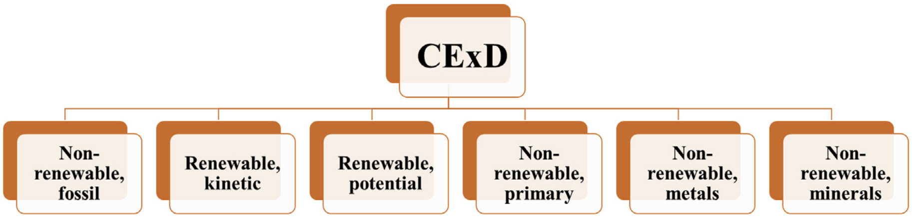


Fig. 3. Energy forms the design of CExD analysis in paddy production.

2.3. CExD approach

Being an incomparable indicator, exergy is used for assessing the quality of energy sources under LCA. CExD is called the entailed exergy amount of all sources demanded, providing a service as well as a product employed to quantify a product's life cycle exergy demand (Bösch et al., 2007). Indeed, CExD evaluates the energy demand quality consisting of energy carrier's exergy along with Non-energetic materials based on Bösch et al. (2007). In other words, CExD quantifies the whole exergy necessity of a service or product (Szargut, 2005). The CExD procedure for LCA has been developed according to the method published by the EcoInvent center (Hischier et al., 2015). There are six important different impact groups in which the CExD method is structured (Bösch et al., 2007), as displayed in Fig. 3.

2.4. LCCA

The LCC was first used by the US Department of Defense in the 1960s (Ilinitch et al., 1998). Many different disciplines since then have been interested in estimating the optimal allocation of budget by calculating the costs involved throughout the entire life cycle of a project, product, service, and investment (Huppes et al., 2004). LCC captures all costs related to the system, product, or structure as applied over the surveyed life cycle (Norris, 2001). Most studies do not calculate the emission costs, but they have been addressed in this study.

The first step of LCCA is computing economic indices for different scenarios. The sale price, total production revenue, LCC including variable, fixed and emissions costs, and net profit value should be determined, which are given in the following formula:

$$\text{Sales price } (\$\ \text{kg}^{-1}) = \text{Financial value per kg of paddy} \tag{5}$$

$$\text{Total production revenue } (\$\ \text{t}^{-1}) = \text{Sale price } (\$) \times \text{Paddy yield (t)} \tag{6}$$

$$\text{Total variable cost } (\$\ \text{t}^{-1}) = \text{Sum of marginal costs over all paddy produced} \tag{7}$$

$$\text{Total fixed cost } (\$\ \text{t}^{-1}) = \text{Cost of production that does not change with changes in the quantity of paddy produced} \tag{8}$$

$$\text{Total emissions cost } (\$\ \text{t}^{-1}) = \text{Cost of elimination emissions effects in the society} \tag{9}$$

$$\text{LCC } (\$\ \text{t}^{-1}) = \text{Total variable cost } (\$\ \text{t}^{-1}) + \text{Total fixed cost } (\$\ \text{t}^{-1}) + \text{Total emissions cost } (\$\ \text{t}^{-1}) \tag{10}$$

$$\text{Net profit } (\$\ \text{t}^{-1}) = \text{Total production revenue } (\$\ \text{t}^{-1}) - \text{LCC } (\$\ \text{t}^{-1}) \tag{11}$$

As can be seen in Eq. (9), the emissions costs are considered as one of the LCC parts, since the economic analysis of climate change often focuses on welfare economics. This cost is the capital required for preventing the effects of emissions from the society (van den Bergh and Botzen, 2015). In this research, the emission cost of paddy production includes two parts. The first part is related to the tariff of emissions in the electricity generated in the power plant, and the second part is related to On-Farm emissions which will be evaluated based on the above explanation. The standard coefficients of emissions determined by Nabavi-Pelesaraei et al. (2019a) are used to calculate emissions costs, as reported in Table 7.

Excel 2019 spreadsheet has been used to analyze the statistical parameters of initial data, economic indices of paddy production, and comparing the scenarios. Further, SimaPro V9.0.0 software has been used to compute environmental damages of IMPACT 2002+ and energy forms of CExD for different scenarios of paddy system.

3. Results and discussion

3.1. LCI analysis

Table 8 indicates the LCI of paddy production under different planting of systems. LCA's objective is to quantify the environmental characteristics to recognize their hot spots. As mentioned earlier, FU includes the yield of paddy in t. Further, all of the production processes for paddy production are considered as the system boundary. It involves the whole life cycle of cultivating as well as all inputs used in these processes, consisting of the agricultural operations such as preparing cultivated bed and nursery, transplanting, manual weeding, fertilizing and spraying practice, and harvesting stage. As can be seen, with the growing impact of inputs usage in CS, it is evident that most GHG emissions are rooted in the way inputs are highly employed by farmers.

Table 7
Standard coefficients of emissions cost for electricity generation and On-Farm emissions elimination in paddy production systems.

Emission	Unit	Electricity generation (kg kWh^{-1})	On-Farm emissions (kg t^{-1})	Emissions cost coefficient (\$ unit-1)
1. NOx	kg NOx eq.	2.79E-03	Based on calculated amounts	0.6
2. SO_2	kg SO_2 eq.	3.12E-03	Based on calculated amounts	1.825
3. CO	kg CO eq.	6.53E-04	Based on calculated amounts	0.187
4. SPM	kg SPM eq.	1.35E-04	–	4.3
5. CO_2	kg CO_2 eq.	0.72	Based on calculated amounts	0.01
6. CH_4	kg CH_4 eq.	1.80E-05	Based on calculated amounts	0.21
7. N_2O	kg N_2O eq.	3.00E-06	Based on calculated amounts	4.58

Table 8
LCI of 1 ha paddy production in the Mazandaran province of Iran under three different scenarios.

Item (unit)	Scenarios		
	CS	LEI	OS
A. Off-Farm			
1. Agricultural machinery (kg)	8.38	8.38	6.6
2. Chemical fertilizers (kg)			
(a) Nitrogen	235.69	103.68	–
(b) Phosphate	186.35	91.98	–
(c) Potassium	85.53	65.06	–
3. FYM (kg)	688.92	830.43	1500
4. Biocides (kg)	56.84	18.92	–
5. Nylon (kg)	13.74	13.85	13.49
6. Lubricating oil (kg)	2.02	1.27	1.16
7. Steel (kg)	6.19	4.4	4
8. Seed (kg)	44.86	43.98	43.94
9. Electricity (kWh)	332.18	289	206.38
10. Diesel fuel (kg)	398.95	229.13	179.25
B. On-Farm			
1. Emissions by diesel fuel to air (kg)			
(a). CO_2	1946.10	1117.70	874.38
(b). SO_2	0.63	0.36	0.28
(c). CH_4	0.08	0.05	0.04
(d). Benzene	4.55E-03	2.61E-03	2.04E-03
(e). Cd	6.24E-06	3.59E-06	2.81E-06
(f). Cr	3.11E-05	1.79E-05	1.40E-05
(g).Cu	1.06E-03	6.09E-04	4.77E-04
(h). N_2O	0.07	0.04	0.03
(i). Ni	4.36E-05	2.51E-05	1.96E-05
(j). Zn	6.24E-04	3.59E-04	2.81E-04
(k). Benzo (a) pyrene	1.87E-05	1.07E-05	8.40E-06
(l). NH_3	0.01	0.01	0.01
(m). Se	6.24E-06	3.59E-06	2.81E-06
(n). PAH	2.05E-03	1.18E-03	9.21E-04
(o). HC, as NMVOC	1.78	1.02	0.80
(p). NOx	27.69	15.90	12.44
(q). CO	3.92	2.25	1.76
(r). Particulates (b2.5 μm)	2.80	1.61	1.26
2. Emissions by fertilizers to air (kg)			
(a). N_2O	4.10	2.10	0.85
(b). NH_3 by FYM	6.06	7.28	13.15
(c). NH_3 by chemical fertilizers	28.62	12.59	–
3. Emission by atmospheric deposition of fertilizers to air (kg)			
(a). N_2O by chemical fertilizers	0.37	0.16	–
(b). N_2O by FYM	0.08	0.09	0.17
4. Emissions by fertilizers to water (kg)			
(a). NO_3^-	34.63	17.76	7.19
(b). Phosphate	4.37	2.37	0.65
5. Emission by N_2O of fertilizers and soil to air (kg)			
(a). NOx	0.95	0.50	0.21
6. Emission by human labor to air (kg)			
(a). CO_2	301.18	304.98	361.73
7. Emission by heavy metals of fertilizers to soil (mg)			
(a). Cd	9290.45	4872.85	1103.75
(b). Cu	56420.65	51131.15	71888.85
(c). Zn	361139.20	287164.32	340564.35
(d). Pb	1292803.95	573532.39	11763.63
(e). Ni	27947.82	18109.69	13833.16
(f). Cr	122945.91	61896.65	6317.51
(f). Hg	107.82	72.13	61.72
8. Emissions by residue burning to air (kg)			
(a). CH_4	7.04	6.64	4
(b). CO	84.53	79.73	48
(c). N_2O	9.86	9.30	5.60
(d). NOx	170.46	160.78	96.80
9. Emissions by biocides to air (kg)			
(a). Butachlor	0.39	0.32	–
(b). Bensulfuron methyl ester	0.02	–	–
(c). Diazinon	2.27	1.30	–
(d). Fipronil	2.25	–	–
(e). Fenitrothion	0.22	–	–
(f). Thiram	0.25	0.26	–
(g). Tricyclazole	0.14	–	–
(h). Propiconazole	0.12	–	–
(i). Iprodione	0.01	0.01	–
(j). Carbendazim	0.003	0.003	–
(k). Tebuconazole	0.01	–	–
(l). Trifloxystrobin	0.01	–	–
10. Emissions by biocides to soil (kg)			
(a). Butachlor	3.29	2.75	–
(b). Bensulfuron methyl ester	0.16	–	–
(c). Diazinon	19.29	11.06	–
(d). Fipronil	19.15	–	–
(e). Fenitrothion	1.90	–	–
(f). Thiram	2.16	2.20	–
(g). Tricyclazole	1.15	–	–
(h). Propiconazole	1.03	–	–
(i). Iprodione	0.04	0.04	–
(j). Carbendazim	0.03	0.03	–
(k). Tebuconazole	0.09	–	–
(l). Trifloxystrobin	0.04	–	–
C. Yield			
1. Paddy (kg)	4614.84	4115.89	3265.63

Table 9
Damages results of IMPACT 2002+ for 1 t of paddy production under three different scenarios.

Damage category	Unit	Scenarios		
		CS	LEI	OS
Human health	DALY [a]	0.01	0.01	3.97E-03
Ecosystem quality	PDF*m^2*yr [b]	9380.37	7098.38	6606.95
Climate change	kg $CO_{2\ eq.}$	1768.55	1260.79	873.18
Resources	MJ primary	13929.44	8383.95	4976.04

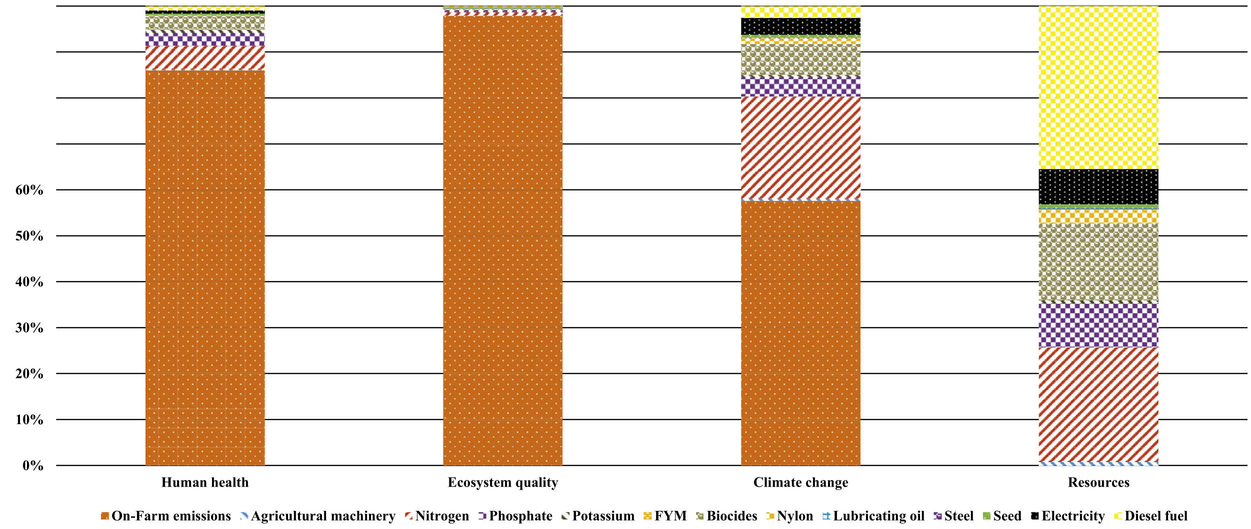
[a] 1 damage is equal to the loss of a person's one life year, or one individual has the disability for 4 years with 0.25 wt

[b] 1 damage is equal to the removal of all the species per 1 m^2 throughout one year, or disappearance of about 10 percent of all species per 10 m^2 over a year, or the disappearance of 10 percent of all species from one m^2 throughout 10 years.

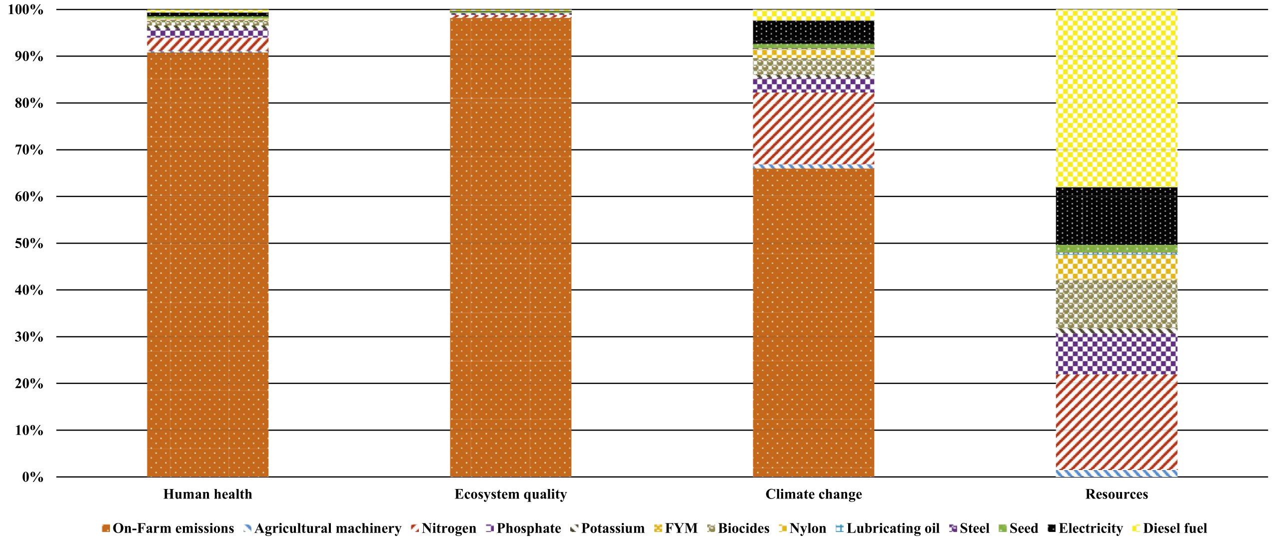
3.2. Environmental damages of paddy production scenarios

Table 9 outlines four paddy production damage categories. Based on Table 9, the total values of human health damage groups produced in CS, LEI, and OS are 0.01, 0.01, and 3.97E-03 DALY, respectively. The total amounts of ecosystem quality damage groups are also 9380.37, 7098.38, and 6606.95 PDF*m2*yr in CS, LEI, and OS, respectively. Furthermore, the amounts of resource damage and climate change damage groups are about 13929.44 MJ primary and 1768.55 kg CO2 eq. for CS, 8383.95 MJ primary, and 1260.79 kg CO2 eq. for LEI, and 4976.04 MJ primary and 873.18 kg CO2 eq. for OS, respectively.

Contributions of different inputs related to the damage categories are indicated in Fig. 4. As shown in Fig. 4, it is evident that in most damage categories cases such as ecosystem quality, human health, and climate change, On-Farm emissions from paddy claim the highest share in all three cultivation systems. Direct emissions of the field are usually a result of burning diesel fuel and application of chemical fertilizers, particularly pesticides in the fields. Due to the reduction in the usage of biocides and chemical fertilizers, the percentage of On-Farm emissions increased in three environmental damages upon moving from the CS to OS. In other words, the share of off-farm emissions in fertilizers and biocides has diminished and replaced by off-farm emissions. Thus, it can be stated that in LEI and OS, most of the On-Farm emissions are related to diesel fuel consumption. It also indicates a wrong approach to define the scenarios in the region. The LEI and OS scenarios focus on reducing biocides



(b) LEI scenario



(c) OS scenario

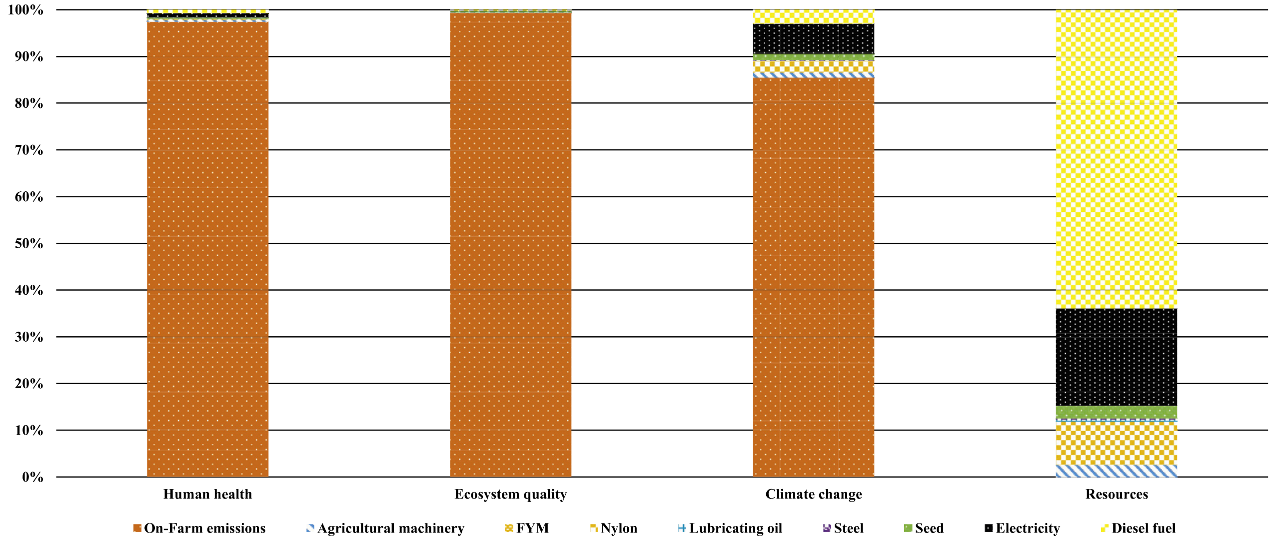


Fig. 4. The distribution of environmental damages under (a) CS, (b) LEI, and (c) OS scenarios of paddy production.

and chemical fertilizers while disregarding fuel consumption.

In terms of resources, diesel fuel has the largest impact on CS, LEI, and OS systems (35.50%, 37.98%, and 63.09%), followed by chemical fertilizers, particularly nitrogen (24.91% and 20.41% for CS and LEI). Since diesel fuel is the most effective input on the resources damage category, it has the highest share in all three scenarios. However, as with other damage categories, upon moving from scenarios where the use of fertilizers is higher (e.g., CS) to those where fertilizers and biocides are reduced (e.g., OS and LEI), the share of diesel increases in the resources damage category. Reduction of the share of fertilizers and biocides in indirect emissions is the main cause of this result. On the other hand, the production of chemical fertilizers in factories as well as electricity in Iranian power stations, due to the use of fossil fuels in the production process, has also made them consume plenty of resources. Obviously, in response to the high consumption of chemical fertilizers in CS, nitrogen fertilizer is ranked second in the highest share of the resource damage category (Fig. 4a). In contrast, with the descending trend of these fertilizers in LEI, and mainly OS (Fig. 4b and c), electricity input would be the second in the resource damage category.

Similarly, Hokazono and Hayashi (2012) recognized that direct emissions and field operations are significant contributors to the environmental effect in the organic rice system. The results of similar research in other crops have shown that the use of chemical fertilizers (particularly urea) and fossil fuels had the most significant effect on GHG emissions and global warming potential (Lu et al., 2018; Moradi et al., 2018). Further, Alam et al. (2019) noted the relative contribution of On-Farm emission was calculated around 67% of total GHG emissions. Their results were almost similar to our findings.

3.3. Energy forms analysis of CExD in paddy production scenarios

Table 10 reports the results of exergy analysis for 1 t of paddy production under three different scenarios, according to CExD. As can be seen, Non-renewable, fossil fuel is the top energy consumer of all forms of energy, with values of 13201.72, 7979.54, and 4862.06 MJ t^{-1} in CS, LEI, and OS, respectively. In CS and LEI, the forms of Non-renewable, minerals, Non-renewable, metals, and Renewable, potential energy are other energy consumers. In contrast, in OS, the Renewable, potential and Non-renewable, metals are the other energy users of the next levels. Note that, regarding energy consumption, there are no significant amounts of other energy forms.

Although the physical values of the forms of energy are more effective in understanding the situation, analyzing the percentages of the constituents of different energy forms is also of importance in decision-making policies. Accordingly, Fig. 5 presents the results obtained from the analysis of energy based on CExD for 1 MJ of 1 t of paddy. As shown in Fig. 5a, diesel fuel with 37.72% followed by nitrogen (25.51%) and biocides (15.69%) have the highest part in Non-renewable, fossil form in CS. Further, these values consist of diesel fuel (around 40.18%) followed by nitrogen (about 20%) and electricity (approximately 12.48%) in LEI (Fig. 5b). For OS, these amounts were related to diesel fuel (65.03%) and electricity (28.35%) (Fig. 5c). In some forms regarding Non-renewable, minerals and Non-renewable, metals and Non-renewable, primary, phosphate (68.11%, 18.56%, and 31.77%) and nitrogen (22.88%, 59.775%, and 48.79%) were the most energy-consuming among inputs for CS. Furthermore, the values of these forms for phosphate and nitrogen were 71.03%, 19.39%, 30.83%, and 21.26%, 55.41%, 42.19% in LEI, respectively (Fig. 5a and b), while agricultural machinery claimed significant shares of Non-renewable, metals and Non-renewable, primary, by about 60.61% and 44.94% in OS (Fig. 5c). Further, the highest share of Renewable, kinetic, belonged to biocides by 38.49% and 28.45% for CS and LEI scenarios, while in this regard, diesel had the main effect of OS by about 28.96%.

Table 10
The energy forms of CExD for 1 t of paddy production under three different scenarios.

Energy form	Unit	Scenarios		
		CS	LEI	OS
Non-renewable, fossil	MJ t^{-1}	13201.72	7979.54	4862.06
Renewable, kinetic	MJ t^{-1}	32.42	16.37	2.99
Renewable, potential	MJ t^{-1}	216.58	120.70	36.43
Non-renewable, primary	MJ t^{-1}	6.13	3.49	0.05
Non-renewable, metals	MJ t^{-1}	319.61	170.04	25.76
Non-renewable, minerals	MJ t^{-1}	402.50	213.61	3.81

According to Table 10 and Fig. 5, a significant part of the CExD belonged to Non-renewable, fossil, with diesel being one of the major components involved. Also, employing nitrogen, phosphorus, and pesticides led to consumption of Non-renewable energy, fossil, metals, and minerals. Note that using high inputs, mainly those mentioned earlier, the fossil resources will be at risk. As can be seen in Fig. 5, the reduction in physical consumption of inputs in OS compared to LEI as well as LEI compared to CS along with the increase in fuel share in energy forms by reducing fertilizer consumption, suggest that the chemical fertilizer production process is very costly from an exergy point of view. Thus, saving on these inputs can lead to a significant reduction in the amounts of energy forms in both CS and LEI. Meanwhile, the OS scenario should focus on managing diesel fuel consumption and agricultural machinery.

3.4. LCCA analysis in different scenarios of paddy production

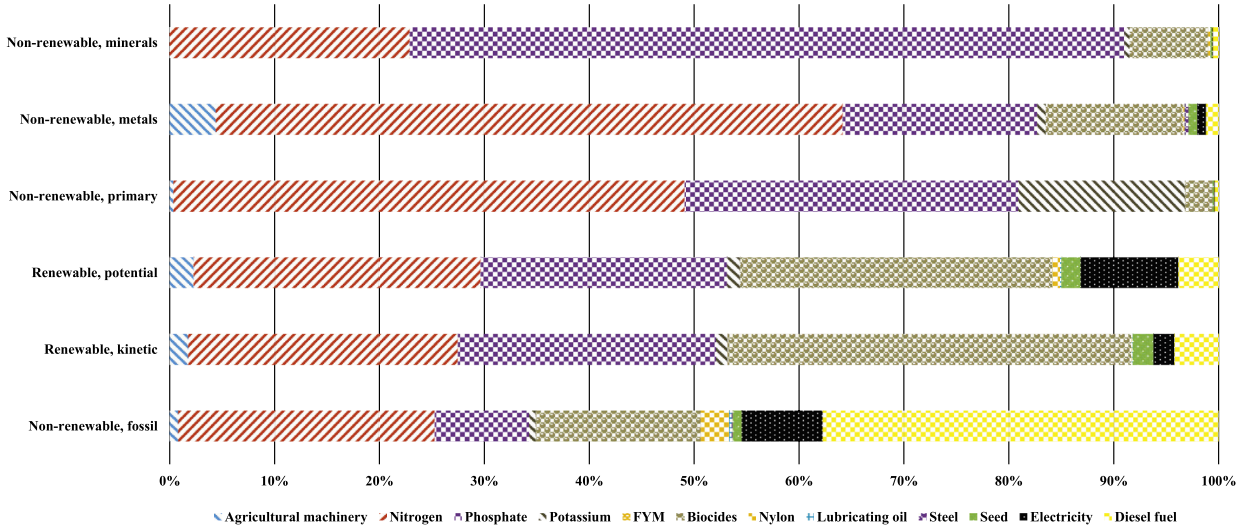
To evaluate the paddy production, an analysis was undertaken from an economic perspective with the results reported in Table 11. This table indicates the economic indices of paddy production under three different scenarios. As shown in Table 11, through multiplying the sale price of paddy by the yield of paddy, the whole conversion of paddy revenue in the three surveyed systems comprising of CS, LEI, and OS scenarios was computed as 790, 790, and 1170 \$ t^{-1}, respectively. For LEI, the variable, fixed, and emissions costs were calculated to be 258.91, 88.13 and 50.93 \$ t^{-1}, accounting for 65.05%, 22.14%, and 12.79% of the total cost, respectively. These values for CS were 253.05, 88.13, and 50.40 \$ t^{-1} accounting for 64.62%, 22.50%, and 12.87% of the total cost, while the shares of these values for OS scenario were about 66.07%, 23.80%, and 10.12%. Further, LCC in CS, LEI, and OS were also calculated approximately 391.58, 397.97, and 370.27 \$ t^{-1}, respectively. Since the amounts of variable and emissions costs in OS were far lower than those of the other two scenarios, LCCA was the minimum in this scenario. At the end of paddy production's economic analysis, the average net profit was estimated 799.73 \$ t^{-1} in OS, 392.03 \$ t^{-1} in LEI, and 398.42 \$ t^{-1} in CS scenarios.

Since OS uses some farm-grown inputs, and is less dependent on market purchased inputs, it is economically attractive to the growers. The OS shows the path to achieving the goal through agricultural diversification in an ecologically, economically, and socially acceptable manner.

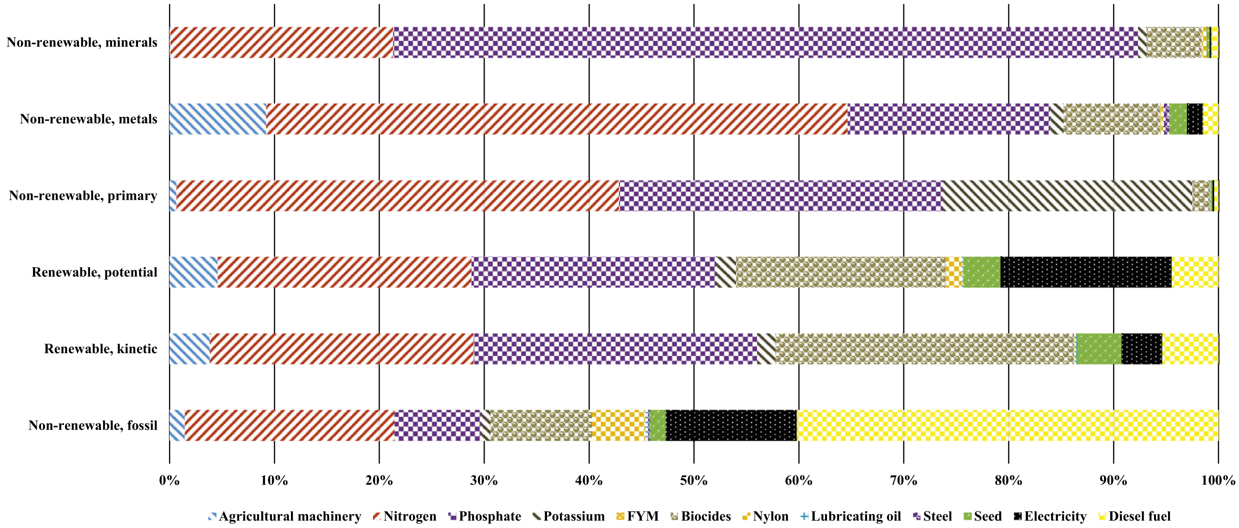
Some factors highlight the necessity of organic agriculture, such as:

❖ Farmer's poor socio-economic state
❖ Rise in the cost of inputs used

(a) CS scenario



(b) LEI scenario



(c) OS scenario

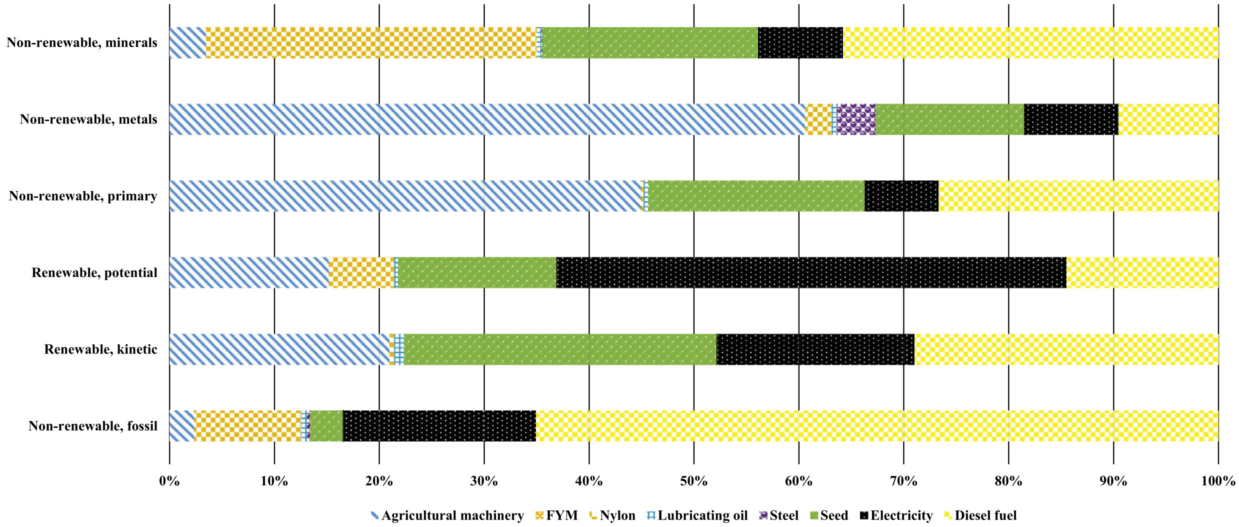


Fig. 5. The share of energy forms in CExD analysis under (a) CS, (b) LEI, and (c) OS scenarios of paddy production.

Table 11
Economic indices of paddy production under three different scenarios.

Item	Unit	Scenarios		
		CS	LEI	OS
1. Sales price	\$ kg^{-1}	0.79	0.79	1.17
2. Total production revenue	S t^{-1}	790	790	1170
3. Total variable cost	S t^{-1}	253.05	258.91	244.66
4. Total fixed cost	S t^{-1}	88.13	88.13	88.13
5. Total emissions cost	S t^{-1}	50.40	50.93	37.48
6. LCC	S t^{-1}	391.58	397.97	370.27
7. Net profit	S t^{-1}	398.42	392.03	799.73

As a result of diminished application of inputs through optimized utilization of diesel fuel, agricultural machinery, and chemical fertilizers, especially in CS, the profit will grow remarkably.

Based on the findings of Pishgar-Komleh et al. (2011), the fixed and variable cost amounts were around 78% and 22% of the whole cost in paddy fields, respectively. Applying some inputs such as electricity, fuel, etc., the share of variable costs is higher than that of the fixed costs.

3.5. Selection of the best scenario

In the last part, the best scenario was chosen based on three main parameters, including weighted environmental damages, CExD, and LCCA, which are explained in the following subsets.

3.5.1. Environmental damages comparison between defined scenarios

Fig. 6 compares every damage category as well as their amounts. The CS scenario is considered as the basis for comparing the three scenarios of this research. The rate of emissions has fallen through applying OS by about 33.57% in the damage category of human health, while LEI is less effective than OS in this damage category. Hence, LEI can reduce human health by 13.20%. On-Farm emissions claim the most substantial portion of human health, with the most influential inputs in this category being diesel, chemical fertilizers, and biocides; accordingly, their rate will diminish upon reduction of chemicals and diesel fuel consumption.

The damage category of the ecosystem quality is reduced by 24.33% and 29.57% in LEI and OS, respectively in comparison with CS. Also, CS has very detrimental effects on the quality of the ecosystem through acidification and eutrophication. The acidification effect is mainly due to the release of SO_2, NH_3, and NO_2 to the air or soil whose quantity will obviously diminish in OS and LEI compared to the CS scenario. Significant reduction in chemical and diesel rates can affect these results.

No use of any agrochemicals in OS removes them from LCI and lower the rate of climate change by 50.63%. GWP is significant as a result of On-Farm emissions in OS. The reduction of climate change for LEI was calculated as 28.71%. Further, the most critical parameter for the climate change category is global warming. According to the findings of Hokazono and Hayashi (2012), the flooding practice of paddy farming would highly contribute highly to GHG emissions.

Two important midpoints affecting the resources damage category are mineral extraction and Non-renewable energy. Diesel, fertilizers, and electricity are very influential in this category. Specifically, the rate of this category is reduced by around 39.81% and 64.28% in LEI and OS in comparison with CS. It is evident that the application of diesel fuels and insecticides in CS was the highest. On the other hand, the first system, in which there are no biocides, used the minimum amounts of diesel fuel. Under the current condition, over-exploitation of Non-renewable resources for electricity generation and diesel significantly increases the climate change category.

Overall, by weighting the relevant data, the OS and LEI showed a 35.31% and 20.34% reduction in the total damage categories. In this regard, use of diesel fuel and fertilizers in smaller amounts, as well as various preventive ecological ways for disease and pest management, could mitigate the environmental effect of the surveyed scenarios.

3.5.2. Energy forms comparison between defined scenarios

In this section, the CS was considered as the basis for comparison between scenarios from the CExD perspective. Fig. 7 demonstrates that less use and no use of agrochemical in LEI and OS can save total CExD in paddy production by more than 40% and 65% in comparison with CS, respectively. In all energy forms, the OS system has outperformed LEI and CS systems. For example, as a result of no use of any chemicals, particularly nitrogen and phosphate, the OS shows 99.15% reduction in emissions in Non-renewable, minerals compared to CS.

As can be seen in Fig. 7, in most of the energy forms, almost about 80−90% can be saved by the OS scenario. The LEI scenario was also more favorable than the CS. In general, between 40 and

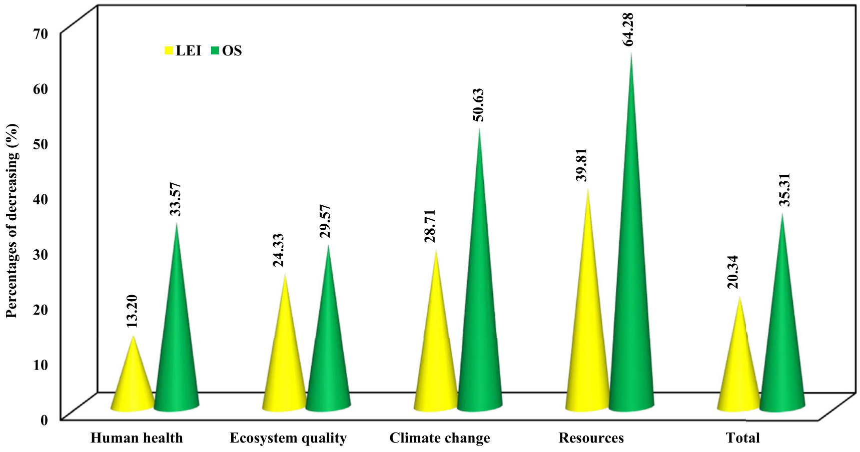


Fig. 6. Potential of environmental damages reduction in LEI and OS scenarios.

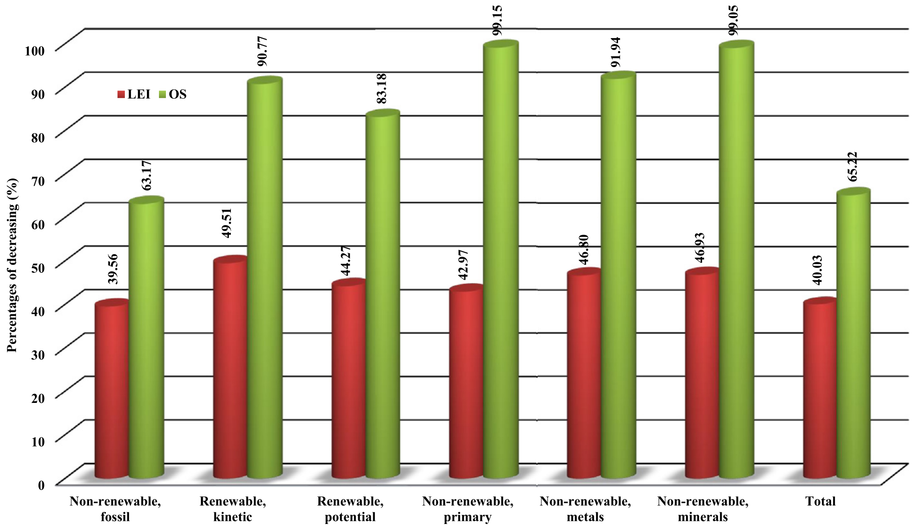


Fig. 7. Potential of energy forms reduction in LEI and OS scenarios.

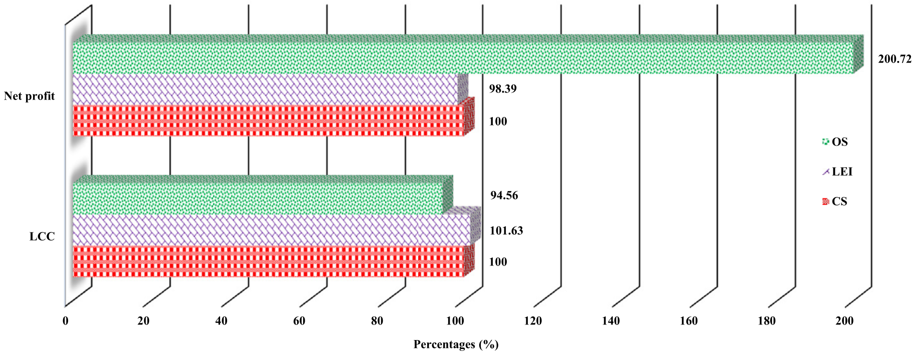


Fig. 8. Economic indices comparison between CS, LEI, and OS scenarios.

50% reduction in most energy forms can be achieved in this production system.

3.5.3. LCCA comparison between defined scenarios

Fig. 8 reveals the comparative LCC and net profit amounts of the three different scenarios. In this figure, the CS is also considered as the base system. As can be seen, the LCC of OS is about 5.44% less than that of the base system, while the LCC of LEI is slightly more than CS's. The total costs studied in LEI are higher than those in the other scenarios. Indeed, in LEI, due to lower costs and input use, variable costs are low; nevertheless, assuming FU to be based on 1 t of paddy and given the differences in the paddy yield, the sum of its total costs is more than that of other systems. There is also a growing trend for the net profit of OS, with a significant difference from the other scenarios. Economically, by reducing consumption costs, including fixed and variable costs as well as the emissions costs resulting from them in the OS scenario, the highest net profit could be achieved.

Concerning the chief factors such as:

- ➢ Insecurity in crop prices
- ➢ Constant elevation of production costs

Factors such as the following may seem necessary economically:

- ✓ Reducing production costs for farmers and improving their benefits
- ✓ Utilizing inputs such as fertilizer, water, and energy efficiently

In this regard, the optimal use of agricultural machinery and diesel fuel will cause lower prices of the product and will finally boost the farmer's profits as well as economic stability. Thus, the most economically viable scenario can be considered OS regarding the high price of organic paddy.

3.6. Managerial implications

Evaluation of exergoenvironmental damages and LCC in all defined scenarios of paddy production indicated that the On-Farm emissions, chemical fertilizers, especially nitrogen and diesel fuel, were the major hotspots in all of them. Among the mentioned items, diesel fuel is significant as the main part of On-Farm emissions and indirect emissions of nitrogen in the factory is dependent on diesel. On the other hand, the reserves of Non-renewable resources are diminishing in response to extraction from the environment and usage for the human economy; thus, the gradual depletion of fossil resources has become a serious challenge. Also, Non-renewable resources are finite in quantity and their stocks would not regenerate. However, since Iran is one of the most important leading producers of Non-renewable resources in the world, the price of diesel is meager; consequently, the irregular usage of this input is observed in paddy cultural systems. The lack of importance of diesel in Iranian agricultural systems has led to defining conservative scenarios such as LEI and OS while neglecting diesel fuel. Another effect of the low price of diesel is the unwillingness to replace systems such as establishing renewable energy systems, while many operations can be handled by alternative non-fossil fuels.

There are some tips for the management of diesel consumption as follows:

- ➢ Timely maintenance of agricultural machinery such as replacing filters, etc.
- ➢ Disposal of depreciated agricultural machinery
- ➢ Right education of operators to use the agricultural machinery correctly; for example, prevention of sudden pressure of gas pedal in a tractor can be effective in diesel fuel use significantly.
- ➢ Determination of optimal patterns for agricultural operation, especially in primary and secondary tillage.
- ➢ No-tillage and minimum tillage practice to minimize the use of agricultural machinery
- ➢ Applying limitation policy for fuel use at low prices, so that fuel prices will rise exponentially.
- ➢ Applying encouragement policy for establishing renewable energy systems such as photovoltaic panels, especially in extractor pumps of water.
- ➢ Tax exemption of efficient farmers who have focused on reducing diesel consumption.
- ➢ Creating a logical boundary for diesel usage to define a conservative scenario, including LEI and OS.

In addition to fuels, chemical fertilizer utilization is another major parameter for the management of the exergoenvironmental-LCC modification of paddy production systems. There is a wrong belief among Iranian farmers that believe more use of chemical fertilizers is equal to a higher yield. However, based on the law of diminishing returns, the irregular use of chemicals can reduce the yield significantly (Shi et al., 2020). Meanwhile, the following managerial policies can be applied to achieve more sustainability in utilization of chemical fertilizers:

- ✓ Use of chemical fertilizers at an appropriate time.
- ✓ Usage of precision farming to apply the rate of chemical fertilizers required for each crop.
- ✓ Biofertilizer production and consumption such as compost, etc.
- ✓ Integrated soil fertility management and plant nutrition as well as serious prevention of burning plant residues in paddy farms.
- ✓ No-tillage practice for protecting the soil structure and increasing soil nutrients.
- ✓ Employment of a supervisor committee for educating and surveying the trends of chemical fertilizers in paddy farms.
- ✓ Application of nitrogen-fixing plants in paddy crop rotation such as clover, as using green manure is an appropriate substitution for chemical fertilizers in agriculture, particularly for nitrogen as well as for soil protection and improvement.

According to the results of this research, environmentally and economically, OS can be highly recommended followed by the LEI system to reach environmentally friendly agriculture as sustainable cultural operations in comparison with CS practice. Due to its lower yield, OS requires more land to generate the same amount of products; however, the low yield in OS will be offset by its high sales price and net profit. The cultural policy must concentrate on enhancing the OS yield rather than expand its scale.

4. Conclusions

This research was novel in analyzing different planting scenarios (CS, LEI, and OS) in the north of Iran in relation to the environmental impacts of paddy via LCA, CExD, and LCCA, as no investigation had been reported in this case so far. Eventually, these scenarios were compared in terms of damage category, exergy, and economic perspectives. The results of this research indicated that:

1 In general, in the ecosystem quality, climate change, and human health damage categories, On-Farm emissions from paddy had the highest share in all three cultivation systems. On the other hand, diesel had the most substantial impact on CS, LEI, and OS in terms of resources.
2 Diesel fuel followed by nitrogen had the most elevated portion in Non-renewable, fossil in CS and LEI. These amounts were related to diesel fuel as well as electricity for OS scenarios.
3 LCC in CS, LEI, and OS were also calculated approximately 391.58, 397.97, and 370.27 \$ t^{-1}, respectively. Also, the average net profit was estimated to 799.73 \$ t^{-1} in OS, 392.03 \$ t^{-1} in LEI and 398.42 \$ t^{-1} in CS scenarios.
4 The comparison results of each damage category and their total amounts revealed that OS and LEI had a 35.31% and 20.34% reduction in damage categories compared to CS, respectively.
5 The comparison among scenarios regarding CExD demonstrated that no use of agrochemicals in OS can save CExD of paddy production. Overall, in investigations of all energy forms, OS was better than LEI and CS scenarios.
6 From an economic perspective, since the amount of variable emission costs in OS was far lower than that of the other two scenarios, in this scenario LCCA was minimum. Accordingly, OS had the highest net profit of all scenarios. The LCC of OS was about 5.44% less than that of the base system, while the LCC of LEI was slightly more than that of the CS.
7 OS can be considered as an exergoenvironmental-economically scenario, followed by the LEI scenario from the mentioned perspective.

To sum up, trends of environmental and energy damage categories can be alleviated and modified by some eco-friendly systems such as OS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zahra Saber: Conceptualization, Methodology, Writing - original draft. **Mohammadali Esmaeili:** Data curation, Validation. **Hemmatollah Pirdashti:** Investigation. **Ali Motevali:** Resources. **Ashkan Nabavi-Pelesaraei:** Formal analysis, Software, Supervision, Writing - review & editing.

Acknowledgments

We gratefully acknowledge the financial support provided by the Department of Agronomy and Plant Breeding Engineering, Sari Agricultural Sciences and the Natural Resources University of Iran.

References

Alam, M.K., Bell, R.W., Biswas, W.K., 2019. Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment. J. Clean. Prod. 224, 72–87.

Bacenetti, J., Fusi, A., Guidetti, R., Fiala, M., 2013. Life Cycle Assessment of maize cultivation for biogas production. J. Agric. Eng. 44, 579–582.

Bacenetti, J., Fusi, A., Negri, M., Bocchi, S., Fiala, M., 2016. Organic production systems: sustainability assessment of rice in Italy. Agric. Ecosyst. Environ. 225, 33–44.

Balaguera, A., Carvajal, G.I., Albertí, J., Fullana-i-Palmer, P., 2018. Life cycle assessment of road construction alternative materials: a literature review. Resour. Conserv. Recycl. 132, 37–48.

Bösch, M.E., Hellweg, S., Huijbregts, M.A.J., Frischknecht, R., 2007. Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. Int. J. Life Cycle Assess. 12, 181.

Brodt, S., Kendall, A., Mohammadi, Y., Arslan, A., Yuan, J., Lee, I.-S., Linquist, B., 2014. Life cycle greenhouse gas emissions in California rice production. Field Crop. Res. 169, 89–98.

Cochran, W.G., 1977. The estimation of sample size. Sampl. Tech. 3, 72–90.

Coltro, L., Marton, L.F.M., Pilecco, F.P., Pilecco, A.C., Mattei, L.F., 2017. Environmental profile of rice production in Southern Brazil: a comparison between irrigated and subsurface drip irrigated cropping systems. J. Clean. Prod. 153, 491–505.

Dijkman, T.J., Birkved, M., Saxe, H., Wenzel, H., Hauschild, M.Z., 2017. Environmental impacts of barley cultivation under current and future climatic conditions. J. Clean. Prod. 140, 644–653.

Durlinger, B., Koukouna, E., Broekema, R., van Paassen, M., Scholten, 2015. Agri-footprint 3.0. Blonk Consultans, Gouda, The Netherlands.

Fallahpour, F., Aminghafouri, A., Ghalegolab Behbahani, A., Bannayan, M., 2012. The environmental impact assessment of wheat and barley production by using life cycle assessment (LCA) methodology. Environ. Dev. Sustain. 14, 979–992.

FAO, 2018. Food and agricultural organization statistical yearbook. http://www.fao.org.

Farahani, S.S., Soheilifard, F., Raini, M.G.N., Kokei, D., 2019. Comparison of different tomato puree production phases from an environmental point of view. Int. J. Life Cycle Assess. 24 (10), 1817–1827.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., 2007. Implementation of life cycle impact assessment methods. Ecoinvent Rep 3.

Fusi, A., Bacenetti, J., González-García, S., Vercesi, A., Bocchi, S., Fiala, M., 2014. Environmental profile of paddy rice cultivation with different straw management. Sci. Total Environ. 494–495, 119–128.

Ghahderijani, M., Pishgar Komleh, S.H., Keyhani, A., Sefeedpari, P., 2013. Energy analysis and life cycle assessment of wheat production in Iran. Afr. J. Agric. Res. 8, 1929–1939.

Gharaei, A., Hoseini Shekarabi, S., Karimi, M., 2019a. Modelling and optimal lot-sizing of the replenishments in constrained, multi-product and bi-objective EPQ models with defective products: generalised cross decomposition. Int. J. Syst. Sci. Oper. Logist. 1–13.

Gharaei, A., Hoseini Shekarabi, S., Karimi, M., Pourjavad, E., Amjadian, A., 2019b. An integrated stochastic EPQ model under quality and green policies: generalised cross decomposition under the separability approach. Int. J. Syst. Sci. Oper. Logist. 1–13.

Gharaei, A., Karimi, M., Hoseini Shekarabi, S., 2019c. An integrated multi-product, multi-buyer supply chain under penalty, green, and quality control polices and a vendor managed inventory with consignment stock agreement: the outer approximation with equality relaxation and augmented penalty algorithm. Appl. Math. Model. 69, 223–254.

Gharaei, A., Karimi, M., Hoseini Shekarabi, S., 2019d. Joint economic lot-sizing in multi-product multi-level integrated supply chains: generalized benders decomposition. Int. J. Syst. Sci. Oper. Logist. 1–17.

Goedkoop, M., Heijungs, R., Huijbregts, M.A.J., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, first ed. (Report I: characterisation).

Goedkoop, M., Spriemsma, R., 2001. The Eco-Indicator 99 A Damage Oriented Method for Life Cycle Impact Assessment.

Guinée, J., 2001. Handbook on life cycle assessment-operational guide to the ISO standards. Int. J. Life Cycle Assess. 6, 255.

Hauschild, M., Potting, J., 2005. Background for Spatial Differentiation in LCA Impact Assessment: the EDIP03 Methodology. Environmental Project No. 996. Institute for Product Development Technical University of Denmark.

Hayashi, K., Makino, N., Shobatake, K., Hokazono, S., 2014. Influence of scenario uncertainty in agricultural inputs on life cycle greenhouse gas emissions from agricultural production systems: the case of chemical fertilizers in Japan. J. Clean. Prod. 73, 109–115.

Hayashi, K., Nagumo, Y., Domoto, A., 2016. Linking environment-productivity trade-offs and correlated uncertainties: greenhouse gas emissions and crop productivity in paddy rice production systems. Sci. Total Environ. 571, 134–141.

He, X., Qiao, Y., Liang, L., Knudsen, M.T., Martin, F., 2018. Environmental life cycle assessment of long-term organic rice production in subtropical China. J. Clean. Prod. 176, 880–888.

Hischier, R., Nowack, B., Gottschalk, F., Hincapie, I., Steinfeldt, M., Som, C., 2015. Life cycle assessment of façade coating systems containing manufactured nanomaterials. J. Nanoparticle Res. 17, 68.

Hokazono, S., Hayashi, K., 2015. Life cycle assessment of organic paddy rotation systems using land- and product-based indicators: a case study in Japan. Int. J. Life Cycle Assess. 20, 1061–1075.

Hokazono, S., Hayashi, K., 2012. Variability in environmental impacts during conversion from conventional to organic farming: a comparison among three rice production systems in Japan. J. Clean. Prod. 28, 101–112.

Hokazono, S., Hayashi, K., Sato, M., 2009. Potentialities of organic and sustainable rice production in Japan from a life cycle perspective. Agron. Res. 7, 257–262.

Hoseini Shekarabi, S., Gharaei, A., Karimi, M., 2019. Modelling and optimal lot-sizing of integrated multi-level multi-wholesaler supply chains under the shortage and limited warehouse space: generalised outer approximation. Int. J. Syst. Sci. Oper. Logist. 6, 237–257.

Hosseini-Fashami, F., Motevali, A., Nabavi-Pelesaraei, A., Hashemi, S.J., Chau, K.W., 2019. Energy-Life cycle assessment on applying solar technologies for greenhouse strawberry production. Renew. Sustain. Energy Rev. 116, 109411.

Hosseinzadeh-Bandbafha, H., Safarzadeh, D., Ahmadi, E., Nabavi-Pelesaraei, A., 2018. Optimization of energy consumption of dairy farms using data envelopment analysis–A case study: Qazvin city of Iran. J. Saudi Soc. Agric. Sci. 17, 217–228.

Huppes, G., van Rooijen, M., Kleijn, R., Heijungs, R., de Koning, A., van Oers, L., 2004. Life Cycle Costing and the Environment. Report of a Project Commissioned by the Ministry of VROM-DGM for the RIVM Expertise Centre LCA.

Ilinitch, A.Y., Soderstrom, N.S., E Thomas, T., 1998. Measuring corporate environmental performance. J. Account. Publ. Pol. 17, 383–408.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 2. Inst. Glob. Environ. Strateg. Hayama, Japan.

ISO, 2006. 14040 International Standard. Environmental Management–Life Cycle Assessment–Principles and Framework. International Organisation for Standardization, Geneva, Switzerland.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. Impact 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324.

Kaab, A., Sharifi, M., Mobli, H., Nabavi-Pelesaraei, A., Chau, K.W., 2019. Use of optimization techniques for energy use efficiency and environmental life cycle assessment modification in sugarcane production. Energy 181, 1298–1320.

Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., O'Dwyer, J., Sharifi, M., 2017. Environmental management of tea production using joint of life cycle assessment and data envelopment analysis approaches. Environ. Prog. Sustain. Energy 36, 1116–1122.

Kouchaki-Penchah, H., Sharifi, M., Mousazadeh, H., Zarea-Hosseinabadi, H., Nabavi-Pelesaraei, A., 2016. Gate to gate life cycle assessment of flat pressed particleboard production in Islamic Republic of Iran. J. Clean. Prod. 112, 343–350.

Kralisch, D., Streckmann, I., Ott, D., Krtschil, U., Santacesaria, E., Di Serio, M., Russo, V., De Carlo, L., Linhart, W., Christian, E., Cortese, B., de Croon, M.H.J.M., Hessel, V., 2012. Transfer of the epoxidation of soybean oil from batch to flow chemistry guided by cost and environmental issues. ChemSusChem 5, 300–311.

Kylili, A., Christoforou, E., Fokaides, P.A., 2016. Environmental evaluation of biomass pelleting using life cycle assessment. Biomass Bioenergy 84, 107–117.

Li, M., Li, R., Zhang, J., Liu, S., Hei, Z., Qiu, S., 2019. A combination of rice cultivar mixed-cropping and duck co-culture suppressed weeds and pests in paddy fields. Basic Appl. Ecol. 40, 67–77.

Lu, B., Yang, J., Ijomah, W., Wu, W., Zlamparet, G., 2018. Perspectives on reuse of WEEE in China: lessons from the EU. Resour. Conserv. Recycl. 135, 83–92.

Margni, M., Rossier, D., Crettaz, P., Jolliet, O., 2002. Life cycle impact assessment of pesticides on human health and ecosystems. Agric. Ecosyst. Environ. 93, 379–392.

Ministry of Jihad-e-Agriculture of Iran, 2019. Annual agricultural statistics (in Persian). www.maj.ir.

Moradi, M., Nematollahi, M.A., Mousavi Khaneghah, A., Pishgar-Komleh, S.H., Rajabi, M.R., 2018. Comparison of energy consumption of wheat production in conservation and conventional agriculture using DEA. Environ. Sci. Pollut. Res. 25, 35200–35209.

Morrissey, K., 2017. Life Cycle Assessment of Sweet Sorghum as Feedstock for Second-Generation Biofuel Production.

Mostashari-Rad, F., Nabavi-Pelesaraei, A., Soheilifard, F., Hosseini-Fashami, F., Chau, K.W., 2019. Energy optimization and greenhouse gas emissions mitigation for agricultural and horticultural systems in Northern Iran. Energy 186, 115845.

Motevali, A., Hashemi, S.J., Tabatabaeekoloor, R., 2019. Environmental footprint study of white rice production chain-case study: northern of Iran. J. Environ. Manag. 241, 305–318.

Mousavi-Avval, S.H., Rafiee, S., Sharifi, M., Hosseinpour, S., Notarnicola, B., Tassielli, G., Renzulli, P.A., 2017a. Application of multi-objective genetic algorithms for optimization of energy, economics and environmental life cycle assessment in oilseed production. J. Clean. Prod. 140, 804–815.

Mousavi-Avval, S.H., Rafiee, S., Sharifi, M., Hosseinpour, S., Notarnicola, B., Tassielli, G., Renzulli, P.A., Khanali, M., 2017b. Use of LCA indicators to assess Iranian rapeseed production systems with different residue management practices. Ecol. Indicat. 80, 31–39.

Mousavi, S.M., Falahatkar, S., 2019. Spatiotemporal distribution patterns of atmospheric methane using GOSAT data in Iran. Environ. Dev. Sustain. 1–17.

Moya, C., Domínguez, R., Van Langenhove, H., Herrero, S., Gil, P., Ledón, C., Dewulf, J., 2013. Exergetic analysis in cane sugar production in combination with Life Cycle Assessment. J. Clean. Prod. 59, 43–50.

Nabavi-Pelesaraei, A., Rafiee, S., Mohtasebi, S.S., Hosseinzadeh-Bandbafha, H., Chau, K.W., 2019a. Assessment of optimized pattern in milling factories of rice production based on energy, environmental and economic objectives. Energy

169, 1259–1273.

Nabavi-Pelesaraei, A., Rafiee, S., Mohtasebi, S.S., Hosseinzadeh-Bandbafha, H., Chau, K.W., 2019b. Comprehensive model of energy, environmental impacts and economic in rice milling factories by coupling adaptive neuro-fuzzy inference system and life cycle assessment. J. Clean. Prod. 217, 742–756.

Nabavi-Pelesaraei, A., Rafiee, S., Mohtasebi, S.S., Hosseinzadeh-Bandbafha, H., Chau, K.W., 2018. Integration of artificial intelligence methods and life cycle assessment to predict energy output and environmental impacts of paddy production. Sci. Total Environ. 631–632, 1279–1294.

Nabavi-Pelesaraei, A., Kaab, A., Hosseini-Fashami, F., Mostashari-Rad, F., Chau, K.W., 2019. Life Cycle Assessment (LCA) Approach to Evaluate Different Waste Management Opportunities. Advances in Waste-to-Energy Technologies. CRC Press, pp. 195–216.

Nabavi-Pelesaraei, A., Rafiee, S., Mohtasebi, S.S., Hosseinzadeh-Bandbafha, H., Chau, K.W., 2017. Energy consumption enhancement and environmental life cycle assessment in paddy production using optimization techniques. J. Clean. Prod. 162, 571–586.

Niero, M., Ingvordsen, C.H., Peltonen-Sainio, P., Jalli, M., Lyngkjær, M.F., Hauschild, M.Z., Jørgensen, R.B., 2015. Eco-efficient production of spring barley in a changed climate: a Life Cycle Assessment including primary data from future climate scenarios. Agric. Syst. 136, 46–60.

Norris, G.A., 2001. Integrating life cycle cost analysis and LCA. Int. J. Life Cycle Assess. 6 (2), 118–120.

Peters, J.F., Petrakopoulou, F., Dufour, J., 2014. Exergetic analysis of a fast pyrolysis process for bio-oil production. Fuel Process. Technol. 119, 245–255.

Pishgar-Komleh, S.H., Sefeedpari, P., Rafiee, S., 2011. Energy and economic analysis of rice production under different farm levels in Guilan province of Iran. Energy 36, 5824–5831.

Rivera, X.C.S., Bacenetti, J., Fusi, A., Niero, M., 2017. The influence of fertiliser and pesticide emissions model on life cycle assessment of agricultural products: the case of Danish and Italian barley. Sci. Total Environ. 592, 745–757.

Sakolwitayanon, H., Soni, P., Damien, J., 2018. Attributes determining consumer preference for organic rice in Bangkok, Thailand. Br. Food J. 120, 2017–2032.

Scialabba, N.E.H., Mller-Lindenlauf, M., 2010. Organic agriculture and climate change. Renew. Agric. Food Syst. 25, 158–169.

Shabanzadeh-Khoshrody, M., Azadi, H., Khajooeipour, A., Nabavi-Pelesaraei, A., 2016. Analytical investigation of the effects of dam construction on the productivity and efficiency of farmers. J. Clean. Prod. 135, 549–557.

Shi, P., Li, Y., Hui, C., Ratkowsky, D.A., Yu, X., Niinemets, U., 2020. Does the law of diminishing returns in leaf scaling apply to vines? – evidence from 12 species of climbing plants. Glob. Ecol. Conserv. 21, e00830.

Singh, I.P., Grover, D.K., 2011. Economic viability of organic farming: an empirical experience of wheat cultivation in Punjab. Agric. Econ. Res. Rev. 24, 275–282.

Smol, M., Włóka, D., Włodarczyk-Makuła, M., 2018. Influence of integrated membrane treatment on the phytotoxicity of wastewater from the coke industry. Water Air Soil Pollut. 229, 154.

Soam, S., Kapoor, M., Kumar, R., Gupta, R.P., Puri, S.K., Ramakumar, S.S.V., 2018. Life cycle assessment and life cycle costing of conventional and modified dilute acid pretreatment for fuel ethanol production from rice straw in India. J. Clean. Prod. 197, 732–741.

Soheili-Fard, F., Kouchaki-Penchah, H., 2015. Assessing environmental burdens of sugar beet production in East Azerbaijan province of IR Iran based on farms size levels. Int. J. Farming Allied Sci. 4 (5), 489–495.

Soheili-Fard, F., Kouchaki-Penchah, H., Raini, M.G.N., Chen, G., 2018. Cradle to grave environmental-economic analysis of tea life cycle in Iran. J. Clean. Prod. 196, 953–960.

Steen, B., 1999. A Systematic Approach to Environmental Priority Strategies in Product Development (EPS): Version 2000-general System Characteristics. Citeseer.

Szargut, J., 2005. Exergy analysis. Mag. Polish Acad. Sci. 3, 31–33.

van den Bergh, J.C.J.M., Botzen, W.J.W., 2015. Monetary valuation of the social cost of CO2 emissions: a critical survey. Ecol. Econ. 114, 33–46.

Verhoeven, E., Decock, C., Barthel, M., Bertora, C., Sacco, D., Romani, M., Sleutel, S., Six, J., 2018. Nitrification and coupled nitrification-denitrification at shallow depths are responsible for early season N2O emissions under alternate wetting and drying management in an Italian rice paddy system. Soil Biol. Biochem. 120, 58–69.

Wang, M., Wu, W., Liu, W., Bao, Y., 2007. Life cycle assessment of the winter wheat-summer maize production system on the North China Plain. Int. J. Sustain. Dev. World Ecol. 14, 400–407.

Yodkhum, S., Gheewala, S.H., Sampattagul, S., 2017. Life cycle GHG evaluation of organic rice production in northern Thailand. J. Environ. Manag. 196, 217–223.