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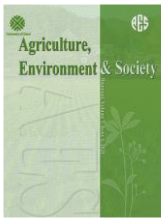

Evaluation of sustainability of rainfed rapeseed production in Gorgan county using Emergy analysis

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ABSTRACT

Excessive use of environmental resources and excessive consumption of chemicals have exacerbated environmental problems and harmed agroecosystem sustainability. As a result, it is beneficial to study energy consumption patterns and efficient energy use in agriculture, which is one of the fundamental principles of sustainable agriculture. The aim of this study was to assess the sustainability of rapeseed production (*Brassica napus* L.) in Gorgan county during the 2017-2018 crop year using emergy essessment. Sixty questionnaires were considered for this purpose. After establishing spatial and temporal boundaries and classifying resources into four categories: renewable environment, non-renewable environment, purchased renewable, and purchased non-renewable, and some emergy indices were calculated in rapeseed agroecosystems. The results indicated that the total emergy input for the rapeseed agroecosystems consumed a total of 6.39E+15 sej ha^{-1} yr^{-1}. In rapeseed agroecosystems, dependence on market and non-renewable inputs was much higher than environmental and renewable inputs. With 59.94 percent of total emergy input in rapeseed agroecosystems, fossil fuels were the primary source of emergy. The transformity of rapeseed agroecosystems was 1.09E+05 sej J^{-1}, the specific emergy was 3.09E+09 sej gr^{-1}, the renewability was 12.46 percent, the emergy yield ratio was 1.22, the standard emergy investment ratio was 4.56, the modified emergy investment ratio was 9.23, the standard environmental loading ratio was 10.25, the modified environmental loading ratio was 7.02, the standard emergy sustainability index was 0.12, and the modified emergy sustainability index was 0.17. Based on the evaluation of emergy indices, the rapeseed agroecosystem has an acceptable crop production efficiency and resource consumption efficiency, and a significant potential for economic productivity increase. By implementing conservation tillage and modernizing machinery, will reduce our reliance on non-renewable and economic inputs, alleviate environmental pressure, and increase the agroecosystem's sustainability.

Highlights

- The purpose of this study was to assess the sustainability of rapeseed production in Gorgan county in 2017-2018.
- Agroecosystem emergy indices were calculated in rapeseed agroecosystems.
- The rapeseed agroecosystems consumed 6.39E+15 sej ha^{-1} yr^{-1}.
- Rapeseed agroecosystems had Tr of 1.09E+05 sej J^{-1}, SpE of 3.09E+09 sej gr^{-1}, EYR of 1.22, EIR of 4.56, ELR of 10.25, and ESI of 0.12.
- With acceptable crop production and resource consumption efficiency, the rapeseed agroecosystem has a significant potential for economic productivity growth.

1. Introduction

Agricultural systems, as consumers of natural and economic resources, have negative effects by over-consuming natural resources and adding polluting compounds to the environment (Quintero-Angel and Gonzales-Acevedo, 2018). Food security depends on the agricultural productivity, resource efficiency, and long-term sustainability of agricultural systems. Sustainability in agriculture is balancing act between food security and maintaining the quality of the environment. Agricultural operations are sustainable when they maintain the quality of the environment and have social acceptance and economic benefits (Kumaraswamy, 2012). Achieving this

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requires assessment methods that provide useful information about the state of the ecosystem and its intensity and direction of change. These methods should include environmental, social, and economic aspects (Quintero-Angel and Gonzales-Acevedo, 2018). Environmental assessment methods are used to assess resource utilization, pollution, and sustainability in a system and include environmental input-output assessment, ecological footprint determination, such as carbon footprint, ecological assessment, life cycle assessment, energy analysis, and emergy analysis (Patterson et al., 2017).

Emergy analysis is a type of energy analysis in which the contribution of the environment and natural resources, which are largely ignored in intensive agriculture, is quantified and evaluated on a unit-by-unit basis (Brown and Ulgiati, 2004). The advantage of the emergy evaluation method over other methods is that it reflects the various flows of energy and matter uniformly in the system under study, which indicates both its quantity and quality (Brown et al., 2016). Emergy analysis thoroughly examines the sustainability of an ecosystem by converting all currents, natural resources, and economic resources into solar emergy units (Odum, 1996). Emergy assessment enhances our understanding of these systems and how they interact with each other by determining the degree of sustainability of continuous ecological and economic systems. Emergy indices are a good tool for integrating ecological and economic systems and make it possible to measure and compare different aspects of these ecosystems (Patterson et al., 2017). These indices are able to determine the efficiency, renewability, environmental pressure, and environmental and economic sustainability of a system (Odum, 2000; Brown and Ulgiati, 2004). Emergy is called embodied energy or energy memory, expressed as the solar emjoule (sej) (Odum, 1996).

Emergy assessment is used to assess the sustainability of production systems at different scales (Xi and Qin, 2009; Zhai et al., 2017). For example, evaluations of three agricultural systems in the United States, including corn production, blackberry production, and the traditional multiple cultivation system, showed that the traditional system had the lowest environmental load and maximum sustainability and that the corn production system had the highest environmental load and the least sustainability (Martin et al., 2006). Evaluation of the sustainability of two subsistence production and commercial rapeseed production systems in Khorramabad based on emergy and economic analysis showed that the subsistence system is more sustainable than the commercial rapeseed production system in this county (Amiri et al., 2019). Also, the evaluation of the sustainability of garlic, onion, and wheat production systems in the Sistan region with emergy analysis showed that wheat production was a superior system for achieving sustainability compared to garlic and onion production (Yasini et al., 2020). A comparison of traditional and mechanized production systems of rapeseed using emergy based production functions in Lorestan province showed that the sustainability of the mechanized production system is less than the traditional production system in this province (Amiri et al., 2020). However, very little research has been done on crop emergy assessment on a case-by-case basis in Iran and worldwide. The purpose of this study was to evaluate the emergy of the rapeseed ecosystem (*Brassica napus* L.) in order to determine its sustainability and to provide suggestions for optimal and sustainable management of the production system of this important crop in the study area, which is one of the rapeseed production hubs in Iran.

2. Materials and methods

2.1. Details of the study area and data collection

This research was conducted in the crop year of 2017-2018 in Gorgan county, in Golestan province. Data was collected through questionnaires and face-to-face interviews with rapeseed growers. Cochran's relation (Equation (1)) was used to determine the number of questionnaires (Cochran, 2003).

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

where n is the sample size, N is the statistical population size (106), z is the standard error of acceptable reliability coefficient (1.96), p is the proportion of the population with a specific attribute (0.5), q is the proportion of the population without a specific attribute (0.5), and d is the desired level of precision (0.07). The number of questionnaires for rapeseed farmers was 60. Farmers were selected by a random sampling method.

2.2. Emergy analysis

The first step in emergy analysis is to determine the spatial and temporal boundaries, the most important inputs into the system, and the material, energy, and economic flows (Figure 1) (Odum, 1996; Odum, 2000). This action divides system inputs into environmental or non-environmental, purchased or free, and renewable or non-renewable (Odum, 2000).

Emergy analysis is based on dividing all inputs into four groups: 1) renewable environmental inputs (R) such as sunlight, rain, and wind; 2) environmental inputs that are potentially renewable but are considered non-renewable environmental inputs due to their long recovery time (N0), such as soil organic matter erosion; 3) renewable purchased Inputs (FR); and 4) purchased non-renewable inputs (FN) (Campbell and Laherrere, 1998; Asgharipour et al., 2019). All selected farms, from land preparation to harvest, are monitored. Information including agricultural farm history, time and type of land preparation operations, planting method, fertilizer spraying, spraying and harvesting, type and amount of inputs such as chemical fertilizers and chemical pesticides, type of machinery and frequency of their use, type and fuel consumption in each field operation, type, number, and duration of labor, and grain yield were recorded. Data related to erosion, soil organic matter, and climatic data were collected from the General Department of Natural Resources and Watershed Management and the General

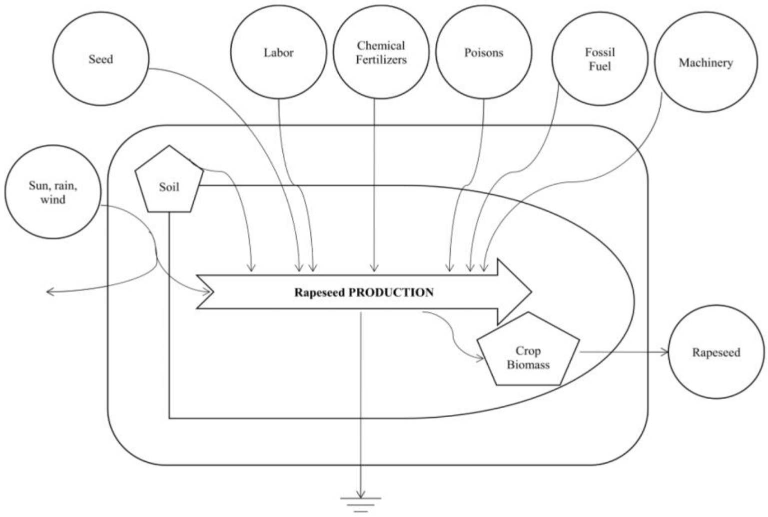

Figure 1. Emergy flow diagram of rapeseed farming ecosystem in Gorgan county

Table 1. Average climatic and edaphic variables in Gorgan county

Variable	Unit	Annual average
Solar radiation	j/m^2	1.74×10^7
Rainfall	mm	500
Wind speed	m/s	6.24
Soil erosion	kg/ha	16000
Soil organic matter	%	1.7

Meteorological Department of Golestan Province, respectively (Table 1).

The emergy flow of renewable resources was considered the same for all farms in this study. The effective composition of fertilizers and chemical toxins was determined (Jafari et al., 2018). To calculate the machine input, the total weight of the machines used was divided by their annual application area and then by their useful life. The annual application area and useful life of machines in Iran are 1000 hectares and 10 years, respectively (Houshyar et al., 2018). The coefficient of renewability was also determined for all inputs. The coefficients for labor and rapeseed are 0.10 (Ulgiati and Brown, 2002) and 0.43 (Amiri et al., 2019), respectively. All calculations related to emergy analysis were performed by EXCEL 2019 software. To calculate the solar emergy of inputs and outputs in the rapeseed ecosystem, most important inputs and outputs (grains) in each of the 60 farms were first determined in terms of mass (g), energy unit (joules), or currency (rials) per hectare per year. The conversion factor for calculating the amount of fossil fuel energy was 56.31 (Houshyar et al., 2018), the labor force was 1.96 (Rajabi Hamedani et al., 2011), and rapeseed was 28.3 (Kazemi et al., 2016). Equations 2-5 were used to calculate the environmental inputs of sunlight, wind, rain, and soil erosion in joules, respectively.

Solar energy= (10000 m^2/ha)×(radiation)×(1-albedo) (2)

In which the amount of albedo for rapeseed was 0.23 (Amiri et al., 2019).

Wind energy= (10000 m^2/ha)×(density of wind)×(drag coefficient)×(wind speed)^3×(time) (3)

In which wind density was 1.3 kg/m^3, drag constant was 0.001 and time was 2.33E+07 s (Ghaley et al., 2018).

Rain energy= (10000 m^2/ha)×(rainfall)×(density)×(gibbs free energy) (4)

Where rain density was 1000 kg/m^3 and Gibbs free energy was 4940 j/kg (Houshyar et al., 2018).

Energy of soil erosion= (soil loss)×(organic matter %)×(organic matter energy)×(conversion) (5)

Where the energy of organic matter was 5400 kcal/kg and the conversion factor was 4186 j/kcal (Houshyar et al., 2018).

After determining the most appropriate solar emergy conversion factor for each input, the solar emergy value was calculated by multiplying the numerical value of that input by its corresponding unit emergy value (UEV) (Odum, 2000). Emergy assessment in this study was based on the planet's coefficient of 12.00E+24 sej yr^{-1}, and UEVs were determined accordingly (Brown et al., 2016). Total emergy input to each farm was calculated by summing the emergy values of all inputs to that farm. Then, emergy input and emergy output for the rapeseed agroecosystem were calculated by averaging across all 60 farms studied. Finally, transformity (Tr), specific emergy (SpE), emergy yield ratio (EYR), standard emergy investment ratio (EIR), and modified emergy investment ratio (EIR*) were calculated to evaluate efficiency and standard environmental loading ratio (ELR), modified environmental loading ratio (ELR*), standard emergy sustainability index (ESI) and modified emergy sustainability index (ESI*) were calculated to assess the sustainability of the rapeseed agroecosystems (Table 2).

Table 2. Specifications and formula of emergy-based indices for evaluation of rapeseed agroecosystems

Index	Formula	Specifications	Reference
Renewable environmental inputs	R	Renewable flows from free local resources	Asgharipour et al., 2019
Non-renewable environmental inputs	N0	Local potentially renewable flows from free local resources that is being used in a non-renewable	Campbell and laherrere, 1998
Renewable purchased inputs	F_R	Renewable flows from purchased resources	Asgharipour et al., 2019
Non-renewable purchased inputs	F_N	Non-renewable flows from purchased resources	Asgharipour et al., 2019
Total emergy input	$U=R+N0+F_R+F_N$	Total emergy resources required to support the production system	Asgharipour et al., 2019
Total emergy output	$Y= R+N0+F_R+F_N$	Total emergy of system products	Asgharipour et al., 2019
Transformity	$Tr = \frac{U}{AE}$	Amount of emergy required to produce an output unit in joules. AE is the accessible energy of the product	Brown and Ulgiati, 2004
Specific emergy	$SpE = \frac{U}{W}$	Amount of emergy required to produce an output unit in grams. W is the mass of the product	Brown and Ulgiati, 2004
Emergy renewability	$R\% = \frac{R + FR}{U} \times 100$	Percentage of the renewable energy used by the system	Odum, 2000
Emergy yield ratio	$EYR = \frac{Y}{FR + FN}$	Ability of a process to use renewable and non-renewable environmental resources with economic resources as a capital	Odum, 2000
Standard emergy investment ratio	$EIR = \frac{FR + FN}{R + N0}$	Indicates the intensity of economic investment and its matching to the free renewable and non-renewable resources of the environment	Asgharipour et al., 2019
Modified emergy investment ratio	$EIR^* = \frac{FR + FN}{R}$	The ratio of purchased resources to renewable environmental resources	Amiri et al., 2021
Standard environmental loading ratio	$ELR = \frac{N0 + FR + FN}{R}$	Environmental pressure produced by a process	Lu et al., 2014
Modified environmental loading ratio	$ELR^* = \frac{N0 + FN}{R + FR}$	Environmental pressure produced by a process	Lu et al., 2014
Standard emergy sustainability index	$ESI = \frac{EYR}{ELR}$	Measure of the sustainability of the system	Lu et al., 2014
Modified emergy sustainability index	$ESI^* = \frac{EYR}{ELR^*}$	Measure of the sustainability of the system	Lu et al., 2014

3. Results and discussion

3.1. Input emergy structure

The emergy values of the most important environmental resource flows, inputs purchased, and the share of each of them in the total emergy input to the rapeseed farming ecosystem are shown in Table 3.

Solar emergy for each input in this table is obtained by multiplying the value of that input by its corresponding solar conversion factor. Total emergy input was calculated as total emergy supporting a rapeseed farming ecosystem equal to 6.39E+15 sej ha^{-1} yr^{-1} (Table 3). Previously, this amount for the subsistence and commercial production systems of rapeseed in Khorramabad county was 2.47E+16 and 4.13E+16 sej ha^{-1} yr^{-1}, respectively (Amiri et al., 2019).

3.2. Renewable environmental inputs (R)

These inputs include sunlight, rain, and wind. The share of these inputs from total emergy input in the rapeseed ecosystem was low (8.89%), which indicates the

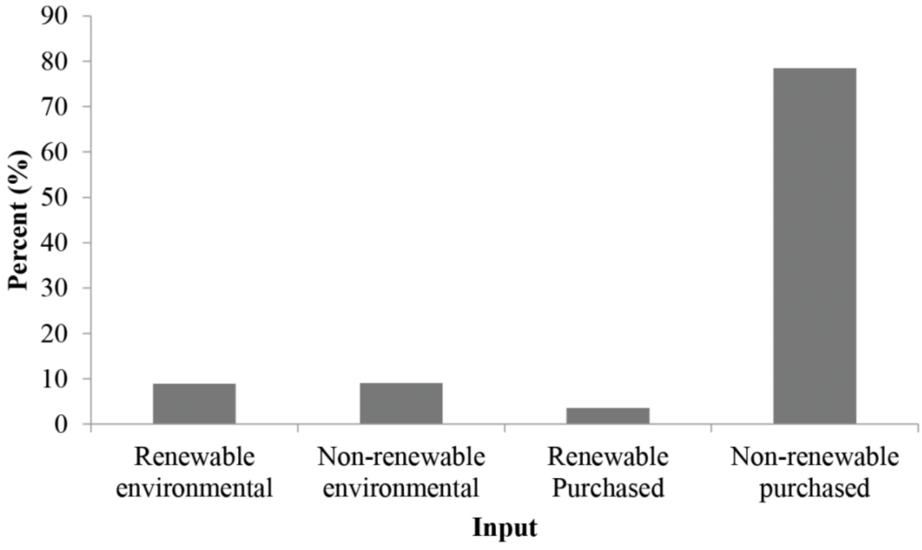

Figure 2. Share of environmental and purchased renewable and non-renewable inputs in rapeseed agroecosystems

low consumption of renewable environmental resources for rapeseed production in Gorgan (Figure 2).

Rain had the highest amount of emergy among the environmentally renewable resources in the rapeseed system (Table 3).

Renewable environmental inputs branch directly from sunlight. Therefore, in order to avoid double counting, the sum of renewable environmental inputs with the highest amount of emergy and emergy of sunlight input is considered as the total renewable environmental emergy (Amiri et al., 2021), which in this study was rain. More rain emergy than other renewable environmental inputs is due to favorable rainfall and high cloudy days as well as low wind speeds in this county. In the study of the evaluation of the sustainability of autumn and spring potato ecosystems in Gorgan county, it was found that the highest amount of emergy among renewable environmental inputs belonged to rain (Shahhoseini et al., 2020).

Table 3. Natural and economic flow, renewability, transformity, and solar emergy for rapeseed

Variable	Unit	Raw annual flow	Renewability factor	Solar transformity (sej unit^{-1})	Solar emergy (sej ha^{-1} yr^{-1})	Solar emergy (%)	References for transformity
Renewable environmental inputs							
Sunshine	J	1.34E+11	1	1	1.34E+11	0.00	Odum, 1996
Rainfall	J	2.47E+10	1	2.30E+04	5.68E+14	8.89	Odum, 1996
Wind	J	7.36E+10	1	1.86E+03	1.37E+14	2.14	Odum, 1996
Subtotal					5.68E+14	8.89	
Non-renewable environmental inputs							
Soil erosion	J	6.15E+09	0	9.42E+04	5.79E+14	9.06	Ghaley et al., 2018
Subtotal					5.79E+14	9.06	
Purchased inputs							
Nitrogen fertilizer	g	9.59E+04	0	4.84E+09	4.64E+14	7.26	Ghisellini et al., 2014
Phosphorus fertilizer	g	5.28E+04	0	4.97E+09	2.62E+14	4.10	Ghisellini et al., 2014
Potash fertilizer	g	2.04E+04	0	1.40E+09	2.86E+13	0.44	Ghisellini et al, 2014
Sulphur fertilizer	g	2.13E+04	0	6.94E+07	1.48E+12	0.02	Martin et al, 2006
Herbicide	g	1.35E+03	0	1.13E+10	1.53E+13	0.24	Bastianoni et al., 2001
Insecticide	g	1.25E+03	0	1.13E+10	1.41E+13	0.22	Bastianoni et al., 2001
Fungicide	g	1.30E+03	0	1.13E+10	1.47E+13	0.23	Bastianoni et al., 2001
Machinery	g	2.92E+03	0	1.01E+10	2.95E+13	0.46	Campbell et al., 2005
Seed	Rials	2.06E+06	0.43	2.50E+08	5.15E+14	8.06	Amiri et al., 2019
Fossil fuel and lubricant	J	4.52E+10	0	8.48E+04	3.83E+15	59.94	Brandt-Wiliams, 2002
Human labor	J	3.11E+07	0.10	2.22E+06	6.90E+13	1.08	Lu et al., 2009
Subtotal					5.24E+15	82.05	
Total					6.39E+15	100.00	
Grain yield	J	5.86E+10		1.09E+05	6.39E+15		Calculated

3.3. Non-renewable environmental inputs (N0)

Non-renewable environmental inputs for this study included soil erosion, and its share of total emergy input was significant (9.06%) (Table 3). The main reasons for this are the relatively high annual rainfall in this county (500 mm), improper tillage operations, and heavy use of machinery in rapeseed fields in Gorgan county. It seems that the implementation of conservation tillage methods and the use of multi-purpose machinery, with the aim of reducing the number of times they enter the field, is effective in preventing increased soil erosion and thus reducing the entry of emergy into the fields. The share of soil erosion from total emergy input in a study with similar conditions to this one study for common forage maize cultivation in Denmark was 3.3% (Ghaley et al., 2018).

3.4. Renewable and non-renewable purchased inputs (FR & FN)

Renewable market inputs had the lowest share among environmental and purchased renewable and non-renewable inputs (3.57%). While the share of non-renewable market inputs was much higher (78.48%) (Figure 2), which shows the high dependence of purchased inputs on non-renewable sources and consequently high pressure on the environment for rapeseed production in Gorgan county. Also, the large share of purchased inputs, which are often foreign, in the rapeseed production system indicates that this cropping system is an open system and is strongly influenced by the inputs purchased from the market. Therefore, optimal management and consumption of market practices, especially non-renewable inputs, is necessary to control and reduce the share of non-renewable resources in product production. In a study, the amount of emergy input purchased for the potato ecosystem in Florida was calculated to be 1.03E+16 sej ha^{-1} (Brandt-Wiliams, 2002).

In this study, fossil fuels had the largest share among all inputs to the rapeseed ecosystem (59.94%) (Table 3). According to the field study, irrigation pumps in most fields were diesel and worn out. Also, frequent tillage operations and the use of worn-out machinery, especially tractors, on most farms increased fuel consumption and as a result, the large share of this input in rapeseed production in the county. Also, the emergy rate of labor input was 6.90E+13 sej ha^{-1} yr^{-1}. The very small share of this input in crop production (1.08%) shows that the rapeseed production system in Gorgan is, to a large extent, commercial. Labor emergy for wheat, onion, and garlic production systems in the Sistan region was calculated to be 5.22E+14, 2.82E+15, and 5.04E+15 sej ha^{-1}, respectively (Yasini et al., 2020).

In this study, the emergy rate for seed input was 5.15E+14 sej ha^{-1} yr^{-1} (Table 3), which is higher than the reported amounts for subsistence production (4.40E+14 sej ha^{-1} yr^{-1}) and commercial production (3.30E+14 sej ha^{-1} yr^{-1}) of rapeseed in Khorramabad (Amiri et al., 2019). According to the information from the questionnaires, the consumption of seeds for sowing in Gorgan county, in both hand-spraying and machine conditions, was more than the recommended amount. Therefore, educating farmers on how to cultivate properly and set up planting machines can be effective in reducing the consumption of this input, which would thus reduce emergy input and increase efficiency in the rapeseed production system. The share of pesticide input in the rapeseed system in Gorgan county was low (0.69%), which indicates the relative health of this product in terms of the use of chemical pesticides on the farms in this county. Manual weed control and the absence of pests and diseases in most fields were effective in significantly reducing the share of this input in rapeseed production. Nitrogen fertilizer also had the largest share of total emergy input among chemical fertilizers (7.26%) (Table 3). Consumption of organic fertilizers can be as effective as possible in reducing the share of this chemical input and thus increasing crop health.

3.5. Evaluation of emergy indices

Emergy indices are used to determine the efficiency, renewability, environmental pressure, and sustainability of production systems (Odum, 2000; Brown and Ulgiati, 2004). Assessing these indices in ecosystems helps to identify and quantify their environmental, economic, and sustainability effects, and their results are effective at the local level for farmers and policymakers to make the best decisions to achieve sustainable agriculture (Jafari et al., 2018).

3.5.1. Transformity (Tr) and specific emergy (SpE)

The average grain yield in the studied farming ecosystem was 2070.6 kg ha^{-1}, which shows the efficiency of the system in converting inputs to economic output. Also, emergy dedicated to grain yield in the rapeseed production system in Gorgan county was estimated at 6.39E+15 sej ha^{-1} yr^{-1}. Transformity and specific emergy, as unit emergy values, indicate the efficiency of a production system. Lower values of these indices indicate greater performance and efficiency of the production process in environmental and economic competition. This means that less emergy input is allocated per unit of output (Odum, 2000). The transformity and specific emergy of the rapeseed cultivation system were 1.09E+05 sej J^{-1} and 3.09E+09 sej gr^{-1}, respectively (Table 4), which shows the rapeseed ecosystem in Gorgan county with high production efficiency. Transformity in this study was less than 8.02E+05 and 2.06E+05 sej J^{-1} for subsistence and commercial systems of rapeseed production in Khorramabad, respectively. Also, the specific emergy in this study was less than 2.25E+10 and more than 7.24E+09 sej gr^{-1} for subsistence and commercial production of rapeseed in Khorramabad, respectively (Amiri et al., 2019).

Table 4. The values of emergy indices in the rapeseed production system

Index	Unit	Rapeseed ecosystem
Transformity	sej j^{-1}	1.09E+05
Specific emergy	sej g^{-1}	3.09E+09
Renewability	%	12.46
Emergy yield ratio	-	1.22
Standard emergy investment ratio	-	4.56
Modified emergy investment ratio	-	9.23
Standard environmental loading ratio	-	10.25
Modified environmental loading ratio	-	7.02
Standard emergy sustainability index	-	0.12
Modified emergy sustainability index	-	0.17

3.5.2. Emergy renewability (%R)

This index indicates the share of renewable resources in supporting a production system (Odum, 2000). The emergy renewability ratio in this study for rapeseed systems was 12.46% (Table 4). In other words, 87.54% of the total input of emery in this production system is dependent on non-renewable resources, the major part of which is related to fossil fuels and soil erosion. By reducing the share of these resources in the rapeseed system as much as possible, it is possible to increase the renewability and, consequently, the sustainability of the farming ecosystem. Increasing the share of renewable resources and reducing the consumption of non-renewable resources in a production system lead to the success of that system in economic competition and thus increase sustainability (Asgharipour et al., 2019) because non-renewable resources become scarcer over time (Brown and Ulgiati, 2004). The amount of renewability in this study was more than 5.30 for the commercial system and less than 19.90% for the subsistence of rapeseed production in Khorramabad (Amiri et al., 2019). This index for the ecosystem of conventional forage maize production in Denmark is reported to be 16% (Ghaley et al., 2018).

3.5.3. Emergy Yield Ratio (EYR)

This index indicates the efficiency of resource consumption and the ability of a system to consume environmental resources by investing in purchased resources, and higher values indicate more absorption of environmental emergy in the system (Brown and Ulgiati, 2004). The EYR value in this study was 1.22 (Table 4), which shows that the rapeseed farming ecosystem in Gorgan county has an acceptable resource consumption efficiency. The minimum value for EYR is 1, in which the share of environmental resources in a production system is the lowest and the dependence on economic resources is at the highest level. Therefore, higher values of this index are more desirable (Asgharipour et al., 2019). Implement strategies to reduce the consumption of economic resources. For example, modernization of irrigation machinery and pumps to increase efficiency and thus reduce fuel consumption, as well as the use of seeds with higher germination percentage to reduce seed consumption (as an economic input) will increase this index and, as a result, will increase consumption efficiency. This index is the result of dividing the total emergy output (environmental and purchased) by the purchased emergy input. Therefore, reducing the consumption of economic resources and increasing the consumption of environmental inputs is effective in increasing this index and improving efficiency (Odum, 2000). EYR values in this study are less than 1.53 and 2.31 values for subsistence and commercial rapeseed production systems in Khorramabad (Amiri et al., 2019) and more than 1.20, 1.15, 1.05, and 1.07, respectively, for corn production systems (Zhang et al., 2012), and rice, vegetables, and rice and vegetable rotation in China (Lu et al., 2010.

3.5.4. Standard emergy investment ratio (EIR) and modified emergy investment ratio (EIR*)

The EIR shows the amount of investment a production system makes in economic resources and the degree of its dependence on the environment (Odum, 2000). The EIR value in this study was 4.56 (Table 4), which indicates the low economic efficiency of the rapeseed system. Lower values for this index in a system indicate lower economic costs and greater dependence on the environment and are therefore more desirable (Odum, 2000). Therefore, some effective factors in reducing this index and increasing economic efficiency and sustainability are increasing the share of environmental resources in the production system, reducing the consumption of economic inputs, and replacing these inputs with environmental resources, such as using environmental energy sources in the fuel supply or biological pest control. The EIR values in this study are higher than the values of 0.76 and 1.86 for the commercial and subsistence systems of rapeseed production in Khorramabad (Amiri et al., 2019), 2.74 and 2.29 for wheat and corn production in Jahrom, respectively (Houshyar et al., 2018), and 2.94 and 1.30 for wheat and oat production in China, respectively (Zhai et al., 2017).

EIR* is introduced as a more direct measure of the compliance of market inputs with renewable environmental resources (Amiri et al., 2019). Therefore, this index was used to test the better adaptation of foreign investment in the rapeseed crop system to free renewable environmental resources, and its value in this cropping system in Gorgan was 9.23. The amount of EIR* obtained for the rapeseed production in this study is higher than the calculated values of 9.00 for commercial production and 8.94 for subsistence production of rapeseed in Khorramabad (Amiri et al., 2019), which indicates more emergy investment in rapeseed production in Gorgan compared to Khorramabad.

3.5.5. Standard environmental loading ratio (ELR) and modified environmental loading ratio (ELR*)

ELR indicates the pressure of a production system on the environment (Asgharipour et al., 2019). This index was 10.25 for rapeseed agroecosystems (Table 4), which indicates the high pressure of this production system on the environment and low environmental sustainability. The main reasons for this are the large amount of soil erosion (as a non-renewable environmental input) in the rapeseed farming ecosystem and the unreasonable use of some economic inputs, especially fossil fuels, in this system, which concentrates a large flow of non-renewable resources into a small environment. This index indicates the pressure caused by the consumption of non-renewable environmental and economic inputs, and its lower values are more desirable (Lu et al., 2014).

ELR is calculated by dividing the non-renewable and market emergy input by the renewable emergy input from the environment (Asgharipour et al., 2019). Therefore, some effective factors in reducing environmental pressure are changing the quantity and quality of consumption of these inputs in order to reduce their share of total emergy input. Increasing the cultivation area with the aim of reducing the concentration intensity of non-renewable inflows and implementing conservation tillage methods to reduce soil erosion (as a non-renewable environmental input) along with the use of renewable resources to provide economic inputs, such as the use of organic fertilizers instead of chemical fertilizers, is effective in reducing environmental pressure and thus increasing the sustainability of the rapeseed production system. Evaluation of the sustainability of bean production systems in Khorramdasht showed that the application of conservation tillage methods and the replacement of chemical fertilizers with organic fertilizers is effective in increasing the environmental sustainability of the production system (Asgharipour et al., 2019). Justifying farmers about the importance of reducing environmental pressure in achieving long-term sustainability and financially supporting them to modernize equipment to consume fewer non-renewable resources is effective in achieving this goal. The ELR value in this study for the rapeseed cultivation system is less than 31 values for potato production in China (Zhai et al., 2017) and 12.68 and 19.75 for subsistence and commercial production of rapeseed in Khorramabad (Amiri et al. al., 2019) and more than 0.47 for corn production in China (Wang et al., 2014), respectively.

ELR* represents the relationship between the total renewable emergy and the total non-renewable emergy and is the inverse scale of sustainability. Therefore, lower values of this index are more desirable (Asgharipour et al., 2019). The ELR* value for the rapeseed ecosystem was 7.02 (Table 4), which indicates the average environmental pressure in this production system. In both the ELR and ELR* indices, values of < 2, 2-10, and >10 indicate low, medium, and high environmental pressure, respectively (Brown and Ulgiati, 2004). The difference between ELR and ELR* is the displacement of the purchased renewable input from the fraction in the ELR to the denominator of the fraction in the ELR*.

Due to the very small share of renewable economic resources from total emergy input in the rapeseed production system, the values of the two indices, ELR and

ELR* in this production system were slightly different. Therefore, the recommended solutions to reduce the amount of ELR, especially reducing the consumption of non-renewable economic inputs, are also effective in reducing the amount of ELR*. This index emphasizes the inconsistency between renewable and non-renewable sources and is a complement to the transformity (Martin et al., 2006). Increasing the share of renewable resources in both environmental and purchased inputs will reduce environmental pressure and increase environmental sustainability in the system. Expanding the facilities and equipment needed to supply renewable environmental energy such as sunlight and wind in supplying electricity required by irrigation pumps reduces the share of non-renewable inputs and thus increases the environmental sustainability of the rapeseed farming ecosystem. Because ELR* is the ratio of non-renewable inputs to renewable inputs, reducing the share of non-renewable resources reduces this index and makes the ecosystem more sustainable in the long run as non-renewable resources become rarer over time. ELR* value in this study is less than 17.85 for the commercial rapeseed production system in Khorramabad (Amiri et al., 2019), and more than 4.00, 4.18, 4.35, 4.46, and 4.62 for the subsistence rapeseed production in Khorramabad (Amiri et al., 2019) and greenhouse production of cucumber, tomato, bell pepper, and eggplant in Jiroft (Asgharipour et al., 2020), respectively.

3.5.6. Standard Emergy Sustainability Index (ESI) and Modified Emergy Sustainability Index (ESI*)

ESI is a composite index that determines the amount of profit earned per unit area relative to its costs in a system. Therefore, it focuses more on the economic aspect of sustainability (Asgharipour et al., 2019). The value of this index for the rapeseed production system was 0.12 (Table 4), which shows the low economic sustainability of this farming ecosystem in Gorgan. The lowest and highest values for this index are zero and infinite, respectively. Systems in which the value of this index is less than one have very high energy consumption, intensify environmental effects, and require a lot of energy to survive (Ulgiati and Brown, 1998).

Despite the importance of efficient energy consumption in sustainable agriculture, according to the questionnaire, the most important reasons for the low ESI in the rapeseed system are the high share of market inputs, especially fossil fuels, seeds, and nitrogen fertilizers, and high soil erosion in this system of production (as a non-renewable environmental input), which reduced sustainability. Therefore, some effective factors in reducing the consumption of non-renewable environmental and economic inputs are Informing, encouraging, and educating farmers about the benefits of implementing conservation tillage methods, modernizing machinery, using quality seeds, using livestock fertilizers instead of chemical ones (as much as possible), and using renewable environmental energy. As a result, these items reduce the pressure on the environment and increase the economic sustainability of the rapeseed production system. In production systems, increasing performance and decreasing environmental pressure increase ESI and thus economic sustainability (Jafari et al., 2018). The ESI value in this study is higher than 0.03 for the potato growing system in China (Zhai et al., 2017), 0.117 for the commercial rapeseed production system in Khorramabad (Amiri et al., 2019), and 0.08, 0.09, and 0.05 for wheat, onion, and garlic production systems in the Sistan region (Yasini et al., 2020), respectively.

ESI*, the inverse measure of stability, is related to the performance ratio of a system and expresses the benefits of the system in relation to its relative sustainability. The minimum and maximum values for this index are zero and infinity, respectively (Lu et al., 2014). The value of this index for the rapeseed production system was 0.17 (Table 4), which shows the high environmental pressure during crop production and the low environmental sustainability of this system in Gorgan. Both the ESI and ESI* indices examine the ecology of a production system from different perspectives, and the higher values of both indices indicate the greater ecological sustainability of the system. In both the ESI and ESI* indices, values of >10, 1--10, and <1 indicate a sustainable system with very low pressure, living and good systems, and resource depleting systems (Asgharipour et al., 2019). Considering the importance of environmental sustainability to maintain the economic advantage of a production system, the most desirable policy for rapeseed production in Gorgan is to maintain a balance between economic advantage and environmental sustainability.

ESI* indicates the environmental sustainability of the system, and its higher values are more desirable (Amiri et al., 2019). The effective factor in reducing pressure and increasing environmental sustainability and thus increasing ESI* in the rapeseed crop system is increasing the share of renewable resources, including the use of renewable resources instead of non-renewable resources in the supply of economic inputs. The value of ESI* in this study is greater than 0.13 for the commercial rapeseed production system in Khorramabad (Amiri et al., 2019), and the values of 0.04, 0.06, and 0.11 for the system with high, medium, and low input for bean production in Khorramdasht (Asgharipour et al., 2019), respectively, and less than 0.38 for subsistence rapeseed production in Khorramabad (Amiri et al., 2019), 0.45 for corn production in China (Zhang et al., 2012), and 1.48 for the ecological system of bean production in Khorramdasht (Asgharipour et al., 2019).

4. Conclusion

The highest share of total emergy inputs in the rapeseed ecosystem was related to non-renewable purchased inputs, and the lowest share was related to renewable purchased inputs. Fossil fuels accounted for the largest share of total emergy inputs of all inputs. Evaluation of transformity and specific emergy indices showed that the rapeseed ecosystem has high production efficiency in Gorgan. Indeed, the evaluation of the emergy renewability index showed that renewability in this production system was low due to its high dependence on non-renewable resources.

Based on the emergy yield ratio, resource efficiency was also acceptable in this cropping system. The analysis of emergy investment ratios showed that the economic costs in this system are high and the economic efficiency is low. Based on the analysis of environmental loading ratios, this system puts a lot of pressure on the environment, and its environmental sustainability is low. This was due to the unreasonable use of some purchased non-renewable inputs such as fossil fuel and nitrogen fertilizers, and high soil erosion as a non-renewable environmental input. Implementation of conservation tillage methods and use of renewable environmental energies, such as solar energy, in supplying electricity required for irrigation pumps, reduces the consumption of non-renewable resources, thus reducing environmental pressure and increasing environmental sustainability in this system.

Evaluation of emergy sustainability indices showed that economic sustainability in this farming ecosystem was low due to high dependence on some economic inputs and high environmental pressure in this system. Reducing the consumption of purchased non-renewable resources along with maintaining or improving performance in this farming ecosystem will improve this index and increase economic sustainability. Reducing the consumption of fossil fuels by modernizing irrigation machinery and pumps and using organic fertilizers instead of chemical ones is as effective as possible. As a final result, production efficiency, resource consumption efficiency, and economic efficiency in the rapeseed farming ecosystem were acceptable. Despite the low dependence on environmental inputs in this system, the high share of soil erosion as a non-renewable environmental input resulted in low renewability, high environmental pressure, and low environmental and economic sustainability in this system. Implementation of recommended strategies to reduce the consumption of non-renewable resources and increase the use of renewable resources in the supply of purchased inputs, along with awareness, education, and encouragement of farmers in this field, is effective in increasing the environmental and economic sustainability of rapeseed agroecosystems.

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