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Research article

A thermodynamic approach to evaluating the ecological health and sustainability of integrated production systems in Goharkuh Taftan agro-industrial complex and sensitivity analysis of the results

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ABSTRACT

In recent times, the increasing influx of energy inputs into farming systems has led to a significant enhancement in their overall efficiency. However, this has happened at the expense of endangering the sustainability of these systems and degrading the environment. Therefore, it is crucial to develop a methodology to evaluate the resilience of agricultural systems. This study utilised the Steinborn and Svirezhev methodology to assess five different production systems (wheat, barley, alfalfa, cotton, and Pistachio) within the Goharkuh Taftan agro-industrial complex. The approach measures the excessive production of entropy, which acts as an indicator of the system's departure from sustainability. The study focuses on four components: overproduction of entropy, limit energy load, maximum crop yield for sustainable agriculture, and deviation from sustainable agriculture. The results indicated that the production systems analysed in this study produce surplus entropy, thus rendering them in an unstable condition. Among all the products, alfalfa had the lowest entropy overproduction, while pistachio had the highest. The three agricultural commodities, namely wheat, barley, and cotton, are situated at a point equidistant from the two opposite ends. Alfalfa has shown greater energy use efficiency compared to pistachios. It surpasses the maximum crop yield for sustainable agriculture and has less deviation from sustainable agriculture than other integrated production systems. The differences in the intensity of energy flow and the structural characteristics of the integrated production systems were responsible for the variations in the values of the examined components. Nevertheless, none of these solutions are sustainable in the long term. An analysis of the energy inputs and components of the harvest index revealed the importance of implementing management techniques that decrease the intensity of energy flows into these systems and enhance the harvest index to attain a sustainable state. Integrating supplementary renewable energy sources will bolster the long-term sustainability of production systems.

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1. Introduction

Intensive agriculture emerged in the early 20th century as a shift from traditional farming practices that relied on natural resources and ecosystem services to modern production methods. The production methods have relied heavily on mechanisation, fertilisers, chemical insecticides, genetically modified seeds, and chemical pest control. These methods have primarily been driven by the need to meet the demands of a growing population [1]. The consequences of intensive agriculture are intricately linked to both human survival and the natural environment. The consequences of heightened production are manifested in various forms of environmental damage, such as land degradation, salinization, water pollution, biodiversity loss, greenhouse gas emissions, and global climate change [2].

Although there are challenges, the concept of sustainability has gained increased attention since the publication of the Brundtland Commission's book "Our Common Future". Aligned with the overarching concept of sustainable development, the phrase "From one Earth to one World" was coined by the Brundtland Commission in 1987 [3]. However, the concept of sustainable agriculture, similar to sustainable development, still lacks a precise definition [4–6]. Various endeavours have been undertaken to elucidate sustainable agriculture, yet it can be asserted that all these explications are founded upon identical principles. Essentially, these principles advocate for the utilisation of renewable resources within a system while preventing the depletion of non-renewable resources. These sustainable systems ensure the preservation of the integrity of natural ecosystems, thereby ensuring the continuous replenishment of natural resources. In addition, sustainable agriculture considers the long-term benefits for all members of society, guarantees economic sustainability, and enhances the welfare of individuals and communities [7,8].

Thermodynamics investigates the correlation between heat, energy, and work in the field of natural sciences. Thermodynamics primarily concerns itself with the movement of energy between different locations and its transformation between different forms. The development of thermodynamics was initiated by Count Rumford, Benjamin Thompson, and Carnot's investigations, and further advanced by Rudolf Clausius who delineated the fundamental and secondary principles of thermodynamics [9]. The fundamental principle of thermodynamics, often regarded as a derivative of the principle of conservation of energy, revolves around the concept of efficiently transforming energy from one form to another. The second principle of thermodynamics states that whenever energy undergoes a transformation, a fraction of its capacity to do work is inevitably lost as heat, which is essentially a measure of disorder or randomness known as entropy. Entropy, a concept in thermodynamics, is a measurable attribute that is commonly linked to a condition of disorder, unpredictability, or uncertainty. In physics, the concept of degradation and the idea of entropy are closely related. entropy is often used as a measure of degradation. On the other hand, the concept of stability is in direct opposition to entropy [10].

Many studies have attempted to utilise thermodynamic principles and techniques (either directly or indirectly) in theoretical and mathematical ecology to explain the overall behaviour of biological communities and ecosystems [11–13]. Nevertheless, a significant obstacle arises from the lack of homeomorphism, or topological equivalence, between models in thermodynamics and those in ecology [14]. Nevertheless, Svirezhev became a trailblazer in acknowledging the difficulties of applying thermodynamic concepts to the field of ecology. He adeptly developed a thermodynamic-ecological model and convincingly showcased its practicality in ecosystems. Utilising these formulas would be extremely advantageous in evaluating the sustainability of ecosystems.

Sensitivity analysis is a technique used to evaluate the effect of changing one input variable on an output variable, given a specific set of assumptions. This technique employs modelling to calculate the percentage change in both the output and input variables. It defines sensitivity as the ratio of the output's percentage change to the input's percentage change [15]. This approach is especially advantageous for making decisions, evaluating risks, and optimising agricultural management practices. Multiple techniques are used to perform sensitivity analysis, as documented by Homma and Saltelli [16], Christopher Frey et al. [17], Saltelli et al. [18], Campolongo et al. [19], and Pianosi et al. [20].

Sistan and Baluchestan, situated in the southeastern part of Iran, covers a vast expanse of 18 million hectares. This province showcases a varied climate, encompassing arid and exceedingly hot desert conditions as well as semi-arid and moderately warm temperate climates. According to Saligeh et al. [21] documentation, this area is officially classified as a region with desert and dry climatic conditions. The arable lands within the province cover an area of 400 thousand hectares. Agricultural water supply is obtained from a variety of sources, such as wells, qanats, springs, and rivers like Hirmand.

The Goharkuh Taftan agro-industry complex is a significant hub for agricultural production in Taftan city and its neighbouring province. This facility is responsible for cultivating a wide array of pistachio varieties, as well as growing different crops and raising livestock. Pistachio cultivation, as a type of orchard plant, has been given a substantial amount of land compared to other agricultural products. This facility plays a crucial role in the production of pistachios in the province, cultivating a wide array of Kalleh Ghouchi, Ohadi, Nokhodi, and Ahmad Aghaei varieties. The wheat crop, covering 130 ha, ranks second in terms of cultivation area within the complex. The mentioned product holds strategic importance as it is one of the main production facilities in the country. Increasing the cultivation capacity within the complex will result in a greater proportion of this product being produced within the province. The Ministry of Agriculture Jihad [22] reported that in the agricultural year 2020–2021, the province had a cultivation area of 76,424 ha for wheat, 14,573 ha for barley, 53 ha for cotton, and 15,695 ha for alfalfa. In the same period, the Ministry of Agriculture Jihad [23] reported that the cultivation area for pistachio was 9929 ha.

This study employs the Steinborn and Svirezhev [24] methodology to assess five production systems in the GoharKuh Taftan agro-industrial complex. The method measures the entropy overproduction, which acts as a measure of how far the system deviates from sustainability. By implementing this approach, we can effectively tackle the following inquiries: Firstly, are the Goharkuh Taftan agro-industrial complex systems environmentally sound? Furthermore, which production system is the most thermodynamically efficient? Furthermore, considering the sensitivity analysis, what managerial strategies can be adopted to improve the sustainability of the production systems? To address these questions, the present study was conducted within the production systems of the Goharkuh Taftan agro-industrial complex.

2. Materials and methods

2.1. Introduction to the study area

This study specifically investigates the geographic area of Taftan county, which is located in the Sistan and Baluchestan province. In 2019, the county mentioned had a population of 44,176 people. The main occupation of the residents in this area is agricultural cultivation and livestock farming. Fig. 1 illustrates the precise geographical location of Taftan county.

Taftan county is renowned as a prominent agricultural hub. The orchard crops in this region consist of pistachio, apricot, grape, pomegranate, peach, and olive. Additionally, the agricultural crops grown here include wheat, barley, maize, alfalfa, cotton, vegetables, and oilseeds. Furthermore, sheep farming is also widespread in the area. The wheat varieties include Sivand (3200 kg ha^{-1}), barley Kavir (4000 kg ha^{-1}), alfalfa Bami (7000 kg ha^{-1}), cotton Varamin (2700 kg ha^{-1}), and pistachios Ouhadi, Kalleh ghouchi, and Ahmad aghayi (1200 kg ha^{-1}). The growth periods are approximately 208 days for wheat, 197 days for barley, 247 days for alfalfa, 190 days for cotton, and 225 days for pistachios, depending on regional climatic conditions. Seedbed preparation involves a moldboard plow, disc plow, and leveler for wheat, barley, alfalfa, and cotton, and a moldboard plow, disc plow, and furrower for pistachios. Pistachio trees are propagated from Badami variety seeds in a nursery and transplanted to the main field in the second year. Topping and grafting are conducted by specialized personnel in the second and third years, respectively. Mechanised harvesting is employed for wheat, barley, and alfalfa, while cotton and pistachio harvesting is manual. Alfalfa is harvested in seven cuts and cotton in three cuts. Chemical pesticides are utilised for pest management through direct application or systemic application via irrigation systems.

The dominant soil texture in the area is categorised as sandy loam. The crops in the region are watered using a centre pivot system, while the pistachio crops are cultivated using a drip irrigation method with a pressurised water supply. The quantities of fertilisers, seeds, and chemicals applied in the integrated systems were precisely quantified using a precision scale. Furthermore, the electricity usage was monitored with a meter, the fuel consumption of the machinery in each system was recorded, and the labour hours for each system were accurately determined. The complex mentioned above consists of a total of 39 wells. Due to the recent droughts and depletion of water resources, only 27 out of the total number of wells are currently functioning, while the rest are not operational (see Table 1). The region has an average annual precipitation of 120 mm and an average temperature of 30 °C.

2.2. Data collection and processing

The data used in this study is obtained from the statistical records provided by the managers of the agricultural and industrial complex from 2020 to 2021. Initially, this study gathered data on the cultivated area, production in diverse terrains, and crop yields.

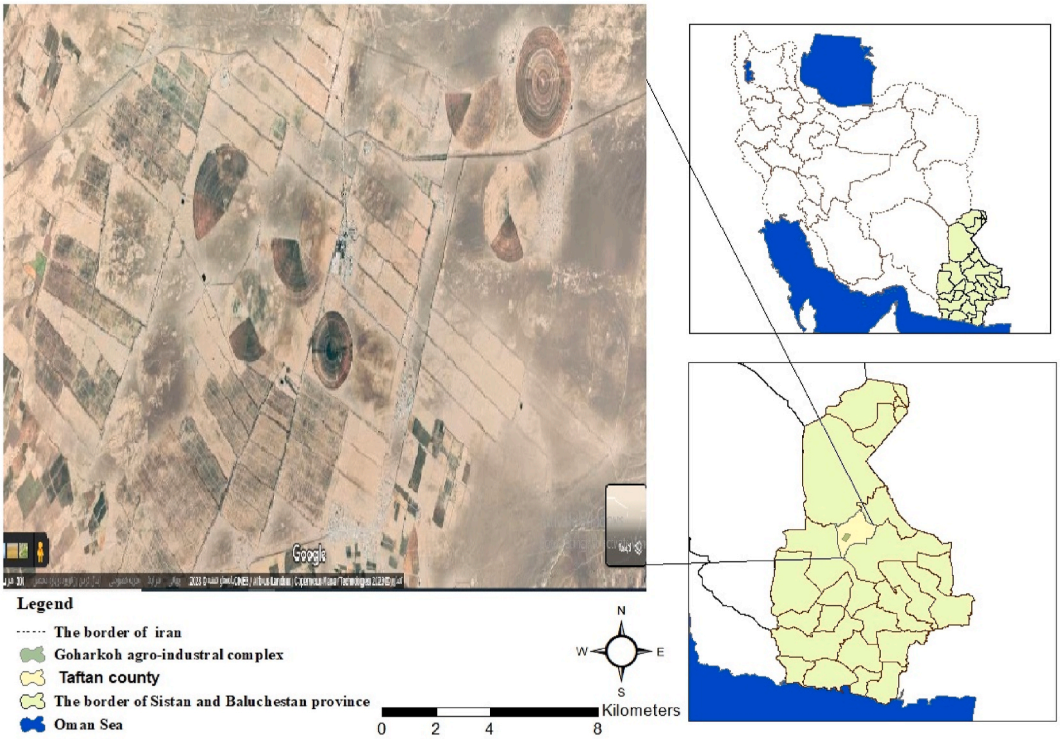


Fig. 1. Study location within Iran and Sistan and Baluchestan Province.

Table 1

Description of the different production systems of Goharkuh Agro-industrial complex in Taftan county, Iran.

	Wheat	Barley	Alfalfa	Cotton	Pistachio
Growth period (days)	208	197	247	190	225
Planting area (ha)	130	10	40	50	800
Common cultivar(s)	Sivand	Kavir	Bami	Varamin	Seedling base: Badami sapling of grafting: Ouhadi- Ahmad aghayi
Seed rate (kg ha^{-1})	230–260	160–190	55–75	25–40	250–280
Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Fertilizer					
Nitrogen (kg ha^{-1})	N as urea (300)	N as urea (250)	N as urea (50, Starter)	N as urea (350)	N as urea (100) Ammonium sulfate (250)
Phosphorous (kg ha^{-1})	P as Triple superphosphate (150)	P as Triple superphosphate (150)	P as Triple superphosphate (150)	P as Triple superphosphate (150)	P as Diammonium phosphate (100)
Potassium (kg ha^{-1})	K as Potassium sulfate (100)	K as Potassium sulfate (100)	K as Potassium sulfate (100)	K as Potassium sulfate (100)	K as Potassium sulfate (50)
Herbicide, Insecticide, Fungicide,	Tebuconazole fungicide, Granstar herbicide	Tebuconazole fungicide, Granstar herbicide, Pirimor insecticide	Diazinon insecticide	Confidor insecticide, Avaunt insecticide	Pirimor insecticide
Seedbed preparation operations	Moldboard plow, Disc plow, Leveler	Moldboard plow, Disc plow, Leveler	Moldboard plow, Disc plow, Leveler	Moldboard plow, Disc plow, Leveler	Moldboard plow, Disc plow, Furrower
Harvesting equipment	Combine harvester- John Deere 1055i	Combine harvester- John Deere 1055i	Mower-Conditioner	Manual harvesting	Manual harvesting
Irrigation water source	Ground water	Ground water	Ground water	Ground water	Ground water
Ecological yield (kg ha^{-1})	3200	4000	7000	2700	1200

Following that, a thorough evaluation was carried out to precisely determine different agricultural activities, such as land preparation, seed consumption, irrigation water usage, electricity consumption, fuel consumption, fertiliser application, chemical pesticide usage, and human labour requirements, for various crop types. The meteorological stations in Khash and Zahedan were used as sources of data for natural factors such as temperature, solar radiation, and wind. In addition, the Goharkuh rainfall station supplied data

Table 2

Energy equivalents for input and output flows used for the different production systems of Goharkuh Agro-industrial complex in Taftan county, Iran.

Input	Unit	Energy equivalent (MJ U^{-1})				
		Wheat	Barley	Alfalfa	Cotton	Pistachio
Human labour	(h)	1.95	1.95	1.95	1.95	1.95
Machinery	(h)	62.7	62.7	62.7	62.7	62.7
Fossil fuel and lubricant	(l)	47.8	47.8	47.8	47.8	47.8
Electricity	(kwh)	11.93	11.93	11.93	11.93	11.93
Nitrogen fertiliser	(kg)	66.14	66.14	66.14	66.14	66.14
Phosphorus fertiliser	(kg)	12.44	12.44	12.44	12.44	12.44
Potash fertiliser	(kg)	11.15	11.15	11.15	11.15	11.15
Herbicide	(kg) or (l)	238	120	120	–	238
Fungicide	(kg)	181.9	216	–	–	216
Insecticide	(kg)	–	101.2	–	–	101.2
Aphicide	(l)	–	–	–	101.2	–
Pesticide	(l)	–	–	–	101.2	–
Micro fertiliser	(kg)	–	–	–	–	120
Manure	(ton)	–	–	–	–	303.1
Water for irrigation	(m^3)	1.02	1.02	1.02	1.02	1.02
Seed	(Kg)	14.7	14.7	17.77	11.8	24.88
Output (s)						
Yield	(kg)	14.7	14.7	17.77	11.8	24.88
Straw	(kg)	12.5	12.5	–	–	–

For the information on production systems, we refer to the following sources.
Wheat [35].
Barley [36].
Alfalfa [37].
Cotton [38].
Pistachio [39].
Fossil fuel and electricity [40].

regarding the quantity of precipitation. In order to ascertain the energy flow values for each input component, the total energy content of different inputs from various sources was extracted. After classifying and processing, the data was transformed into energy equivalents. All input and output elements were transformed into units of energy. The amount of entropy overproduction in the system and the deviation from sustainable agriculture were calculated based on the relevant relationships. Table 2 provides the energy equivalents of different inputs to accurately assess the amount of energy used and produced in fields. Table 3 shows amounts of inputs, output and energy inputs and output for the different production systems of Goharkuh Agro-industrial complex in Taftan county. The supplementary calculations are provided in Appendix A.

2.3. *Framework for entropy assessment*

This study utilises the Steinborn and Svirezhev [24] thermodynamic approach to assess the sustainability of the integrated production systems within the Goharkuh Taftan agro-industrial complex. This methodology evaluates "unsustainability" through the lens of "excessive entropy production". Entropy is a thermodynamic quantity representing disorder within a system. Higher entropy production indicates a system is further from equilibrium and thus less sustainable in the long term [25].

The fundamental components in the study of thermodynamics are the system and its surroundings. The boundary of a system defines its structure in relation to the surrounding environment. The system interacts with its environment by exchanging matter and energy across this boundary. Systems can be classified based on these criteria. an isolated system is defined by the lack of any exchange of energy or matter with its surroundings. Closed systems have the ability to exchange energy with their surroundings, but they are unable to exchange material. open systems are characterised by their ability to transfer both energy and matter across their boundaries [10]. Agricultural ecosystems are categorised as open systems because they engage in the exchange of energy (such as solar radiation and heat) and matter (such as water, carbon dioxide, and nutrients) with their boundaries [26]. Pimentel's hypothetical equation [27] establishes a direct correlation between crop yield (y) and artificial energy input (w), represented as $y = \eta W$. The factor η represents a type of thermodynamic efficiency and is a result of the First Law of Thermodynamics. As per the Second Law of Thermodynamics, this factor is invariably smaller than one. However, in agricultural ecosystems, the value often surpasses one because the calculation of energy does not include the input of solar energy.

According to the hypothetical Pimentel equation [27], when the input energy value, w, is low, the crop yield will be significantly reduced. Therefore, with an increase in the energy input flow to our agricultural ecosystems, we can expect a corresponding increase in yield. Nevertheless, the Second Law of thermodynamics imposes practical limitations that prohibit an unlimited increase in crop yield. Put simply, our heightened productivity has resulted in environmental deterioration, specifically the degradation of soil [14].

In open systems, the total variation of entropy arises from two sources (Eq. (1)):

$$dS(t) = \sigma = d_iS(t) + d_eS(t) \tag{1}$$

The symbol dS(t) represents the overall entropy of the system, $d_iS(t)$ represents the entropy generated within the system, and $d_eS(t)$ represents the entropy transferred from outside the system.

$$diS(t) = dQ(t)/T(t) \tag{2}$$

dQ(t) represents the heat produced by irreversible reactions within the system, while T(t) represents the ambient temperature (in Kelvin) at a specific location on Earth's surface where the agricultural ecosystem is present (Eq. (2)).

Svirezhev [14] proposed a theory that calculates the total annual entropy rate using Eq. (3):

$$dS = \sigma = \frac{1}{T}\,(W + \lambda\, P_1 - P_0) \tag{3}$$

T represents the temperature during the entire period of plant growth, while W represents the amount of energy supplied artificially on a yearly basis. If λP_1 is included in the annual gross agro-ecosystem production, P_1 represents the portion of production that is lost due to respiration and residue, and remains within the field. Therefore (Eq. (4)):

$$d_iS = (W + \lambda P_1)/T \tag{4}$$

In addition, the equation $d_eS = -P_0/T$ represents the relationship between deS, which is a variable, and P_0, which represents the annual gross primary production (GPP) of a natural ecosystem that is comparable to the agricultural ecosystem. The net production in a system is directly proportional to the product of $(1- r)\,P_1$. r represents the respiration coefficient, which indicates the proportion of gross primary production that plants utilise for their own essential functions. Hence, the crop yield is determined by Eq. (5):

$$y = k\,(1- r)\,P_1 \tag{5}$$

K represents the portion of net production that is being extracted from the system with the yield. Therefore, the residues can be expressed as the product of (1–k), (1–r), and P_1. Then (Eq. (6)):

$$\lambda\, P_1 = (1- k)\,(1- r)\,P_{1\ \text{residue}} + rP_{1\ \text{respiration}} = (1- k + kr)\,P_1 \tag{6}$$

$P_{1\ \text{residue}}$ and $P_{1\ \text{respiration}}$ respectively, the portion of yield that is lost as residue and respiration. By utilising Eq. (5), we can represent the value of P_1 in relation to the established plant value, y, and subsequently re-write Eq. (7).

Table 3

Amounts of inputs, output and energy inputs and output for the different production systems of Goharkuh Agro-industrial complex in Taftan county, Iran.

Inputs	Unit	Quantity per unit area (ha)					Total energy equivalent (MJ ha^{-1})				
		Wheat	Barley	Alfalfa	Cotton	Pistachio	Wheat	Barley	Alfalfa	Cotton	Pistachio
Human labour	(h)	150	150	213	310	475	292.5	292.5	415.35	604.5	926.25
Machinery	(h)	36	36	83	43	41	2257.2	2257.2	5204.1	2696.1	2570.7
Fossil fuel and lubricant	(l)	284	284	735.5	315	301	13575.2	13575.2	35156.9	15057	14387.8
Electricity	(kwh)	330.5	374.4	465.5	512	268.7	3942.86	4466.59	5553.41	6108.16	3205.59
Nitrogen fertiliser	(kg)	300	250	50	350	350	19842	16535	3307	23149	23149
Phosphorus fertiliser	(kg)	150	150	150	150	100	1866	1866	1866	1866	1244
Potash fertiliser	(kg)	100	100	100	100	50	1115	1115	1115	1115	557.5
Herbicide	(kg) or (l)	0.25	0.25	2	–	–	59.5	30	240	–	–
Fungicide	(kg)	0.5	0.5	–	–	–	90.95	108	–	–	–
Insecticide	(kg)	–	1	–	–	1	–	101	–	–	101.2
Aphicide	(l)	–	–	–	1	–	–	–	–	101.2	–
Pesticide	(l)	–	–	–	0.25	–	–	–	–	25.3	–
Micro fertiliser	(kg)	–	–	–	–	3	–	–	–	–	360
Manure	ton	–	–	–	–	1	–	–	–	–	303.1
Water for irrigation	(m^3)	207	155	138	241	164	211.14	158.1	140.76	245.82	167.28
Seed	(Kg)	250	180	65	25	250	3675	2646	1155.05	295	6220
Total energy input (MJ)							**46927.35**	**43150.59**	**54153.57**	**51263.08**	**53192.42**
Output (s)											
Yield	(kg)	3200	4000	7000	2700	1200	47040	58800	124390	31860	29856
Straw	(kg)	2000	2000	–	–	–	25000	25000	–	–	–
Total energy output (MJ)							**72040**	**83800**	**124390**	**31860**	**29856**

Energy content was assigned to the pesticides by equating it to the energy content of their active ingredients.

$$\lambda P_1 = (1 - k + kr)\, P_1 = \frac{1-s}{s}\, y \tag{7}$$

S represents the portion of gross production that is removed from the system as a tangible economic product. Therefore, $S = k\,(1 - r)$. And finally, the agro-ecosystems' entropy balance will be (Eq. (8)):

$$\sigma = \frac{1}{T}\left(w + \frac{1-s}{s}\, y - P_0\right) \tag{8}$$

When using the Pimentel's equation [27] $y = \eta W$, then (Eq. (9)):

$$\sigma = \frac{1}{T}\left[w\left(1 - \eta + \frac{\eta}{s}\right) - P\_(0)\right] = \frac{1}{T}\left[y\left(\frac{1}{\eta} + \frac{1}{s} - 1\right) - P\_()\,0\right] \tag{9}$$

It is evident that when a system accumulates entropy, this occurs as a consequence of the preceding condition. However, a system that accumulates entropy is inherently unstable and will ultimately undergo self-destruction. Therefore, an additional procedure is necessary to remove entropy from the system. The quantity σ, representing the surplus entropy production of the system, can serve as a metric for assessing environmental deterioration. Surplus entropy can be understood as the entropic expense that our society incurs when employing advanced industrial technologies in agriculture. Given that the system has zero excess entropy production ($\sigma = 0$), as indicated by the first term in Eq. (9) which only includes w, Eq. (10) offers a calculation for the highest allowable energy input needed to sustain system stability:

$$W_{cr} = \frac{P_0}{1 - \eta + \left(\frac{\eta}{s}\right)} \tag{10}$$

W_{cr} represents the uppermost level of energy that can be supplied to the system without compromising its stability, commonly known as the limit energy load. This energy encompasses all human activities related to agriculture, such as tillage, fertilisation, irrigation, pest control, harvesting, transportation, drying, and so on. If the value of w is greater than w_{cr}, then the value of σ becomes positive, resulting in the degradation of the environment.

The maximum yield of a stable system can be determined by using Eq. (9), where the second term only involves the variable y.

$$Y_{cr} = \frac{P_0}{\left(\frac{1}{s}\right) + \left(\frac{1}{\eta}\right) 1} \tag{11}$$

Y_{cr} denotes the highest level of plant production (measured in terms of dry matter weight) that a farm can achieve in a stable condition. This is commonly known as the maximum crop yield for sustainable agriculture.

This study utilised a flow-based ecosystem model (FBEM) as described by Wu et al. [28] to calculate the values of P_0 and plant canopy respiration. Essentially, this technique computes the P_0 value and plant canopy respiration by utilising environmental variables. The estimation of plant canopy respiration was based on the Van't Hoff Q_{10} equation [29], which takes into account the temperature (T, °C), Eq. (12).

$$ER = ER_0 \times Q_{10}^{T/10} \tag{12}$$

ER_0 represents the measurement of ecosystem respiration at 0 °C, while Q_{10} is the proportionate increase (ER/ER_0) in respiration for every 10 °C increase in temperature. The estimation of gross primary production (GPP) was conducted using Eq. (13):

$$P_0 = NEE + ER \tag{13}$$

The equation consists of three variables: NEE, which represents the net ecosystem exchange; P_0, which denotes the gross primary production; and ER, which stands for the ecosystem respiration.

2.4. Sensitivity analysis

Sensitivity analysis is a method employed to examine the effect of changing an input variable on an output variable, while keeping a specific set of assumptions constant. Through the utilisation of modelling techniques, it calculates the precise percentage variation in both the output and input. Sensitivity is defined as the quotient of the percentage change in the output divided by the percentage change in the input. One way to conduct sensitivity analysis is by performing tests that investigate the response of the system's output to the doubling or halving of each input variable [15].

Sensitivity analysis is a crucial tool in agriculture for evaluating the effects of changes in input variables or parameters on the results and outcomes of agricultural systems. This method is especially beneficial for facilitating decision-making, conducting risk assessments, and improving agricultural management practices. Sensitivity analysis enables us to gain a deeper understanding of the potential consequences that alterations to various variables may have. This allows us to make well-informed decisions, mitigate risks, and enhance the efficiency of agricultural management techniques. Multiple techniques are accessible for performing sensitivity analysis in the field of agriculture. One-way sensitivity analysis refers to the deliberate and organised alteration of individual input parameters, while keeping all other parameters unchanged. The aim of this approach is to examine the resultant alterations in the output and determine the factors that exert the greatest influence on the ultimate outcome [18–20,30,31].

2.4.1. *Input energy flow sensitivity analysis*

In this study, the values of input energy flows were determined and all input and output factors were converted into energy units. Indicators related to the entropy generated in systems were then determined. As a result, the input energy flows that make up a large portion of the total input energy to the system (specifically nitrogen fertiliser and fossil fuel) were chosen as variables for sensitivity analysis. Ultimately, the alterations in the model output in relation to the initial state were determined by modifying these values.

2.4.2. *Harvest index sensitivity analysis*

Eqs. (8), (10) and (11) indicate that modifications in the harvest index value will lead to variations in the model output. As a result, the entropy-based indicators being studied will be impacted. By implementing this strategy, we enhance the harvest index values of the agricultural systems (wheat, barley, cotton, and pistachio) by 10 %. Consequently, this method will illustrate the alterations in the indicators being examined in relation to the initial condition.

These findings can greatly aid in choosing management practices that either improve or at least sustain the harvest index when input energy flow to the production systems decreases.

3. Results and discussion

3.1. *Input energy flows and energy efficiency of production systems*

Fig. 2 illustrates the energy input composition of the production systems in the Goharkuh Taftan agro-industrial complex. According to Table 3, the energy input values for the wheat, barley, alfalfa, cotton, and pistachio systems were 46.92, 43.15, 54.15, 51.26, and 53.19 GJ ha^{-1}, respectively. According to Fig. 2, fossil fuels contribute the largest amount of energy in the alfalfa system, while nitrogen fertiliser contributes the highest amount of energy in the wheat, barley, cotton and pistachio systems.

3.2. *Overproduction of entropy*

Below, the calculation of entropy overproduction, energy load limits, maximum crop yield for sustainable agriculture, and deviation from sustainable agriculture for wheat is presented Uniform. Methodology was employed for all remaining crops, and the specifics of the computations are presented in Appendix B. It is essential to determine the parameters in Eq. (8) in order to achieve the entropy balance. The parameters in question are w, y, η, s = k (1−r), P_0, and T. The calculated input energy, denoted as w, for wheat was 46.92 GJ ha^{-1}. The output energy, denoted as y, was determined to be 72.04 GJ ha^{-1} based on the crop yield. This calculation resulted in an energy efficiency, represented by the symbol η, of 1.54 (Table 4). The reported value of k for wheat was 0.74, as shown in Table 5. The study area's ecosystem respiration coefficient was determined to be 0.33 through the utilisation of the flow-based ecosystem model (FBEM). The value of S was computed as 0.496 using equation S = k (1-r).

Artemisia sieberi is the prevailing plant species in the natural ecosystem of this region. By employing the approach developed by Wu et al. [28] and taking into account the climatic attributes of the area, the P_0 value for this species at the climax state was calculated to be 22 GJ ha^{-1}. According to the weather data, the air temperature during the wheat growing season was estimated to be 290.5 K

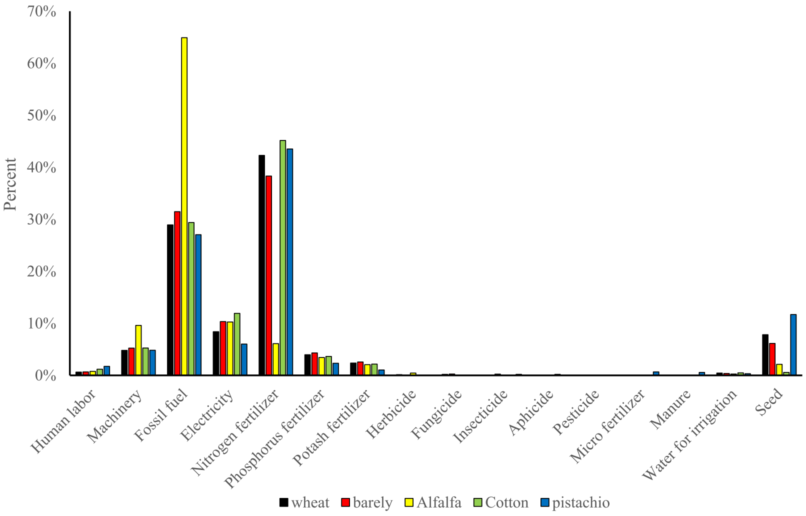


Fig. 2. Energy inputs structure of the different production systems of Goharkuh Agro-industrial complex.

Table 4

Amount of energy input (w), energy output (y), and energy efficiency (η), production systems of Goharkuh Agro-industrial complex in Taftan county, Iran.

Crop	w (GJ ha^{-1})	y (GJ ha^{-1})	η
Wheat	46.92	72.04	1.54
Barley	43.15	83.80	1.94
Alfalfa	54.15	124.39	2.30
Cotton	51.26	31.86	0.621
Pistachio	53.19	29.85	0.561

Table 5

Values of various indices for the studied products in the Goharkuh Agro-industrial complex.

Crop	K	S	T (°K)	r
Wheat	0.74	0.496	290.54	0.33
Barley	0.73	0.489	289.04	0.33
Alfalfa	1	0.67	300.04	0.33
Cotton	0.36	0.24	300.65	0.33
Pistachio	0.15	0.10	294.75	0.33

K: the portion of net production that leaves the farm as an economic product.
S: the portion of gross production that leaves the farm as an economic product.
T: the temperature in Kelvin during the crop growing period.
The values of K and S were derived from [41].

(Table 5).

By plugging in the given values into the entropy balance equation (Eq. (8)), we determined that the entropy production in the wheat system is 0.337 GJ $ha^{-1}{}^{\circ}k^{-1}$. By substituting numerical values into the variables of Eq. (10), the limit energy load was determined to be 8.59 GJ $ha^{-1}{}^{\circ}k^{-1}$. Eq. (11) was used to calculate the maximum crop yield for sustainable agriculture of the wheat production system, which was determined to be 13.19 GJ $ha^{-1}{}^{\circ}k^{-1}$.

In 2000, Steinborn and Svirezhev [24] introduced a criterion to estimate the extent to which a system deviates from a sustainable state (Eq. (13)).

$$S_d = \frac{W - Wcr}{Wcr} = \frac{y - ycr}{ycr} \tag{13}$$

This equation enables the computation of the discrepancy between a system and sustainable agriculture. In the current investigation, the determined value for the wheat system was 4.46. Calculations were conducted for different crops within the complex, and the results are presented in Table 6.

The current study found that the alfalfa agricultural system had the lowest amount of entropy excess compared to the other three crop systems being studied. The higher energy yield of alfalfa compared to wheat, barley and cotton is the reason for this result, despite the fact that it requires more energy input. As a result, the energy efficiency of alfalfa was higher than that of the other crops, leading to a decrease in entropy generation within the alfalfa system. Therefore, these results suggest that alfalfa exhibits superior thermodynamic stability in comparison to the other crops examined. Despite having the highest energy input, the pistachio system had the lowest energy output compared to the other production systems. As a result, it exhibited the lowest energy efficiency in comparison to the other systems. Based on these factors, the pistachio system exhibits thermodynamic instability, as it has an entropy production of 1.01 GJ $ha^{-1}{}^{\circ}k^{-1}$, which is greater than that of the other production systems. Wheat, barley, and cotton are categorised within the spectrum of these two systems. The wheat and barley systems exhibit comparable levels of entropy production as a result of their similar energy input flows, as shown in Table 6. The outputs of wheat and barley systems include not only grain but also straw, which hold economic and thermodynamic significance. The incorporation of these supplementary outputs leads to reduced entropy production in these systems in comparison to pistachio and cotton systems (Table 3).

A thermodynamic analysis was conducted to assess the sustainability of agricultural ecosystems in the Kiel Ecology research area in

Table 6

Entropy overproduction (σ, E+ 09 J ha^{-1} K^{-1}), energy load limits (W_{cr}, E+ 09 J ha^{-1}), maximum crop yield for sustainable agriculture (Y_{cr}, E+ 09 J ha^{-1}), and deviation from sustainable agriculture (S_d) for production systems of Goharkuh Agro-industrial complex.

Crop	σ (GJ ha^{-1} K^{-1})	W_{cr} (GJ ha^{-1})	Y_{cr} (GJ ha^{-1})	S_d
Wheat	0.337	8.59	13.19	4.46
Barley	0.376	7.26	14.1	4.94
Alfalfa	0.311	10.32	23.70	4.25
Cotton	0.432	7.41	4.6	5.92
Pistachio	1.01	3.63	2.04	13.63

northern Germany from 1988 to 1997 [24]. The region consists of cultivable land, semi-natural woodlands, additional natural habitats, and rural communities. In summary, the findings indicate that there was a significant decrease of around 49 % in the total energy input over a span of 9 years. Conversely, the average yield experienced a slight increase of approximately 6 % during the same time frame. As a result, the surplus of entropy, which quantifies the ecological consequences of agriculture, decreased by approximately 11 %. The departure from sustainable agriculture also diminished by a comparable extent. Overall, their findings demonstrated a gradual advancement of the examined system towards a state that is more environmentally sustainable. The entropy state indicates that maize, oat, and wheat crops had a detrimental effect on the environment. In contrast, rye, barley, and rapeseed, despite a small increase in entropy, managed to maintain a balance through technological advancements that resulted in significant yield improvements with reduced energy input. Asgharipour et al. [32] conducted a study on the ecological health of the agroecosystems in the Jowain Sabzevar agro-industrial complex in Iran. They found that the entropy excess in the wheat production system increased from 1.16 to 1.17 GJ ha^{-1}°k^{-1} over a period of 6 years (2005–2010). The researchers ascribed the rise in entropy during this timeframe to heightened energy consumption and diminished energy utilisation efficiency within the complex. The sustainability deviation of the wheat production system within the complex was 12.25 in 2005–2006, which decreased to 12.42 in 2010–2011, indicating a decline in sustainability. However, these changes occurred slowly and were not substantial. Nevertheless, these alterations were gradual and inconsequential. When comparing different production systems, the entropy of alfalfa production systems was found to be lower than that of other systems, while the entropy of sugar beetroot production systems was the highest.

3.3. *Sensitivity analysis*

3.3.1. *Input energy flow sensitivity analysis*

The current study focused on analysing the sensitivity of two major energy input components, namely nitrogen fertiliser and fossil fuel, which play a significant role in production systems. The potential use of nitrogen fertiliser was evaluated for the wheat, barley, cotton and pistachio production systems, while the use of fossil fuel was assessed for the alfalfa production system. Within this section, we determine the alterations in the model's output by multiplying the initial values by two and dividing them by two. The alterations in energy input flows were taken into account while assuming that the energy output values remained consistent. This is a form of unidirectional sensitivity analysis. By employing this methodology, we will illustrate the alterations in entropy indicator values in relation to the initial state. Implementing this method will enhance our comprehension of the alterations in the disorder of production systems. As a result, it will enhance future management decisions regarding the management of energy input flows to these systems.

The findings indicated that increasing the nitrogen fertiliser by two-fold resulted in a rise in the deviation from sustainable agriculture for the wheat, barley, cotton, and pistachio systems by approximately 20 %, 15 %, 18 %, and 8 % respectively. Furthermore, this method resulted in a reduction in the highest achievable crop yield for the purpose of maintaining sustainable agriculture in all four production systems. These findings suggest that as the amount of nitrogen fertiliser used in production systems increases, the entropy production of these systems also increases, leading to a shift towards instability. By reducing the amount of nitrogen fertiliser used in the wheat, barley, cotton, and pistachio systems, the deviation from sustainable agriculture decreased by approximately 11 %, 8 %, 10 %, and 4 % respectively. In contrast, the maximum crop yield for sustainable agriculture in these systems experienced an increase of approximately 8 %, 6 %, 8 %, and 4 % respectively, as shown in Table 7.

Increasing the input of fossil fuel energy in the alfalfa production system resulted in a 38 % increase in the system's generated entropy and deviation from sustainable agriculture. Due to the significant reliance on fossil fuels in the alfalfa production system, doubling their usage will result in a 23 % decrease in maximum crop yield for sustainable agriculture. However, reducing the fossil fuel energy input into the alfalfa system by half resulted in a 23 % decrease in the system's deviation from sustainable agriculture. Conversely, the maximum crop yield for sustainable agriculture experienced a 15 % increase, as shown in Table 7.

Table 7

Sensitivity analysis results of two inputs—nitrogen fertiliser and fossil fuel—on the studied indices of production systems of Goharkuh Agro-industrial complex.

Crop	Input	Variable Change	σ		W_{cr}		Y_{cr}		S_d	
			(GJ ha^{-1} K^{-1})	Change (%)	(GJ ha^{-1})	Change (%)	(GJ ha^{-1})	Change (%)	__	Change (%)
Wheat	N fertiliser	Double	0.406	+20.2	10.49	+22.1	11.32	−14.1	5.36	+20.2
		Half	0.303	−11.2	7.38	−16.3	14.38	+8.2	4.00	−11.2
Barley	N fertiliser	Double	0.433	+15.2	8.91	+22.7	12.51	−11.2	5.69	+15.2
		Half	0.347	−8.23	6.26	−15.8	15.05	+6.3	4.56	−8.1
Alfalfa	Fossil fuel	Double	0.428	+37.6	13.04	+26.4	18.17	−23.3	5.84	+37.5
		Half	0.252	−23.1	8.22	−25.5	27.97	+15.2	3.44	−23.2
Cotton	N fertiliser	Double	0.509	+17.7	9.33	+25.9	3.99	−13.2	6.97	+17.7
		Half	0.394	−9.7	6.22	−19.3	4.98	+7.6	5.39	−9.8
Pistachio	N fertiliser	Double	1.09	+7.7	4.86	+33.8	1.90	−6.7	14.68	+7.7
		Half	0.97	−4.01	2.95	−23.2	2.11	+3.6	13.1	−4

Entropy overproduction (σ).
Energy load limits (W_{cr}).
Maximum crop yield for sustainable agriculture (Y_{cr}).
Deviation from sustainable agriculture (S_d).

3.3.2. Harvest index sensitivity analysis

In this section, we analyse the variations in the model's output outcomes by altering the value of the crop harvest index. In order to accomplish this objective, the crop harvest index values of the intricate system consisting of wheat, barley, cotton, and pistachio are enhanced by 10 %. Consequently, the value of S will be altered according to equation S = k (1-r). Ultimately, the acquired values are contrasted with the original values, and the percentage of alterations is displayed in Fig. 3. Due to the alfalfa harvest index reaching its peak value, it is excluded from this analysis (Table 5). The findings demonstrated that a 10 % increase in the harvest index resulted in a reduction of approximately 21 %, 23 %, 29 %, and 67 % in the entropy generated and deviation from sustainable agriculture for the wheat, barley, cotton, and pistachio systems, respectively. In contrast, the maximum crop yield for sustainable agriculture and energy load limits in four production systems of wheat, barley, cotton, and pistachio increased by 14 %, 15 %, 19 %, and 37 %, respectively. The results clearly demonstrate the significant impact of a 10 % increase in the harvest index on the sensitivity of the pistachio production system. Hence, any factors that augment the harvest index of the pistachio production system by 10 % have the potential to not only enhance product yield but also ensure long-term sustainability of the production system, while simultaneously boosting the maximum crop yield for sustainable agriculture. The disparity in the harvest index of pistachio products compared to other agricultural products can be ascribed to the following factors: varying growth periods, alternating bearing, extended maturity periods, distinct water and nutrient needs, diverse climatic factors, and pest and disease control [33,34]. The presence of these factors results in a decreased harvest index for pistachios in comparison to other agricultural commodities. Hence, a 10 % augmentation in the harvest index of this product can result in a significant 67 % reduction in the quantity of entropy production by this system (Fig. 3).

The results of this study suggest that increasing the amount of energy used in production systems leads to a decrease in their ability to be sustained, an increase in the production of disorder, and a decrease in the highest possible crop yield for sustainable agriculture. These results contribute to the divergence of a system from its equilibrium state over a prolonged duration. On the other hand, decreasing the amount of energy used in production systems improves their ability to be maintained over time, reduces the amount of disorder created, and increases the highest possible crop yield for sustainable agriculture. These factors play a crucial role in maintaining the long-term viability of a production system.

Eq. (9) can be restated by substituting the expression k(1-r) for s:

$$\sigma = \frac{1}{T}\left[\mathrm{w} + \left(\frac{1}{k\,(1-r)} - 1 \right) \mathrm{y} \right] \tag{14}$$

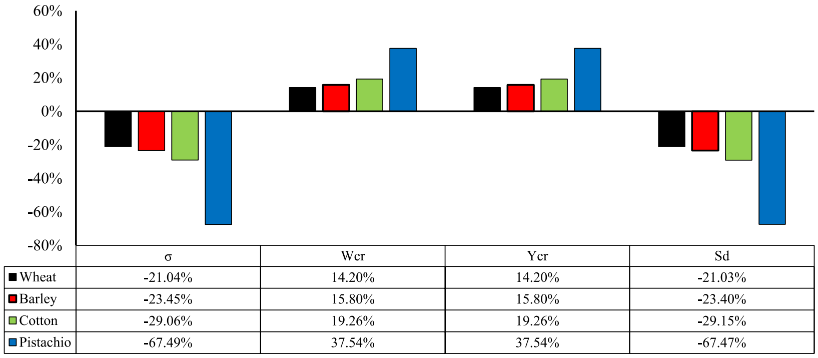
According to Steinborn and Svirezhev [24], in order to increase plant yield (higher harvest index), it is necessary to increase the amount of energy put into production systems. Furthermore, the sensitivity analysis conducted in this study revealed that higher energy input to a system leads to an increase in entropy production, resulting in system instability. Eq. (14) suggests that if it is feasible to enhance plant productivity while using less energy, it can help in establishing a sustainable system in the future.

Our findings demonstrate a clear correlation between entropy production and harvest index. Agricultural systems with lower harvest indices, such as pistachios in this study, exhibited higher entropy production, indicating a greater degree of disorder within the system. Conversely, systems with higher harvest indices, like alfalfa, demonstrated lower entropy production. This suggests that improving harvest efficiency can be a viable strategy for reducing a system's overall entropy and enhancing its sustainability in the long term.

However, the question arises: should the primary goal be to minimise entropy regardless of yield, or to minimise entropy per unit of yield? While minimising entropy is undeniably desirable for long-term sustainability, completely disregarding yield might not be a practical approach for agricultural production systems.

Finding an optimal balance between minimising entropy and maximising yield efficiency is likely the most sustainable approach. This can be achieved through targeted management strategies that enhance harvest index without significantly increasing energy input. Examples include enhancing water efficiency [42], employing conservation tillage methods [43], utilising sustainable energy sources [44], implementing precision agriculture [45], improving the efficiency of agricultural machinery [46], using cover crops as living mulch [47], applying integrated pest management (IPM) techniques [48,49], selecting high-yield crop varieties [50], optimising planting density [51], and executing efficient nutrient and water management practices [52].

In this study, the deviation from the Sustainable Agriculture (Sd) index serves as an indicator of a system's stability. Additionally, this index can be used to demonstrate the stability of a system over multiple years. The emergy assessment approach, developed by Odum [53] to evaluate the sustainability of production systems, has been widely utilised by researchers in various studies. One crucial emergy analysis index is the emergy renewability ratio (%R). This index reveals the extent to which a system relies on renewable resources. Production systems that leverage more renewable resources exhibit greater long-term sustainability than systems that primarily derive their resource inputs from non-renewable sources [54]. Although the methodology adopted in this study differs from the emergy assessment approach, both Sd and the %R underscore the fact that achieving greater sustainability in production systems requires a significant reduction in the quantity of input energies (reduced reliance on non-renewable energies) and an increase in the utilisation of renewable energies. Numerous emergy studies acknowledge this reality [55–58]. Artuzo et al. [25] propose a new metric called the emergy unsustainability index for agricultural systems (EUIAS) to assess the unsustainability of agricultural systems. A higher EUIAS indicates that an agricultural system is more dependent on non-renewable economic resources than renewable resources, and has higher environmental impacts. The EUIAS is intended to shift the perspective from sustainability to unsustainability when analysing agricultural systems. The overproduction of entropy, caused by anthropogenic energy inputs, can lead to environmental degradation, particularly soil degradation [59]. In contrast, agricultural systems that rely more on renewable energy sources like solar or wind power tend to have lower entropy production [60].



	σ	Wcr	Ycr	Sd
⬛ Wheat	-21.04%	14.20%	14.20%	-21.03%
🟥 Barley	-23.45%	15.80%	15.80%	-23.40%
🟩 Cotton	-29.06%	19.26%	19.26%	-29.15%
🟦 Pistachio	-67.49%	37.54%	37.54%	-67.47%

Fig. 3. Results of sensitivity analysis of a 10 % increase in harvest index (k).

4. Conclusion

This study employed a thermodynamic approach, specifically the Steinborn and Svirezhev methodology, to assess the sustainability and ecological health of five integrated production systems (wheat, barley, cotton, alfalfa, and pistachios) within the Goharkuh Taftan agro-industrial complex. The analysis focused on four key components: entropy production, limit energy load, maximum crop yield for sustainable agriculture, and deviation from sustainable agriculture.

Our findings revealed variations in the sustainability of the analysed systems. Among them, alfalfa exhibited the lowest entropy production (indicating the least system disorder) and the lowest deviation from sustainable agriculture, signifying its greatest resilience. Conversely, the pistachio system displayed the highest entropy production and deviation from sustainability, suggesting the most unstable and unsustainable condition. These results highlight the contrasting levels of sustainability within the Goharkuh Taftan complex.

Eq. (14), introduced in the Results section, demonstrates the relationship between harvest index and entropy production. This equation underscores the significance of optimising harvest index for achieving long-term sustainability.

Sensitivity analysis explored the impact of adjusting nitrogen fertiliser application (for wheat, barley, cotton, and pistachios) and fossil fuel use (for alfalfa) on the evaluated components. Doubling nitrogen fertiliser input generally increased entropy production and deviation from sustainability, while halving it produced mixed effects across the systems. Similarly, for alfalfa, reducing fossil fuel use led to a decrease in both entropy production and deviation from sustainability. These findings emphasise the potential benefits of optimising resource use for enhancing system sustainability.

It is important to acknowledge the limitations of the employed methodology. The Steinborn and Svirezhev approach primarily focuses on energy flows and may not fully capture the influence of other environmental factors like soil quality and emissions. Future research could explore the integration of additional sustainability assessment methods. Additionally, while this study discussed various management practices and technological options for reducing energy input (e.g., increased planting density, contemporary harvesting machinery, solar panels), a comprehensive evaluation of their energetic implications necessitates further investigation. These areas present valuable opportunities for future research endeavors.

CRediT authorship contribution statement

Mahdi Motakefi: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Mehdi Dahmardeh:** Validation, Supervision. **Seyed Ahmad Ghanbari:** Validation. **Mohammad Reza Asgharipour:** Writing – review & editing, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mehdi Dahmardeh reports financial support was provided by University of Zabol. Mehdi Dahmardeh reports a relationship with University of Zabol that includes: board membership. Mehdi Dahmardeh has patent issued to University of Zabol. Nothing to declare If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39210.

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