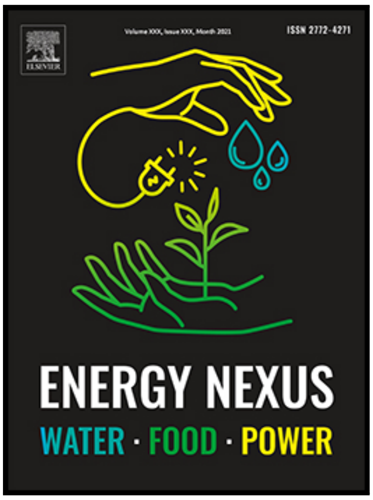

Energy analysis in Water-Energy-Food-Carbon Nexus

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Highlights

- The Water-Energy-Food-Carbon Nexus were studied using real farm data
- Optimization were applied for allocating resources and environmental impacts of them
- There is a direct relationship between input energy and global warming potential
- The WEFC Nexus by the interrelation between resources can help to achieve sustainable development

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Abstract

This study evaluated the comprehensive Water-Energy-Food-Carbon Nexus (WEFC) by focusing on energy assessment in northwest Iran. The energy evaluation indices for different products were calculated by estimating the total input and output energies. Multi-objective optimization based on five individual objectives and WEFC Nexus policies was used to identify the optimal land-use allocation of wheat, barley, rapeseed, and sugar beet, silage corn, and potato while minimizing water and energy consumption and CO_2 emissions, and maximizing food production and profit. The results indicate that the suggested framework provides a practical methodology for determining the optimal land-use allocation considering quantitative WEFC Nexus. To increase economic efficiency and reduce energy consumption, agricultural practices and policy recommendations should be adopted, including promoting renewable energy sources, implementing energy-saving technologies, improving fertilizer management, improving crop rotation practices, conservation tillage, and improving water management and adoption of sustainable farming practices. The results allow policymakers to optimize multiple resources and recommend the best resource allocation under recommendation policy, technology, and constraints to achieve sustainable development in agriculture.

Keywords: Water-Energy-Food-Carbon Nexus, CO_2 emissions, land use, multi-objective programming, Optimization, Sustainable development

1. Introduction

Water and energy are the fundamental resources for economic growth. An anticipated 35% rise in energy demand by 2035 could increase water withdrawals in the energy sector by 20%, whereas water consumption for energy is expected to increase by 85% [1]. China, India, and the Middle East will account for most of the growth in energy needs by 2035; however, these are also among the countries with the lowest renewable water resources per capita, meaning that as the energy demand grows, the strains on limited water resources could intensify [2]. In the Middle

East, Iran is one of the countries facing a severe water problem. Rapid population growth, urban migration and urban development, declining water quality, inefficient agriculture, increasing water demand, cheap water and energy prices, drought, climate change, sanctions, and economic instability, poor water governance and environmental ignorance are among Iran's major water problems [3]. The share of water consumption in the agricultural sector in Iran is more than 90% of the total annual renewable resources, while the world average is estimated at 70% [3]. Much of the mismanagement is due to the lack of a dynamic relationship between the amount, manner, and method of using water and energy in food production. Hence, processes and approaches are needed to achieve this dynamic more than ever.

Today, water, energy, and food security are hampered by the rapid growth of population and economic development, followed by unbearable pressures on the limited resources of watersheds. More than 70% of the world's current water consumption is in agriculture. Therefore, it is necessary to balance the utilization of resources and agricultural production. However, water, energy, and food demand will increase by 30 to 50 percent in the next two decades. The relationship between these cases depends more on the issue of their growing demand. Economic inequalities and the encouragement of short-term response in production and consumption will undermine long-term sustainability. Resource scarcity can lead to social and political instability, geopolitical conflict, and irreparable environmental damage. In this regard, focusing on one of the interconnected sectors of water, energy, and food without considering their interaction will create serious risks. Understanding WEF Nexus allows for more integrated planning, development, policy-making, monitoring, and evaluation of the nexus sectors [4].

Many recent studies focused on various aspects of the Nexus approach, including the, water-energy-food-land requirements, and CO_2 emissions for food security in Japan [5], decision-making based on the water-energy-food security Nexus under climate change uncertainties [6], analyzing economic aspect of water-energy-food-greenhouse gases Nexus [7], water-energy-carbon emissions Nexus [8], and water-food-energy nexus in Gavkhuni basin in Iran [9]. Developing a cultivation pattern based on economic criteria and resources that provide essential support in meeting human needs and nature conservation goals can play a significant role in managing agriculture in a particular region. For this, the optimal cultivation pattern in the region must be identified using optimization techniques by finding the optimal solution of the objective function presented in some studies. These studies also addressed the optimization of water-food Nexus [10], optimization of complex water-energy Nexus using graph theory-based network [11, 12], synergistic benefits of water-food-energy Nexus through multi-objective reservoir optimization [13], food-energy-water Nexus approach for land use optimization [14], optimization of water-energy-food-carbon Nexus [15], optimization of water-energy-food Nexus considering CO_2 emissions [16], and future direction of multi-sector Nexus research [17].

About 30% of the world's energy consumption is used for food production, provided by fossil fuels [18]. The availability of cheap and abundant fossil fuels has improved human well-being and increased food production, but today, major problems have arisen with fossil fuels. These problems include shortages of fossil fuels for future generations, rising energy prices, and, most importantly, the release of greenhouse gases (such as carbon dioxide, nitrogen oxides, and methane) into the atmosphere due to fossil fuels usage. Due to the energy crisis and greenhouse gas emissions caused by the excessive consumption of fossil fuels, every effort is made to reduce energy consumption as much as possible. The agricultural sector is no exception. In most developed and even developing countries, the energy entered at the surface is studied for the production of various agricultural products, and by calculating the intensity of energy efficiency, tried to optimize agricultural systems in terms of energy consumption [19].

Preliminary estimates show that agricultural activities account for about half of the world's gas emissions [20]. Since 1860, the area under cultivation of agricultural products has increased by approximately 900 million hectares. The release of 116 Mg of carbon from 696 Mg of usable carbon reserves from 1860 to 1980 has caused global warming of nine percent [21]. Concerns about fossil fuel conservation and greenhouse gas emissions have led to increased research on energy balance in crop production systems [22]. Effective use of energy in agriculture is one of the essential conditions in the emergence of sustainable agriculture because it saves money, preserves fossil fuels, and reduces air pollution [23]. It is possible to understand all forms of energy by analyzing different agricultural systems to protect limited resources, including land, water, and biological resources, for future generations [24]. One of the appropriate approaches to reduce input energy and increase output energy is to review and evaluate the indicators (including: energy use efficiency, energy productivity, specific energy, and net energy) obtained from regional studies. How and to what extent do the factors have the greatest impact on the value of these indicators examining the possibility of replacing them with other elements and considering economic and technical considerations can ultimately optimize energy consumption patterns in agricultural products [25]. On the other hand, energy consumption analysis can reduce the energy input to the production system and increase energy efficiency [26].

Given that the study of energy flow in agricultural production systems has many advantages, researchers have studied the production of agricultural products concerning input energy. Various studies have been performed on energy balance in agricultural systems, including the effect of reducing water and energy uses on renewable water resources in the WEF Nexus [27], the energy balances analysis to determine the best double-cropped cereals in Isfahan province of Iran [28], energy input from alfalfa production in the Sistan region of Iran [29], investigate the energy consumption and global warming potential in wheat production fields in the central parts of Mazandaran province in Iran [30].

There have been few studies on the Water-Energy-Food-Carbon; none has been done on WEFC Nexus, focusing on energy consumption in several crop productions using real farm data. In this study, the environment sector, especially CO_2 emission, is considered a critical sector of the Nexus systems. The objective of this study was: 1) to allocate limited water and energy resources among various crop productions, 2) to evaluate energy-related indicators, containing energy efficiency, specific energy efficiency, and net energy performance in the WEFC Nexus concept, and 3) providing suggestions and solutions to reduce water consumption, energy consumption, and CO_2 emission and increase food production and profit by optimization. In addition to the study objectives, the optimization objectives focused on: (1) minimizing total water use (TW), (2) minimizing total energy use (TE), (3) maximizing total food production (TF), (4) maximizing total profit (TP), and (5) minimizing total CO_2 emissions (TCO).

2. Material and Methods

A three-step approach was used to select the optimal cropping pattern considering low water and energy use, high production, and low CO_2 emissions. First, energy consumption including direct, indirect, renewable, and non-renewable was obtained based on actual data from the study area. Then CO_2 emissions were calculated. In the last step, a multi-objective optimization technique was applied to compare the five following scenarios: 1) Crop cultivation pattern with minimized water usage; 2) Crop cultivation pattern with minimized energy usage; 3) Crop cultivation pattern with maximized food production; 4) Crop cultivation pattern with maximized profit and; 5) Crop cultivation pattern with minimized CO_2 emissions. Considering these five objectives, the optimal cultivation pattern was determined based on field constraints. Figure 1 shows the conceptual model of the WEFC Nexus.

2.1. Case study area

The present study was conducted in Heris plain in Northwest Iran (38°14'9''N, 46°57'49''E) 1379 meters above sea level (Figure 2). The total farming area is 150 ha, with a share of wheat (Triticum aestivum), barley (Hordeum vulgare), silage corn (Zea mays L.), rapeseed (Brassica napus), potato (Solanum tuberosum), alfalfa (Medicago sativa), and sugar beet (Beta vulgaris). This study used labor usage, electricity, machinery, diesel fuel, fertilizers, biocide, seed, and water consumption. Data were collected in field measurement campaigns during 2017-2019 from Sahand Agro-Industry Co., established in 1996. The mean annual precipitation and temperature of the study area are 356 mm and 10.1 °C, respectively. Although the case study is only 150 ha, it represents agricultural activities in the northwest or even the whole of Iran. However, data availability is the main requirement for similar studies on a bigger scale which is not available or is very difficult to access.

2.2. Energy assessment

The basis of energy assessment in this research was established based on energy consumption in agriculture. Energy can be consumed directly or indirectly for agricultural production. Direct energy consumption included human labor, diesel fuel (land preparing, planting, storage, harvesting, and transportation), electricity from fossil fuels (for irrigation pumps), and water for irrigation. However, the energy consumption by seeds, chemical fertilizers, herbicides, pesticides, fungicides, and machinery was considered to calculate the indirect energy. Among different consumed energy, human labor, seeds, and water for irrigation are renewable, and machinery, diesel fuel, electricity, chemical fertilizers, herbicides, pesticides, and fungicides are considered non-renewable energy. The energy consumption ($E_{c,t}$) per hectare of crop *c* at time *t*, calculated as:

$$E_{ca,t} = \sum q_h h_{c,t} + q_m m_{c,t} + q_d d_{c,t} + q_f f_{c,t} + q_p p_{c,t} + q_s s_{c,t} + q_w w_{c,t} \qquad (1)$$

where $E_{ca,t}$ is energy consumption per unit area of crop *c* (MJ ha^{-1}); q is energy equivalents of (q_h: human labor (MJ h^{-1}), q_m: machinery (MJ h^{-1}), q_d: diesel oil (MJ h^{-1}), q_f: fertilizer (MJ kg^{-1}), q_p: pesticides (MJ kg^{-1}), q_s: seeds (MJ kg^{-1}), and q_w: irrigation water (MJ m^{-3})); $h_{c,t}$: human labor requirement (h ha^{-1}), $m_{c,t}$: machinery requirement (h ha^{-1}), $d_{c,t}$: diesel fuel use (L ha^{-1}), $f_{c,t}$: fertilizer use (kg ha^{-1}), $p_{c,t}$: pesticide use (kg ha^{-1}), $s_{c,t}$: seed rate (kg ha^{-1}), and $w_{c,t}$: use of irrigation water (m^3 ha^{-1}) in crop *c* production at time *t* [4]. On the other hand, the output energy was calculated based on the amount of harvested product. Information on the energy equivalents of inputs and outputs was taken from different sources in the literature in Table 1.

The input-output technique has been widely used in energy consumption analysis in agriculture, which is usually used to evaluate the efficiency of the production system and its environmental effects. Analyzing input and output energy makes it possible to increase energy use efficiency and move towards sustainability in agriculture. Energy assessment indices include energy use efficiency, energy productivity, specific energy, and net energy for each crop production calculated using the following equations [28]. $E_e = E_{out}/E_{in}$ (2)

$$E_p = C_{out}/E_{in} \quad (3)$$

$$E_s = E_{in}/C_{out} \quad (4)$$

$$E_n = E_{out} - E_{in} \quad (5)$$

Where E_e is the energy use efficiency, E_{out} is energy output (MJ ha^{-1}), E_{in} Energy input (MJ ha^{-1}), E_p is energy productivity (Kg MJ^{-1}), C_{out} is crop output (Kg ha^{-1}), E_s in specific energy (MJ Kg^{-1}), E_n is net energy (MJ ha^{-1}). The energy use efficiency (Eq.2) is used to determine the ratio of output to input energies. This equation should be high, as it measures how efficiently energy is used in a production. A high energy use efficiency indicates that the process is using energy efficiently. Additionally, energy productivity (Eq.3), which measures the production rate per unit of energy consumed, is another important statistic. Equation 3 should be high, as it measures the efficiency of energy usage. A high energy productivity indicates that the production process is using energy efficiently. Specific energy is the rate of energy consumed to crop production (Eq.4). This equation should be low, as it measures the energy intensity of a given product. A low specific energy indicates that the production process is using energy efficiently. The difference between the total energy input and output is the net energy return (Eq. 5). Equation should be high, as it measures the difference between the total energy input and output. A high net energy return indicates that the production process is using energy efficiently.

2.3. CO_2 emissions

The CO_2 emissions was calculated based on the data obtained from the literature (Table 2) and the field data based on the CO_2 emission for all products [16]. The quantity of CO_2 (CO_2eq) emissions was calculated by multiplying the input application rate (e.g., diesel fuel, chemical fertilizer, biocide, water for irrigation) by the emissions coefficient given in Table 2.

2.4. WEFC assessment and optimization

The novelty of this approach is that it provides an optimal cultivation pattern by selecting four crops from seven studied crops for cultivation in the desired area and land allocation between these four crops. It also considers five different objectives. The objectives of the optimization include the following: 1) Total Water Use (TW): The objective of minimizing total water use is to optimize cropping patterns to use the least amount of water possible in order to reduce water waste and conserve resources, (2) Total Energy Use [20]: The objective of minimizing total energy use is to optimize cropping patterns to use the least amount of energy possible in order to reduce energy waste and conserve resources, (3) Total Food Production (TF): The objective of maximizing total food production is to optimize cropping patterns to maximize crop yield in order to produce more food and increase profits, (4) Total Profit (TP): The objective of maximizing total profit is to optimize cropping patterns to maximize profits by considering the costs associated with production, and (5) Total CO_2 Emissions (TCO): The objective of minimizing total CO_2 emissions is to optimize cropping patterns to reduce the amount of CO_2 emissions produced by agricultural activities.

Considering these optimization objectives, four products were selected among seven products. The five different objectives are applied for optimization based on minimizing water use (W, Eq. 6), minimizing energy use (E, Eq. 7), maximizing crop yield (F, Eq. 8), maximizing profit (P, Eq. 9), and minimizing CO_2 emissions (CO, Eq.10). Each objective can be solved directly to optimality using the R software [31].

$$\mathrm{TW} = \sum_{c\in C}\sum_{a\in A} W_{ca} \tag{6}$$

$$\mathrm{TE} = \sum_{c\in C}\sum_{a\in A} E_{ca} \tag{7}$$

$$\mathrm{TF} = \sum_{c\in C}\sum_{a\in A} F_{ca} \tag{8}$$

$$\mathrm{TP} = \sum_{c\in C}\sum_{a\in A} P_c F_{ca} - TC_{ca} \tag{9}$$

$$\mathrm{TCO} = \sum_{c\in C}\sum_{a\in A} Co_{ca} \tag{10}$$

Where $c \in C$ and $a \in A$ are production units and land allocation of the crop (C), these objectives are calculated based on water use (W_{ca}), energy use (E_{ca}), yield output (F_{ca}), economic cost (TC_{ca}), and CO_2 emissions (Co_{ca}). The total cost for production units is calculated based on energy, water, and other costs (e.g., fertilizer, fuel, and labor).

Also, the WEFC Nexus is designed as the integrated objective of the above five objectives and is solved as an optimization programming. The optimum objective is to maximize the WEFC Nexus, using less water and energy resources and emitting less CO_2 (compared with the TF and TP-based objectives) while achieving more output yield and profit (compared with the solution based on TE, TW, and TC objectives). Equation 11 (Opt) represents the final WEFC optimization problem.

$$\mathrm{Opt} = \sum_{c\in C}\sum_{a\in A}((\mathrm{F}_{ca} + (\mathrm{P}_c\mathrm{F}_{ca} - \mathrm{TC}_{ca})) - (\mathrm{W}_{ca} + \mathrm{E}_{ca} + \mathrm{Co}_{ca}))\mathrm{X}_i \tag{11}$$

The R software was used to solve this multi-objective optimization problem. The selection of constraints was defined as a total cultivated area (150 ha, Eq.12), four crops per year, and each crop's minimum and maximum cultivated area (varied between 10 and 50 ha, Eq.13). Due to market limitations, the cultivated area for rapeseed and silage corn was set to less than 80 ha (Eq.14). As wheat and barley are strategic crops in Iran, more than 50% of the cultivated area was allocated to cultivate these crops (Eq.15). The constraints are as follows:

Subject to: $\sum \mathrm{X}_i \leq 150$; i: 1-7 (12)

$10 \leq \mathrm{X}_i \leq 50$; i= 1-7 (13)

$$\mathrm{X}_3 + \mathrm{X}_5 \leq 80 \tag{14}$$

$$\mathrm{X}_2 + \mathrm{X}_7 \leq 90 \tag{15}$$

Eq. 12 represents the total area under cultivation, and Eq. 13 shows the conditional constraint of each crop's minimum (10 ha) and maximum (50 ha) cultivable area. In Eqs. 14 and 15, X_3, X_5, X_2, and X_7 are areas (ha) under cultivation for silage corn, rapeseed, barley, and wheat.

The primary focus of this study is to optimize the WEFC. To achieve this, evaluation methods are employed to assess the energy requirements and outputs of diverse agricultural products. The objective of the assessment is to understand the comprehensive WEFC Nexus with an emphasis on energy assessment. The assessment results provide insights into the energy consumption, CO_2 emissions, water usage, food production, and profit associated with different land-use allocations for these crops. Using a multi-objective optimization approach, these assessment metrics are considered along with WEFC Nexus policies, as objectives. The assessment process serves as a foundation for the optimization process, with the evaluation results informing the multi-objective optimization.

3. Result and Discussion

3.1. Energy consumption and CO_2 emissions

The percentage of input energy consumed for the studied crops is shown in Table 3. The direct input energy evaluation results showed that the human labor application consumes less energy which was due to mechanization and machinery development. The agricultural implements and the number of farming operations are directly related to the fuel consumed. Therefore, they can be considered the reason for high fuel consumption in alfalfa and sugar beet fields. Regarding irrigation water, the highest water used, and energy consumption were obtained for alfalfa (as harvested several times) and the lowest energy consumption for barley. The indirect energy input evaluation results showed that chemical fertilizer was the highest energy consumer which the highest amount was calculated in silage corn. The results were similar to those [32], [33] that chemical fertilizer was one of the most critical inputs in crop production. Regarding the biocides used in the fields, it was found that herbicides had the highest percentage of input energy compared to pesticides and fungicides.

In alfalfa production, the highest percentage of input energy related to diesel fuel, nitrogen fertilizer, and machinery. The same trend was observed for barley, rapeseed, sugar beet, silage corn, and wheat. In potato, the highest percent of input energy was related to nitrogen fertilizer, followed by diesel fuel and seed. Therefore, diesel fuel accounts for most of the input energy compared to other direct inputs. Similar results were obtained for alfalfa [34], barley [28], silage corn [28], potato [32], rapeseed [35], sugar beet [36], and wheat [28], which have identified diesel fuel as one of the factors contributing the most to input energy. Finally, by comparing the share of each of the inputs, it was found that the largest share was consumed by diesel fuel among the direct energies, followed by irrigation water, electricity, and human labor. Chemical fertilizers have the largest share of indirect energy, followed by machinery, seeds, and pesticides. The results show that indirect energy had a larger share in the production of crops than direct energy.

The percentage of CO_2 emissions from crop production is shown in Table 3. As can be seen, diesel fuel made the most noteworthy contribution to total CO_2 emissions in wheat production. Among the chemical fertilizers, nitrogen, was the most noteworthy contributor to CO_2 emissions from alfalfa production. Using chemical fertilizers (especially nitrogen) over plant requirements produces high CO_2 emissions. Moreover, soil and water pollution from using high chemical fertilizers is unfavorable to the agricultural environment. The lowest emissions from wheat production were related to electricity use. A similar trend in emissions contributions, with only slight differences, was observed for all products except potatoes. Nitrogen fertilizer, seeds, and diesel fuel significantly contributed to CO_2 emissions in potato production.

Previous studies have reported lower values of total CO_2 emissions obtained in the present study, including for wheat in Germany [37], and in Finland [38], and for potato in Portugal [39], which could be due to differences in fertilizer rate, soil type, climate, and irrigation type between studied. For every 1 M.J. increase in input energy, CO_2 emissions increased by 0.047 kg ha^{-1} for alfalfa, 0.049 kg ha^{-1} for barley, 0.047 kg ha^{-1} for silage corn, 0.054 kg ha^{-1} for potato, 0.046 kg ha^{-1} for rapeseed, 0.046 kg ha^{-1} for sugar beet, and 0.047 kg ha^{-1} for wheat.

3.2. Energy indicators

The energy evaluation indices for different products were calculated using Eq. 2 to Eq. 5 (Table 4) by estimating the total input and output energies. The highest and lowest total input energy was obtained for potatoes and barley. There are differences in crop production methods, including farming operations (tillage and planting), more chemical fertilizers, and manure usage. In several studies, the total input energy required to produce crops has been reported 98788.3 for sugar beet [40], 59042.5 for barley, and 72317.7 for silage corn [28], 21062.27 for rapeseed [35], 313518.6 for alfalfa [29], and sugar beet and wheat 27848.92, and 22339 MJ ha^{-1} [41]. Comparing the yield of different crops showed that sugar beet had the highest output energy. Alfalfa and potato were placed in the following ranks, and barley's lowest output energy was obtained.

The highest energy use efficiency was obtained in sugar beet and alfalfa; no remarkable difference was observed in the rest of the products. Based on energy use efficiency, sugar beet is the desired product considering input and output energy consumption. In contrast, potato is the most inefficient one due to excessive consumption of inputs in energy consumption and has a low rank in input energy. In similar studies, energy use efficiency was reported to be 1.7 for wheat and 1.83 for barley in Khorasan Razavi Province, Iran [42], 1.22 for barley, and 14.5 for sugar beet in Xinjiang Province, China [40], 1.59 for wheat in Pakistan [43], 3.12 for wheat, and 26.45 for sugar beet in Belgrade, Serbia [41] which is greater than the value obtained in this study. In rapeseed farms, overall energy use efficiency is very low compared to farms in Turkey [44], Poland, and the Netherlands [45], which were 2.7, 2.07, and 2.28, respectively. Also, alfalfa production [29] reported a lower value in Iran's Sistan region. The highest energy productivity was obtained, 0.63 kg MJ^{-1}, for silage corn, followed by sugar beet and potato, and the lowest energy productivity was for rapeseed. This means that 0.63 kg of silage corn was obtained per unit of energy (MJ) and can produce more output than other cultivated crops. Other studies have reported energy productivity for sugar beet 0.9

kg MJ^{-1} [40], for wheat, barley, and sugar beet, 0.098 kg MJ^{-1}, 0.086, and 0.804 kg MJ^{-1}, respectively [28], for alfalfa, 0.077 to 0.145 kg MJ^{-1} for different years [46]. Silage corn, with the lowest specific energy of 1.59 MJ kg^{-1} was selected as the most suitable crop for cultivation. The specific energy determines the amount of energy consumed for the yield obtained. The highest and lowest specific energy was obtained for rapeseed and silage corn. Therefore, it can be concluded that to produce one kilogram of rapeseed, about 13 times more energy is needed compared to produce one kilogram of silage corn. The highest net energy was obtained for sugar beet and alfalfa, while the lowest for barley. Based on net energy results, it can be stated that energy loss has occurred in barley, potato, rapeseed, and wheat. This can be due to overuse and waste of inputs like chemical fertilizers, water.

The total energy input consumed could be direct or indirect (DE vs. IDE) and renewable or non-renewable (RE vs. NRE). Table 4 shows the distribution of total energy input as DE, IDE, RE, and NRE. As shown in Table 4, IDE was more striking than DE, and NRE about nine times was greater than RE in all crop production. About DE, diesel fuel is the input with the greatest consumption in all crops, also, more than 70 % of the IDE is used through fertilizers, irrigation, and seeds in all crop production (Table 4). On the other hand, the most remarkable part of NRE consumption of all crops resulted from fertilizer, diesel fuel, and machinery. Several researchers have found that IDE and NRE are higher than DE and RE consumption in the cropping system. The research results were consistent with other authors findings, including [28, 29, 35, 40-42, 47] . The agricultural sector has not been efficient in consuming inputs, which will cause environmental problems such as global warming, and greenhouse gas emissions. Based on the results of energy forms, all crop productions in the study region mainly depend on NRE sources, which are the main sources of greenhouse gas emissions. To prevent resource depletion and its negative impact on sustainability, we need to replace renewable energy with non-renewable energy. Agriculture can become a non-renewable energy source, improve the environment, lead to economic prosperity, and increase national energy security.

3.3. Multi-objective optimization and assessment

Table 5 and Fig 3 summarize solutions based on five objectives and WEFC Nexus, including optimal objective values, water use, energy use, output yield, profit, and CO_2 emissions. Fig. 3A shows the optimal relative values based on five objectives: minimizing TE, TW, and TCO, which have the lowest relative values than TP, and TF objectives. The solution based on minimizing TW shows that the total profit and food production are lower than the solution based on TF and TP objectives. Therefore, to achieve the TW objective, it largely avoids meeting the objectives of TF and TP.

Based on the maximizing TF and TP (Objective 3 and 4), the amount of water consumption, energy consumption, and CO_2 emissions are higher than based on TW, TE, TCO objectives. Objectives based on TF and TP result in a high output yield, consume large amounts of water and energy and make enormous negative impacts on the environment through the high emission of CO_2. In other words, while the goal of TP is met, the water consumption, energy consumption, and CO_2 emissions are not minimum and deviate from these goals. The following are the appropriate land allocation for each of the five objectives studied in Table 5. Fig. 3B shows the results in the spider maps with five indexes, which comprehensively represent the assessment of five individual objectives, respectively. The solutions of land allocation for five objectives are illustrated in Fig. 3C.

Considering TW, TE, and TCO as objectives, most of the land will be allocated to barley, rapeseed, and wheat and banned from cultivating alfalfa, potato, and sugar beet (Table 5). On the other hand, to maximize crop production (TF as objective), alfalfa, sugar beet, and potato cultivation are recommended for the cultivation pattern without considering barley, rapeseed, and wheat. However, in the cultivation pattern to maximize profit (TP), alfalfa, sugar beet, and rapeseed are the best, and the cultivation of wheat, barley, and silage corn must be excluded.

By comparing these five models, it can be understood that the intended objectives conflict, and the provision of one objective cause distance from another. Therefore, developing a multi-objective programming model is necessary to achieve all objectives simultaneously. In the optimal cultivation (considering all five objective functions), 50, 50, 40, and 10 ha were allocated to wheat, rapeseed, barley, and sugar beet. Although alfalfa and potato are the favored crops in the region (in terms of profit or high food yield), they were not recommended by optimal multi-objective cultivation pattern due to high water and energy consumption and high CO_2 emissions. Due to the constraint set for the problem, wheat, barley, and rapeseed achieve the highest area under optimal cultivation despite low food yield and profit. The allocated land (Based on TW objective) was 20% lower for barley and 25% higher for wheat, and fixed cultivated area for rapeseed in the optimal condition. The recommended area based on TF and TP objectives for sugar beet exceeded the optimal pattern. Still, due to high water and energy consumption and CO_2 emission, this product should be cultivated 80% less in the optimal pattern than the current pattern.

The complicated agricultural system was simplified based on input and output WEFC flow. It combined the interdependence among diverse process units, generating all the possible pathways for the system. The results indicate that the suggested framework provides a practical methodology for determining the optimal land-use allocation considering quantitative WEFC Nexus. The results demonstrate that energy consumption and CO_2 emission can be reduced by implementing appropriate land-use allocation and agricultural management strategies. By optimizing land-use allocation concerning five objectives, it was found that cultivating wheat, barley, and rapeseed, with approximately 50, 50, and 40 ha, respectively, can provide the best balance between the objectives. This result aligns with previous studies showing that wheat, barley, and rapeseed crops are the most energy-efficient and profitable. Moreover, the results of this study demonstrate that alfalfa and potato, despite their high profit and food yield, should be avoided due to their high water and energy consumption and high CO_2 emissions. These findings highlight the importance of considering multiple objectives when making land-use decisions to achieve an optimal balance among profit, food production, water consumption, energy consumption, and CO_2 emissions.

The results suggest that the following agricultural practices and policy recommendations should be adopted to increase economic efficiency and reduce energy consumption: 1) Promote renewable energy sources: Renewable energy sources such as solar, wind, and biomass can replace non-renewable energy sources, thereby reducing energy consumption and emissions. 2) Implement energy-saving technologies: Energy-saving technologies such as drip irrigation, mulching, and other water-saving techniques can be adopted to reduce energy consumption. 3) Improve fertilizer management: Fertilizers should be applied in the right amounts and at the right time to reduce energy consumption and emissions. 4) Improve crop rotation practices: Crop rotation can be used to improve soil fertility and reduce energy consumption and emissions. 5) Practice conservation tillage: Conservation tillage can reduce energy consumption and emissions by reducing soil erosion and water loss. 6) Improve water management: Improved water management practices such as water harvesting, and rainwater harvesting can be used to reduce energy consumption and emissions. 7) Adopt sustainable farming practices: Sustainable farming practices such as integrated pest management and organic farming can reduce energy consumption and emissions.

The study's limitations include data availability, scale, and simplifications. Data availability can be challenging, impacting the accuracy and generalizability of the findings. The study's scale was limited to a small farming area, potentially limiting its applicability to larger regions. The optimization approach used simplifications and assumptions, which may not fully capture real-world agricultural systems' complexity. Additionally, reliance on literature data for energy and CO_2 emission calculations introduces potential inaccuracies and uncertainties.

The findings of this study provide insights into optimizing land-use allocation and balancing multiple objectives at a specific farming area. However, upscaling the analysis to a larger area like a catchment introduces additional complexities. To upscale the analysis, several steps need to be taken, including understanding the catchment's characteristics, adapting the optimization model, and obtaining relevant data at a larger scale. Upscaling offers benefits such as a holistic understanding of interactions, informing land-use planning and resource management, and promoting sustainability and resilience. However, challenges include data availability, heterogeneity of the catchment, and the need for sophisticated modeling techniques. In conclusion, upscaling the analysis to a catchment can guide sustainable land-use decisions and resource management by considering unique characteristics, incorporating data, and adapting the optimization model.

4. Conclusion

Understanding the connections between diverse resources in agriculture can lead to sustainable development. In this regard, the WEFC Nexus approach was made to control the interlinkage between water and energy consumption, food production, and CO_2 emission to meet these limited resources' sustainable development and future demands. This approach can be helpful for organizations and policymakers whose goal is the sustainable management of natural resources, and by formulating policies, it helps to allocate natural resources optimally to meet the needs of society.

An actual case study evaluated the impact of crop type, water, and energy usage on each cropping pattern and optimal condition. The result of the study indicated that attention to inter-linkages of the WEFC Nexus, along with implications for sustainable development and adaptation, must be considered in developing national policies and strategies. In conclusion, the results of this study suggest that the energy indicators of crop production, such as energy use efficiency, energy productivity, specific energy and net energy, can be used to assess the energy consumption and efficiency of crop production. Additionally, indirect energy had a larger share in the production of crops than direct energy and the agricultural sector is inefficient in consuming inputs, which will cause environmental problems such as global warming, greenhouse gas emissions, soil degradation, water pollution, biodiversity loss, waste generation, and land use change. Agricultural practices and policy recommendations should be adopted to increase economic efficiency and reduce energy consumption, such as promoting renewable energy sources, implementing energy-saving technologies, improving fertilizer and crop rotation management, practicing conservation tillage, and improving water management. Sustainable farming practices such as integrated pest management and organic farming can also be adopted to reduce energy consumption and emissions. The optimization result found that a multi-objective linear programming model should maximize the WEFC Nexus while minimizing water and energy resources and CO_2 emissions while achieving higher yields and profits. This approach can be used in different regions and under socio-economic and geographical constraints (climate, access to resources, food habits, population). It provides a decision-making tool to analyze the concept of the WEFC Nexus and develop strategies for optimal resource allocation.

Future research in this area could focus on collecting comprehensive data on energy consumption, CO2 emissions, water usage, and other factors in agriculture to improve optimization models and assessments. Additionally, exploring scalability, integrating additional sustainability factors, and involving stakeholders in decision-making would enhance the applicability and acceptance of sustainable cropping patterns.

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Table 1. Energy equivalents of inputs and outputs (Mj/unit) per unit area (ha)

Input		Unit	Energy equivalents (MJ unit^{-1})	Ref
Labor		h	1.96	[36]
Electricity		KWh	3.6	[28]
Machinery		h	62.7	[36]
Diesel oil		L	56.31	[36]
Chemical fertilizer	N	kg	66.14	[36]
	P	kg	12.44	[36]
	K	kg	11.15	[36]
Micronutrients		kg	120	[28]
Biocides	Pesticides	kg	101.2	[36]
	Fungicides	kg	216	[36]
	Herbicides	kg	238	[36]
Water for irrigation		m^3	0.63	[36]
Seed	Alfalfa	kg	28.1	[46]
	Barley	kg	14.7	[28]
	Silage corn	kg	14.7	[28]
	Potato	kg	3.6	[32]
	Rapeseed	kg	25	[35]
	Sugar beet	kg	50	[36]
	Wheat	kg	20.1	[28]
Output	Alfalfa	kg	15.8	[46]
	Barley	kg	14.07	[28]
	Silage corn	kg	2.25	[28]
	Potato	kg	3.6	[32]
	Rapeseed	kg	25	[35]
	Sugar beet	kg	16.8	[36]
	Wheat	kg	14.9	[28]

Table 2. CO_2 emissions equivalent of input and output per unit area (MJ ha^{-1})

Input		Unit	Carbon emissions equivalent (kg CO_2eq)	Ref
Electricity		KWh	0.0612	[48]
Machinery		h	0.071	[32]
Diesel oil		L	3.56	[49]
Chemical fertilizer	N	kg	3.1	[50]
	P	kg	1	[50]
	K	kg	0.7	[50]
Biocides	Pesticides	kg	5.1	[51]
	Fungicides	kg	3.9	[51]
	Herbicides	kg	6.3	[51]
Seed	Alfalfa	kg	2.63	[52]
	Barley	kg	0.11	[52]
	Silage corn	kg	1.05	[52]
	Potato	kg	0.33	[53]
	Rapeseed	kg	0.61	[54]
	Sugar beet	kg	3.54	[51]
	Wheat	kg	0.11	[52]

Table 3 Percentage of energy consumption and CO_2 emissions of products.

Products		Alfalfa		Barley		Silage corn		Potato		Rapeseed		Sugar beet		Wheat	
Input		Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %	Total energy input %	CO_2 emission %
Labor		0.1	-	0.1	-	0.1	-	0.05	-	0.07	-	0.07	-	0.08	-
Electricity		3.4	1.24	1.3	0.44	2.3	0.81	2.3	0.72	2.3	0.87	2.78	1.03	1.7	0.61
Machinery		14.6	0.35	7.2	0.16	10	0.24	9.6	0.2	10.3	0.25	11.9	0.29	8.5	0.2
Diesel Oil		35.4	47.49	36.4	46.75	28	37.64	21.9	25.5	28.9	39.92	29.3	40.18	34	45.74
Chemical Fertilizers	N	26.3	26.17	35.9	34.21	46.1	45.91	34.7	30	42.8	43.73	38.4	39.05	33.6	33.47
	P	3.3	5.63	4.5	7.36	1.7	2.96	3.3	4.84	2	3.53	2.9	5.04	4.2	7.2
	K	3	3.94	4	5.15	1.6	2.07	2.3	2.71	1.8	2.47	2.6	3.53	3.8	5.04
Micro		1	-	0.7	-	1.2	-	2.1	-	4.3	-	3.2	-	0.6	-
Biocides	Pesticides	0.2	0.19	0.3	0.3	0.9	0.92	0.16	0.15	0.3	0.36	0.1	0.13	0.3	0.28
	Fungicides	0.4	0.16	0.6	0.2	0.9	0.33	0.34	0.11	0.5	0.21	0.4	0.15	0.3	0.11
	Herbicides	2.7	1.54	1.1	0.58	1.1	0.61	0.37	0.18	0.5	0.31	1.2	0.67	1.2	0.66
Water for Irrigation		8.8	11.81	3.2	4.13	5.8	7.72	5.9	6.84	6	8.27	7.1	9.77	4.3	5.83
Seed		0.7	1.48	4.8	0.73	0.5	0.78	17	28.75	0.2	0.08	0.1	0.18	7.5	0.87
Total		100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 4 Total energy input in direct, indirect, renewable, and non-renewable energy for different productions.

Source	Unit	Alfalfa	Barley	Silage corn	Potato	Rapeseed	Sugar beet	Wheat
Total Energy Input	MJ ha^{-1}	75437	55207	71732	95257	61868	86149	59093
Total Energy Output	MJ ha^{-1}	237000	63315	101250	108000	75000	672000	74500
Energy Use Efficiency	-	3.14	1.15	1.41	1.13	1.21	7.8	1.26
Energy Productivity	Kg MJ^{-1}	0.20	0.08	0.63	0.31	0.05	0.46	0.08
Specific Energy	MJ Kg^{-1}	5.0	12.3	1.6	3.2	20.6	2.2	11.8
Net Energy	GJ ha^{-1}	161.6	8.1	29.5	12.7	13.1	585.9	15.4
Direct Energy [a]		35982	22626	25891	28656	23107	33822	23714
		(47.7%)	(41%)	(36.1%)	(30.1%)	(37.3%)	(39.3%)	(40.1%)
Indirect Energy [b]		39455	32581	45841	66601	38761	52327	35379
		(52.3%)	(59%)	(63.9%)	(69.9%)	(62.7%)	(60.7%)	(59.9%)
Renewable Energy [c]		7264	4473	4545	21841	3846	6301	7032
		(9.6%)	(8.1%)	(6.3%)	(22.9%)	(6.2%)	(7.3%)	(11.9%)
Non-Renewable Energy [d]		68173	50733	67187	73416	58022	79848	52061
		(90.4%)	(91.9%)	(93.7%)	(77.1%)	(93.8%)	(92.7%)	(88.1%)

a Human labor, diesel, electricity, and water

b Seeds, chemical fertilizers, herbicides, pesticides, fungicides, and machinery

c Human labor, seeds, and water

d Diesel, electricity, chemical fertilizers, herbicides, pesticides, fungicides, and machinery

Table 5 Solutions based on five individual objectives and optimal WEFC Nexus.

Nexus	TW	TE	TF	TP	TCO	Opt WEFC
Alfalfa (ha)	0	0	50	50	0	0
Barley (ha)	50	50	0	0	50	40
Silage corn (ha)	10	10	10	0	10	0
Potato (ha)	0	0	40	10	0	0
Rapeseed (ha)	50	50	0	40	50	50
Sugar beet (ha)	0	0	50	50	0	10
Wheat (ha)	40	40	0	0	40	50
Water (Mm^3 ha^{-1})	0.019	0.019	0.036	0.035	0.019	0.023
Energy (Gj ha^{-1})	247.9	247.9	328.6	318.7	247.9	262.3
Food (ton ha^{-1})	57.5	57.5	130	88	57.5	52.5
Profit ($ ha^{-1})	5215.6	5215.6	8648.1	8959.7	5215.6	6391.3
CO$_2$ (ton ha^{-1})	11.7	11.7	16.1	15.5	11.7	12.3
Total water use (Mm^3)	0.66	0.66	1.43	1.34	0.66	0.71
Total energy use (GJ)	8934.8	8934.8	12606.8	11506.5	8934.8	9117.8
Total food production (ton)	1025	1025	4400	3170	1025	980
Profit ($)	186036	186036	351112	356236	186036	203620
CO$_2$ emissions (ton)	422.6	422.6	616.6	541.2	422.6	429.2

Graphical Abstract

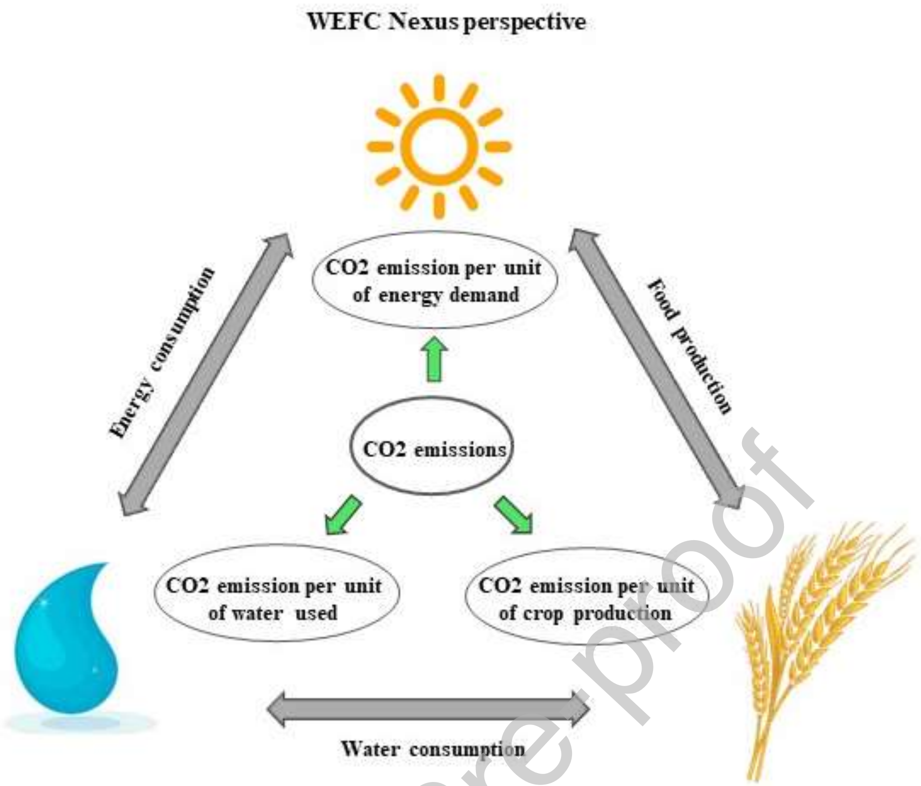


Fig 1 Optimization and perspective of Water-Food-Energy-Carbon Nexus

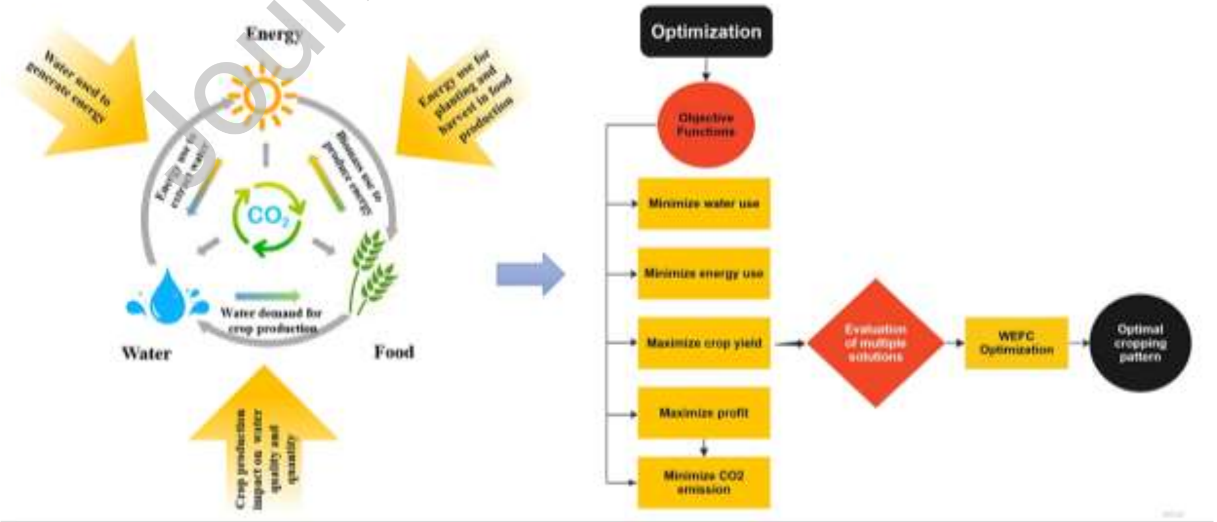


Fig 2 Geographical location of the study area. (a) location of the study farm (from Google Earth T.M. and ArcMap); (b) map of Iran indicating the layout of the study farm (Sahand Agro-Industry Co.)

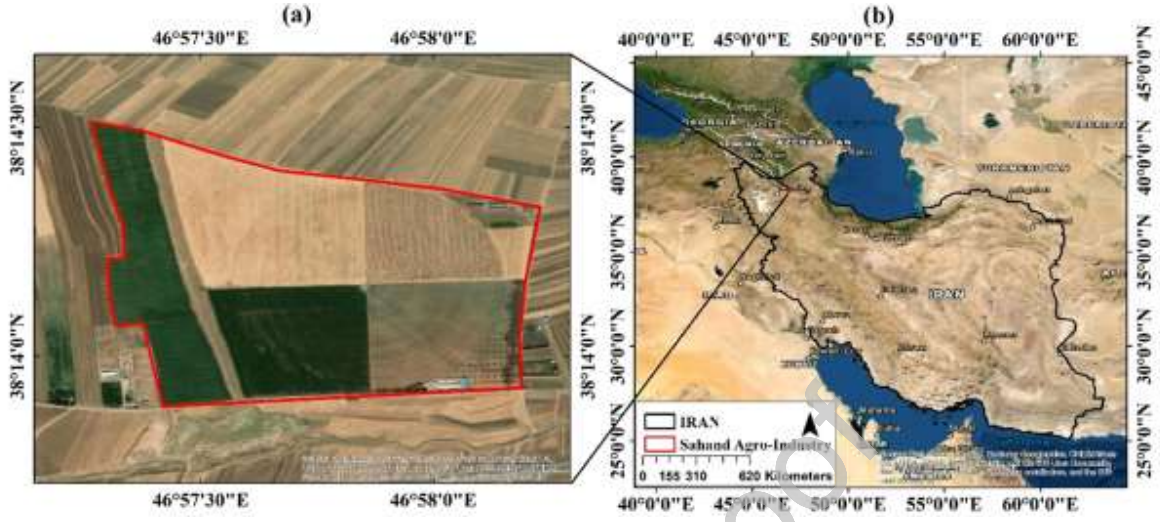
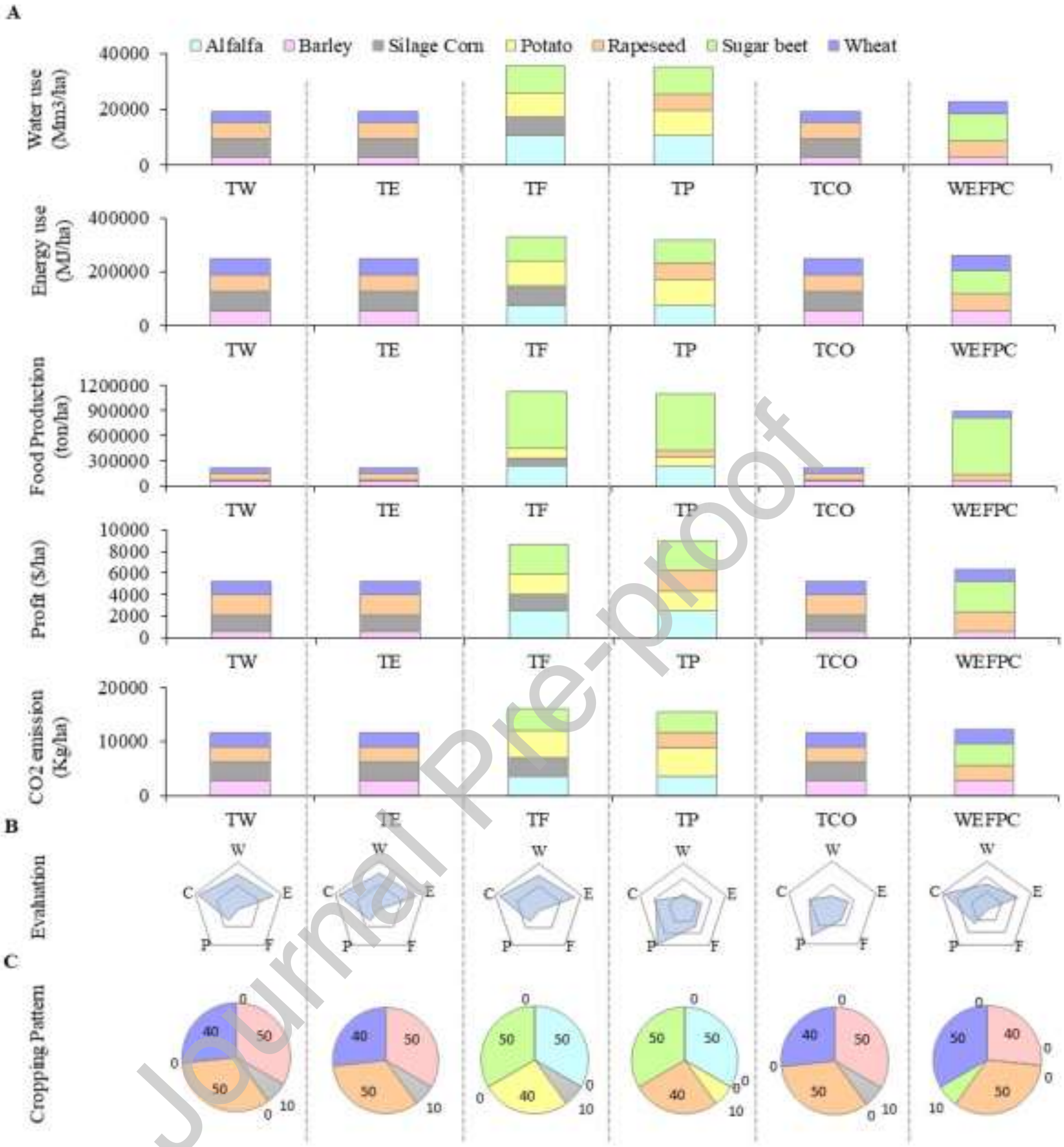


Fig 3 Solutions based on five individual objectives and WEFC Nexus; (A) the optimal relative values based on five objectives: TW (total water use), TE (total energy use), TF (total food production), TP (total profit), and TCO (total CO_2 emissions), (B) the results in the spider maps with five indexes, (C) the solutions of land allocation.



Author Contribution

Marzieh Hasanzadeh Saray: Methodology, Software, Writing-Original Draft, Resources, Formal analysis

Ali Torabi Haghighi: Conceptualization, Methodology, Validation, Supervision, Writing-Review & Editing

Declaration of interests

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

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