Received: 24 June 2022 | Revised: 17 September 2022 | Accepted: 3 October 2022

DOI: 10.1002/sd.2427

RESEARCH ARTICLE

Sustainable Development WILEY

Developing a new water–energy–food-greenhouse gases nexus tool for sustainable agricultural landscape management

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Abstract

A new comprehensive water, energy, food, greenhouse gas (WEFG) nexus index was developed to capture the interrelationships between them. A total of 11 indicators were applied to consider the interplay of resources consumption, productivity, economic issues, and carbon emission as one of the most critical issues regarding sustainable agricultural development. The proposed WEFG index was evaluated for crop pattern optimization. The results showed that the WEFG ranged from 0.162 to 0.658, which were calculated respectively for almonds and rice due to their energy consumption and carbon emission levels. The optimal cultivation pattern based on WEFG leads to 11% and 15.8% reductions in water and energy consumption, even with a 2.3% increase in cultivation area. The estimated profit for optimal pattern based on WEFG decreased by 13.67% due to lower cultivation levels of high-yield crops such as onion and potatoes. However, the optimal cultivation pattern based on the WEFG index has decreased greenhouse gas emissions by 2%, leading to sustainable agricultural management. Therefore, the presented WEFG nexus index can be a practical metric for sustainable planning and management in the agriculture sector.

KEYWORDS

crop pattern, economic productivity, energy, food nexus, greenhouse gas, index development, optimization, sustainable development, water

1 | INTRODUCTION

Limited access to water, food, and energy resources has been the most crucial global concern in recent decades (Mohtar & Daher, 2016; Ravar et al., 2020). It is expected that global demand for these essential resources for human societies will increase because of continuous population growth and socioeconomic development (El-Gafy et al., 2017; Ravar et al., 2020). Therefore, effective management of available resources is crucial to balancing supply and demand in the water, food, and energy sectors (El-Gafy et al., 2017; Sadeghi et al., 2020). Isolation policy-making for each sector with no attention to inter-linkages between these resources may entail unintended consequences that exacerbate the long-term problems. Tracking the interplay between water, food, and energy can be hence necessary to provide a holistic insight into how we can improve behavior towards more sustainability and how decisions based on changes in the environment, in turn, affect the state of the natural environment (Khan et al., 2021).

Several attempts have been made to study water–energy–food (WEF) nexus in different sectors, including urban areas (Cai et al., 2019; Chen & Chen, 2020; Chhipi-Shrestha et al., 2017; Schlör et al., 2018; Wang et al., 2017), agriculture (Bell et al., 2016; El-Gafy

et al., 2017; Li et al., 2019; Sadeghi et al., 2020; Smidt et al., 2016) and watershed systems (Elsayed et al., 2018; Ravar et al., 2020; Sadeghi et al., 2020; Spiegelberg et al., 2017). Due to the limited access to sufficient water and energy resources, food security has become one of the most important constraints for sustainable development, especially in arid regions worldwide (Erdogan, 2022; Torabi Haghighi et al., 2020; Webersik & Wilson, 2009; Zoveda et al., 2014). Recently, WEF Nexus has been widely used to improve agricultural productivity by optimizing the cropping patterns (El-Gafy, 2017; El-Gafy et al., 2017; Jagadeesh & Sampath, 2020; Kaur et al., 2010; Negm et al., 2006; Sadeghi et al., 2020).

Nowadays, manufactured greenhouse gas emissions resulting from industrialization and urbanization have contributed to climate change. Climate change alters the Earth's atmosphere system leading to plausible changes in the global hydrological cycle, especially the precipitation levels and patterns (Solomon, Dahe et al., 2007; Stocker, 2014). Frequent exposure to climate change, including floods and droughts with amplified frequency, hinders agricultural productivity, raises concerns about its impact on future food production, and jeopardizes food security, especially in developing countries (Ribeiro et al., 2021). Therefore, the sustainable management of natural resources is essential to mitigate the climate change impacts (Roberts & Finnegan, 2013).

One of the most critical issues regarding sustainable agriculture is greenhouse gases emissions from agricultural activities (Behan & McQuinn, 2004; Platis et al., 2019). The industrialization of agriculture and the excessive utilization of fertilizers, pesticides, and other high-energy inputs such as fossil fuels, electricity, and machinery have dramatically accelerated greenhouse gas emissions (Li et al., 2016). The most important sources of greenhouse gases emission in the agriculture sector are known fossil fuels, tillage, incineration, and fertilizer. About 11% of global greenhouse gas emissions account for agriculture's energy sector (Solomon, Qin et al., 2007). Therefore, optimal land, energy, and water operation are essential to increase crop productivity with minimum greenhouse gas emissions in agricultural systems. Reviewing of existing research shows that, so far, achieving the optimal use of resources by considering economic and social issues has been widely discussed in agricultural policies (El-Gafy, 2017; El-Gafy et al., 2017; Ravar et al., 2020; Sadeghi et al., 2020). Despite the great importance of greenhouse gas emissions, little attention has been focused on greenhouse gases emission from agricultural activities (Duxbury, 1994; Fan et al., 2020; Gan et al., 2020; Mohammed et al., 2020; Rebolledo-Leiva et al., 2017).

Analyzing the water–energy–food-greenhouse gases (WEFG) nexus can improve the behavior towards sustainability and how decisions based on changes in the environment affect the state of the natural environment. In the present study, an integrated nexus index is presented to regulate the cultivation pattern of crops using the WEFG nexus concept. The presented WEFG nexus index can be a practical metric for optimal management of water, food, and energy resources, considering the amount of greenhouse gas emissions. Therefore, the proposed index can be a desirable indicator for long-term planning in the agriculture sector. The Zayendeh-Rud River basin as a water-limited basin in Central Iran, has been selected as a test case to evaluate this index. The main objectives of this study include: (1) developing an integrated WEFG nexus index to approach sustainable resources management in the agricultural sector; (2) optimizing the crop pattern in the test case based on the proposed WEFG nexus index and comparing the results with the Water-Energy-Food Nexus Index (WEFNI) proposed by El-Gafy et al., 2017.

2 | METHOD

This study presents an integrated criterion for the interrelationship of WEFG to minimize water consumption, energy resource, and greenhouse gas emissions in the agriculture sector. The main steps of this study include (1) proposing 11 indicators to capture the relationships between water, food, energy, and greenhouse gas emission in agricultural activities; (2) developing an integrated WEFG nexus index based on the mentioned 11 indicators and (3) optimizing the cultivation pattern based on the developed WEFG nexus index to compare with WEFNI developed by El-Gafy et al., 2017 (El-Gafy et al., 2017).

2.1 | Study area

Zayandeh-Rud River Basin has an area of 26,917 km^2 and is part of the Central Plateau Basin of Iran (Gohari et al., 2013). It is extended between 50° 2′ to 53° 24′ E and 31° 12′ to 33° 42′ N, as shown in Figure 1. The highest area of the Zayendeh-Rud River basin is Karbush Mount, with an altitude of 3974 m above sea level and the lowest point is Gav-khoni swamp, with an altitude of 1450 m (Hajian & Hajian, 2015). In terms of climate, the Chelgerd area located on the west side of the basin has an average annual rainfall of more than 1400 mm, while in the east, next to the Gav-khoni swamp, the average annual rainfall is about 50 mm (Gohari et al., 2013).

This area is one of Iran's most densely populated industrial basins. Food supply depends on agriculture, so agriculture is vital for this region. After the Zayandeh-Rud Reservoir construction and the improvement of modern irrigation and drainage networks, numerous inter-basin water transfer projects have been implemented to solve the water shortage problem. Such water resource development projects have led to agricultural development and higher water demand in this sector (Ravar et al., 2020; Sharifi et al., 2021). The Zayendeh-Rud River has an average flow of about 1400 MCM per year, including 46% natural flow and 54% transferred flow. More than 73% of water resources in the basin are allocated for agricultural activities in six irrigation networks, including Abshar, Nekuabad, Rudasht, Mahyar-Jarghuyeh, Borkhar, and Traditional networks (Gohari et al., 2013). About 20% of electricity consumption is also related to the agricultural sector (Statistical Yearbook System, 2018), which is due to the change in the type of applied pump motors from diesel to electric.

As the climatic condition (i.e., rainfall) is different across the basin, a wide range of crops and horticulture products are cultivated. In this study, eight main traditional staple irrigated crops (wheat, barley,

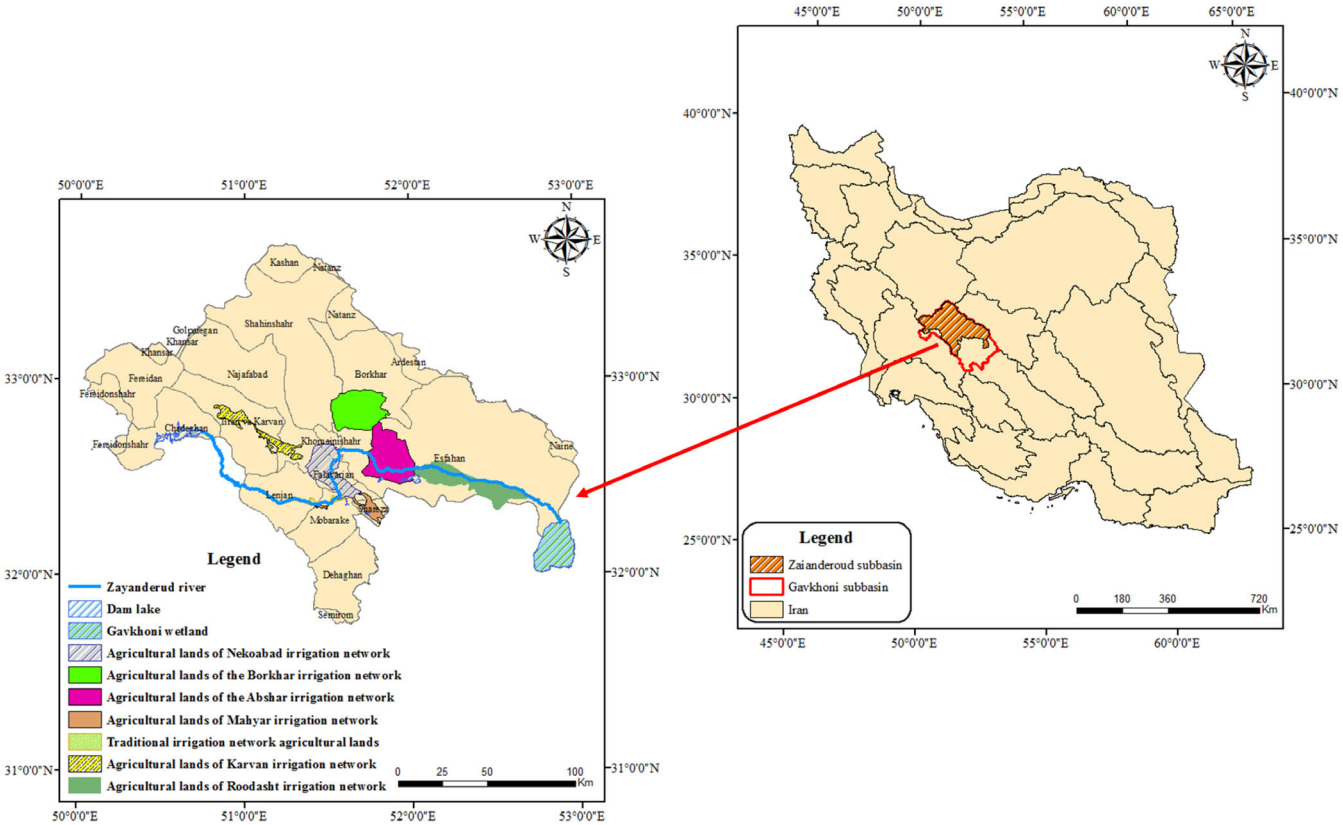

FIGURE 1 The location of the Zayendeh-Rud River basin. [Colour figure can be viewed at wileyonlinelibrary.com]

silage corn, potatoes, alfalfa, onions, rice, and almonds) cover about 65% of the total cultivation area considered. Table 1 presents the crop coverage percentages and crop yield from 2015 to 2019.

2.2 | WEFG nexus index

In this study, 11 different indicators were applied to consider the interplay of resources consumption, productivity, economic issues, and greenhouse gas emission in farming activities (Figure 2).

2.2.1 | Consumption indicators

1. Indicator 1: Water consumption indicator (WC): Water consumption indicator ($W_{[c,\ t]}$) is the amount of water consumed per hectare of crop c cultivation at time t. In this study, the NetWat dataset (Mirzaei et al., 2019; Sadeghi et al., 2020) was used to calculate the irrigation water requirement of different crops according to irrigation efficiency in the case study. NetWat is the national dataset of crops and horticulture water requirements for Iran.
2. Indicator 2: Energy consumption indicator (EC): Energy consumption indicator ($E_{[c,\ t]}$) is the amount of energy (MJ) consumed per hectare of crop c cultivation at time *t*. The required energy for crop production can be categorized as direct and indirect. Direct energy consumption includes fossil fuels and electricity. Indirect energy consumption can be defined as the energy equivalent of fertilizer, herbicides, pesticides, fungicides, agricultural machinery, seeds, and human labor. The energy consumption indicator is calculated using Equation (1).

$$E_{c.t} = \sum q_h h_{(c.t)} + q_m m_{(c.t)} + q_d d_{(c.t)} + q_f f_{(c.t)} + q_p p_{(c.t)} + q_s s_{(c.t)} + q_w W_{(c.t)} \quad (1)$$

where, $q_h, q_m, q_d, q_f, q_p, q_s,$ and q_w are the energy equivalents of human labor (MJ/h), agricultural machinery (MJ/h), fossil fuels (diesel oil) (MJ/L), fertilizer (MJ/kg), pesticides and herbicides (MJ/kg), seeds (MJ/kg), and water (MJ/m^3), per hectare respectively. $h_{(c.t)}, m_{(c.t)}, d_{(c.t)}, f_{(c.t)}, p_{(c.t)}, s_{(c.t)}, and\, w_{(c.t)}$ are respectively working hours of human labor (h/ha), agricultural machinery (h/ha), fossil fuel (L/ha), fertilizer (kg/ha), pesticides and herbicides (kg/ha) seeds (kg/ha) and irrigated water (m^3/ha) inputs for crop c cultivation at time *t* (El-Gafy, 2017).

2.2.2 | Carbon emission indicators

The main greenhouse gases are methane, nitrogen dioxide, and carbon dioxide. In this study, various greenhouse gas emissions were calculated as equivalent to CO_2. The effect coefficient for each greenhouse gas for 100 years is 1 for CO_2, 310 for N_2O, and 21 for CH_4 (Smith et al., 2007).

TABLE 1 The cultivation area and yields of selected crops (2015–2019) and changes in crop coverage and consumed resources for each crop (2005–2019).

Crop	Yield of crops (tons/hectare) (Crop and Horticultural Statistics, 2020)					Percentage of crop coverage (Crop and Horticultural Statistics, 2020)					Area (ha) (Crop and Horticultural Statistics, 2020)		Energy consumption (MJ)		Water consumption (MCM)		Carbon emission (tons)	
	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019	Max	Min	Max	Min	Max	Min	Max	Min
Wheat	4.37	4.82	4.30	4.42	4.40	23.80	24.88	23.61	15.35	10.49	62,430	25,217	5,391,328,207	2,177,688,986	400	161.38	230,441	93,081
Barley	3.72	4.25	4.18	4.05	4.34	15.04	12.90	11.64	12.09	7.65	34,925	19,858	2,298,204,957	1,306,739,720	174.62	99.3	100031.5	56,877
Silage corn	56.04	56.81	58.56	57.00	62.66	7.87	6.88	6.55	7.24	5.12	18,565	11,896	1,551,559,336	994,201,447	125.73	80.5	71,012	45502.8
Potatoes	28.46	28.54	30.48	32.16	34.13	6.77	6.20	6.08	6.24	8.18	14,800	10,251	4,264,274,694	2,953,442,416	128.168	88.76	72384.3	50133.45
Alfalfa	10.77	10.84	11.09	10.95	11.06	8.86	8.70	9.00	10.61	2.08	19,830	17,430	1,601,216,183	1,407,422,999	214.42	188.47	57017.2	50116.48
Onion	69.91	61.99	62.32	75.00	67.46	2.00	1.83	1.83	2.41	2.19	5044	3328	632,860,378	417,598,758	53.4	35.23	34146.16	22531.66
Almond	0.98	1.28	1.35	1.07	1.30	2.60	2.52	2.55	3.17	2.80	5915	5158	393,658,740	343,274,148	49.94	43.54	14017.36	12223.28
Rice	5.57	5.78	5.70	5.27	5.76	2.43	2.04	2.21	0.66	23.20	6789	1089	956,725,111	153,512,289	108.63	17.43	43180.45	6928.56

1. Indicator 3: Carbon emission from energy consumption (CEE): Carbon emission of energy consumption ($CE_{c,t}$) indicator is the amount of carbon dioxide emission (kg) because of direct energy consumption (fossil fuels and electricity) per hectare of crop c, at time t. Table 3 presents the carbon dioxide equivalent (kg) per unit consumption of fossil fuel and electricity (Equation 2).

$$CE_{c.t} = \sum c_e e_{(c.t)} + c_d f_{(c.t)} \tag{2}$$

Where, c_d and c_e are the emitted carbon dioxide for fossil fuels (diesel oil) (kg/L) and electricity (kg/kWh), respectively, for crop c per hectare at time t. $f_{(c.t)}$ and $e_{(c.t)}$ are the fossil fuel (L/ha) and electricity (kWh/ha) inputs in crop c production at time t.

2. Indicator 4: Carbon emission indicator of production crop (CEP): Carbon emission indicator of production crop ($CF_{c,t}$) is the amount of carbon dioxide emission for indirect energy consumption per hectare of crop c at time t (Table 3). This indicator was calculated using Equation (3).

$$CF_{c.t} = \sum c_m m_{(c.t)} + c_f f_{(c.t)} + c_h h_{(c.t)} + c_s s_{(c.t)} \tag{3}$$

Where, c_m, c_f, c_h, and c_s are the emitted carbon dioxide of agricultural machinery (kg/h), fertilizer (kg/kg), pesticides and herbicides (kg/kg), and seeds (kg/kg) inputs in crop c production per hectare. $m_{(c.t)}, f_{(c.t)}, h_{(c.t)}$, and $s_{(c.t)}$ are agricultural machinery (h/ha), fertilizer (kg/ha), pesticides (kg/ha), and seeds (kg/ha) inputs in crop c production.

2.2.3 | Productivity indicators

1. Indicator 5: Water mass productivity indicator (WMP): Water mass productivity ($W_{pro.t}$) for crop c, at time t, was calculated using Equation (4).

$$W_{pro.t} = Y_{c.t} / w_{c.t} \tag{4}$$

Where, $Y_{c.t}$ is the yield of crop c per hectare (ton/ha) at time t, and $w_{c.t}$ is the water consumption per hectare (m^3/ha) of crop c at time t (El-Gafy, 2017). Indeed, WMP is defined as the amount of crop (ton/ha) produced by using 1 (m^3/ha) gross water. In this research, the water consumption is the same as the gross irrigation requirement, which is obtained as dividing the net irrigation requirement by the irrigation efficiency.

2. Indicator 6: Energy mass productivity indicator (EMP): Energy mass productivity indicator ($E_{pro.t}$) for crop c at time t was calculated using Equation (5) (El-Gafy, 2017).

$$E_{pro.t} = Y_{c.t} / E_{c.t} \tag{5}$$

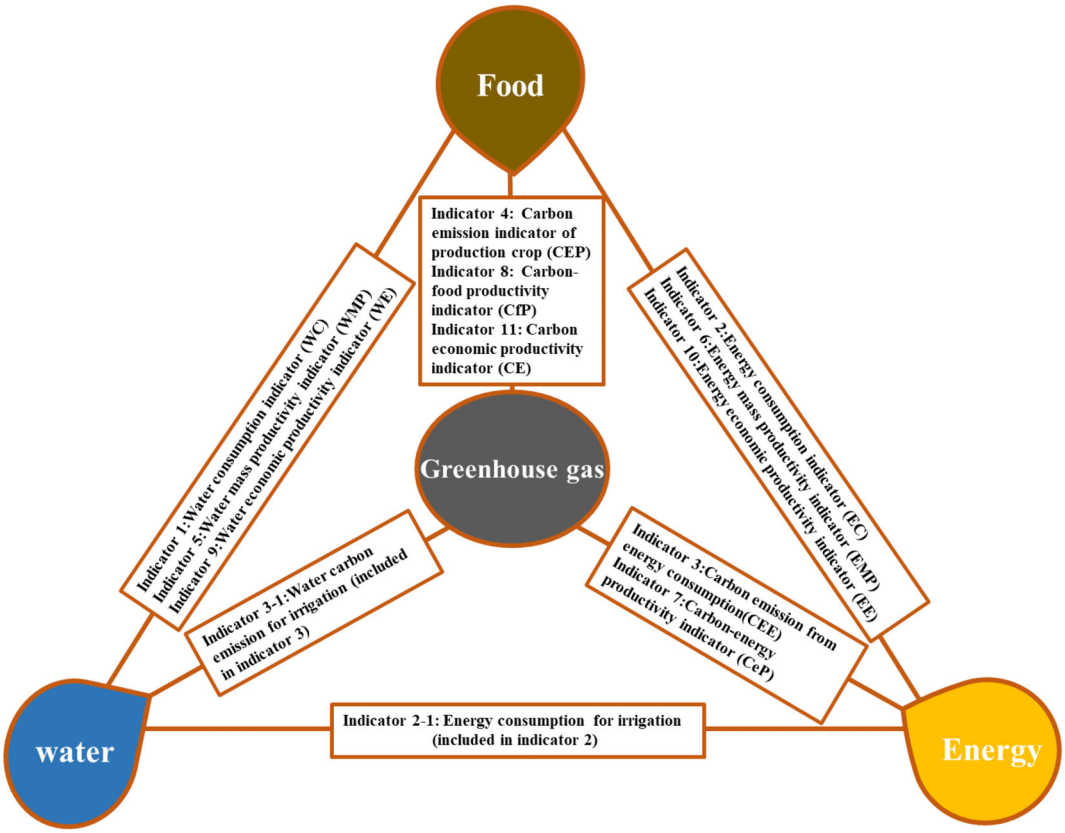

FIGURE 2 Assessment method of water, food, energy, and greenhouse gas nexus. [Colour figure can be viewed at wileyonlinelibrary.com]

Where, $Y_{c.t}$ is the yield of crop c per hectare (ton/ha) at time t and $E_{c.t}$ is the energy consumption per hectare (MJ/ha) of crop c at time t (El-Gafy, 2017).

3. Indicator 7: Carbon-energy productivity indicator (CeP): Carbon-energy productivity indicator ($CE_{pro.t}$) for crop c, at time t, was calculated using Equation (6).

$$CE_{pro.t} = E_{c.t}/CE_{c.t} \tag{6}$$

where, $E_{c.t}$ is the energy consumption of crop c per hectare (MJ/ha) at time t and $CE_{c.t}$ is the carbon dioxide emitted by direct energy consumption per hectare (kg/ha) for crop c, at time t.

4. Indicator 8: Carbon-food productivity indicator (CfP): Carbon-food productivity indicator ($CF_{pro.t}$) for crop c, at time t, was calculated using Equation (7).

$$CF_{pro.t} = CM_{c.t}/CF_{c.t} \tag{7}$$

where, $CM_{c.t}$ the consumption of fertilizer, pesticides, and seeds for crop c per hectare (kg/ha), at time t and $CF_{c.t}$ is the carbon dioxide emitted by indirect energy consumption per hectare (kg/ha) of crop c, at time t.

2.2.4 | Economic productivity indicators

1. Indicator 9: Water economic productivity indicator (WE): The economic irrigation water productivity ($E_{EV.t}$) at time t, for crop c was calculated as follows (Equation 8).

$$W_{EV.t} = N_{c.t}/w_{c.t} \tag{8}$$

where, $N_{c.t}$ is net profit (profit minus cost) of production for crop c per hectare (Rial/ha) (Hailemariam et al., 2019).

2. Indicator 10: Energy economic productivity indicator (EE): Energy economic productivity ($E_{EV.t}$) at time t, for crop c, was calculated using Equation (9) (Hailemariam et al., 2019).

$$E_{EV.t} = N_{c.t}/E_{c.t} \tag{9}$$

3. Indicator 11: Carbon economic productivity indicator (CE): The economic productivity of carbon ($C_{EV.t}$) at time t, for crop c, was calculated using Equation (10).

$$C_{EV.t} = N_{c.t}/(CE_{c.t} + CF_{c.t}) \tag{10}$$

2.2.5 | Water, energy, food, and greenhouse gas nexus index

In the current study, the aforementioned indices were combined to develop an integrated WEFG nexus index as Equation (11):

$$WEFG = \sum_{i=1}^{n} w_i X_i / \sum_{i=1}^{n} w_i \tag{11}$$

As the values of the applied indicators were presented in different units, it is necessary to normalize the above indices before using Equation 11. According to their positive or negative impacts, Equations (12) and (13) were used to normalize each indicator, respectively.

$$X_i = (x_i - Min(x_i))/(Max(x_i) - Min(x_i)) \tag{12}$$

$$X_i = (Max(x_i) - x_i)/(Max(x_i) - Min(x_i)) \tag{13}$$

where X_i is the value for indicator i that defined above, and $Max(x_i)$ and $Min(x_i)$ are the maximum and the minimum thresholds of the indicator i. The values of the WEFG index vary between 0 and 1; the closer values to 1 indicate the optimal state in the study area. In Equation (11), w_i is the weight taken for each indicator, which according to the concept of WEFG nexus for the same view of all effective parameters, the mentioned coefficient is considered the same for all, so the mentioned equation becomes arithmetic mean.

2.3 | WEFNI index

According to El-Gafy, 2017, 6 different indicators including WC (Indicator 1), EC (Indicator 2), WMP (Indicator 5), EMP (Indicator 6), WE (Indicator 9), *EE* (Indicator 10) were applied to consider the interplay of resources consumption, productivity, and economic issues. These 6 indices were combined to develop an integrated WEFNI index by using Equation (11).

2.4 | Optimization

In order to present an optimal cultivation pattern, the WEFG nexus index and WEFNI (El-Gafy et al., 2017) was applied through a linear optimization. The objective function (Equation 14) was defined to maximize the WEFG index or WEFNI and compare the results. In addition, the constraints include water constraint (Equation 15), energy constraint (Equation 16), cultivated land constraint (Equation 17), and the limitation of carbon emissions (Equation 18).

$$Max\, z = \sum_{i=1}^{n} WEFG_i \times A_i \tag{14}$$

$$\sum_{i=1}^{n} A_i \le A_{(a,t)} \tag{15}$$

$$\sum_{i=1}^{n} W_i \times A_i \le W_{(a,t)} \tag{16}$$

$$\sum_{i=1}^{n} E_i \times A_i \le E_{(a,t)} \tag{17}$$

$$\sum_{i=1}^{n} C_i \times A_i \le C_{(a,t)} \tag{18}$$

Equation (14) is the objective function, which, taking into account the WEFG calculated for each crop, makes it possible to calculate the optimal crop area (A_i) for crop i, so this function reaches its maximum value. The optimization consists of two constraints (1) to examine the sum of areas (A_i) that are less than land available for agriculture ($A_{(a,t)}$) (Equation 15) and (2) to check the available water limit ($W_{(a,t)}$) by considering the water consumption (W_i) and the area cultivation (A_i) of each crop (Equation 16). In Equations 17 and 18, E_i, and C_i are respectively energy consumption and carbon released to produce crop i, which is limited by less than the current level ($E_{(a,t)}, C_{(a,t)}$). The optimization process was executed separately in MATLAB for the WEFG and WEFNI indices.

The cultivation area of the main traditional staple crops of the Zayandeh-Rud River Basin from 2005 to 2019 was surveyed. The calculated water and energy consumption as emitted carbon dioxide are given in Table 1.

3 | RESULTS AND DISCUSSION

3.1 | Water and energy consumption

Water and energy consumption indicators were calculated, and irrigation water inputs and energy consumption for a hectare in the production system were shown in Figure 3a. The results showed that rice/barley consume the biggest/least amount of water. In general, barley, wheat and corn silage are crops with less water requirement.

Potatoes and rice have the highest indirect and direct energy consumption, respectively. In general, potatoes, rice, onions, wheat, silage corn, alfalfa, almonds, and barley were the largest energy consumers in the production process, respectively (Figure 3a).

As groundwater is the main water resource for irrigation in the study area, increasing water consumption requires more energy to pump water (indicator 1–1 in Figure 2), leading to higher direct energy consumption. Energy production also requires water. These connections represent the interrelationship between water and energy resources and the concept of nexus.

According to Figure 4, the indirect using of energy sources is more than 50% of the total energy consumption for wheat, barley, alfalfa, silage corn, onion, potato, and almond productions. However,

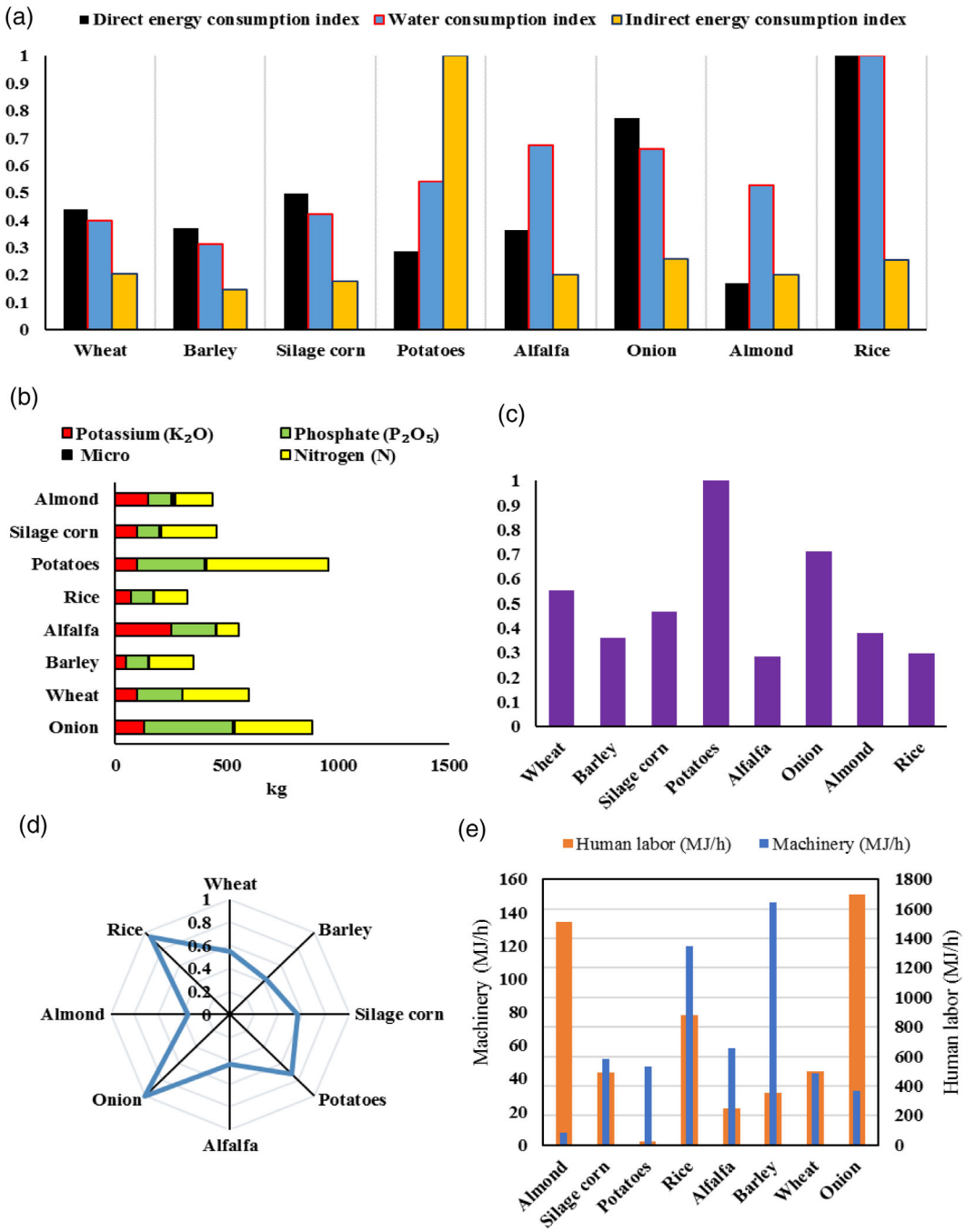

FIGURE 3 Consumption to produce per hectare of crops and carbon emissions from their cultivations in 2019. (a) Water and energy consumption (relative to the maximum values); (b) Fertilizers consumption; (c) Fertilizer energy consumption (relative to the maximum values); (d) The contribution of each crop in carbon emissions equivalent to greenhouse gases (relative to the maximum value), (e) Human labor and machinery consumables. [Colour figure can be viewed at wileyonlinelibrary.com]

rice's direct energy consumption is the highest because of high fossil fuel consumption, while almonds have the lowest fossil fuel consumption. The amount of fossil fuel consumption varies between the different agricultural operations and required agricultural machinery (Hasanzadeh Saray et al., 2022).

As explained in the indicators, indirect energy includes the energy of human labor, machinery, fertilizers, and pesticides; electricity and diesel oil are known as direct energy consumption (Figure 4). The most considerable indirect energy consumption is fertilizer and irrigation in most crops (i.e., wheat, barley, silage, almonds, potatoes, onions, alfalfa, and rice) (Figure 4). For example, 80% of the energy used to produce potatoes is indirect energy, and fertilizer consumption accounts for about 50% of this indirect consumption. The fertilizers used for crops production (Figure 3b and Table 2) were divided into four categories, including potassium, phosphate, nitrogen, and micro; for each unit, the amount of energy

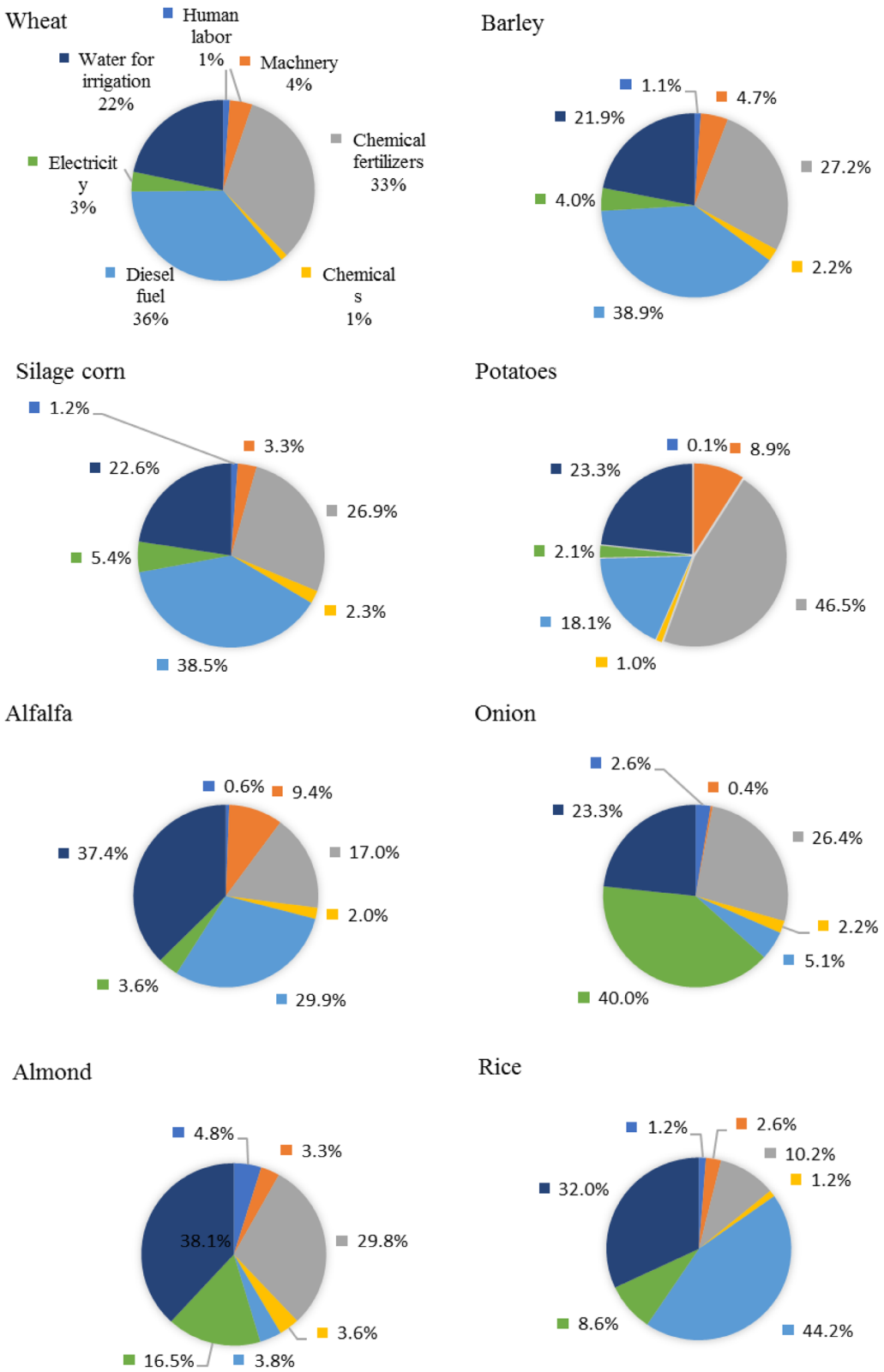

FIGURE 4 The share of agricultural inputs in total energy consumption for agricultural production in 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

consumed is defined; most of this amount is first related to micro (120 MJ/kg) and then to nitrogen (75.46 MJ/kg). Out of eight crops, potatoes and rice have the maximum and minimum fertilizer consumptions, respectively (Figure 3b). According to Figure 3c, the energy consumption through fertilizer for rice and alfalfa is almost equal (rice a little more), while the fertilizer requirement of alfalfa

TABLE 2 Energy footprint of inputs in the production of agricultural in Zayandeh-Rud River basin.

Input	Unit	Energy equivalent (MJ/unit)	References
Human labor	h	1.95	(Zahedi et al., 2015)
Machinery	h	62.7	(Zahedi et al., 2015)
Diesel fuel	L	50.23	(Zahedi et al., 2015)
Chemical fertilizers			
Nitrogen (N)	kg	75.46	(Zahedi et al., 2015)
Phosphate (P_2O_5)	kg	13.07	(Zahedi et al., 2015)
Potassium (K_2O)	kg	11.15	(Zahedi et al., 2015)
Micro	kg	120	(Zahedi et al., 2015)
Chemicals			
Herbicides	L	238.32	(Zahedi et al., 2015)
Pesticide	L	101.2	(Zahedi et al., 2015)
Fungicide	kg	181.9	(Zahedi et al., 2015)
Electricity	kWh	3.6	(Zahedi et al., 2015)
Water for irrigation	m^3	1.02	(Zahedi et al., 2015)
Seeds			
Wheat	kg	20.1	(Zahedi et al., 2015)
Barely	kg	14.7	(Zahedi et al., 2015)
Silage corn	kg	14.7	(Zahedi et al., 2015)
Potato	kg	53	(Sadeghi et al., 2020)
Alfalfa	kg	10	(Sadeghi et al., 2020)
Onion	kg	14.7	(Sadeghi et al., 2020)
Almond	kg	24.08	(Sadeghi et al., 2020)
Rice	kg	14.7	(Zahedi et al., 2015)

TABLE 3 Carbon dioxide equivalent for agricultural processes.

Input	Unit	Carbon emission (kg/unit)	References
Machinery	h	0.071	(Pishgar-Komleh et al., 2015)
Diesel fuel	L	3.56	(Kramer et al., 1999)
Electricity	kwh	0.0612	(Tzilivakis et al., 2005)
Chemical fertilizers			
Nitrogen (N)	kg	3.1	(Snyder et al., 2009)
Phosphate (P_2O_5)	kg	1	(Snyder et al., 2009)
Potassium (K_2O)	kg	0.7	(Snyder et al., 2009)
Chemicals			
Herbicides	L	6.3	(Šarauskis et al., 2018)
Pesticide	L	5.1	(Šarauskis et al., 2018)
Fungicide	kg	3.9	(Šarauskis et al., 2018)
Seed			
Wheat	kg	0.11	(West & Marland, 2002)
Barely	kg	0.11	(West & Marland, 2002)
Silage corn	kg	1.05	(West & Marland, 2002)
Potato	kg	0.33	(Holmes et al., 2010)
Alfalfa	kg	2.63	(West & Marland, 2002)
Onion	kg	3	(Adewale et al., 2016)
Almond	kg	1.92	(Volpe et al., 2015)
Rice	kg	0.58	(Zhang et al., 2021)

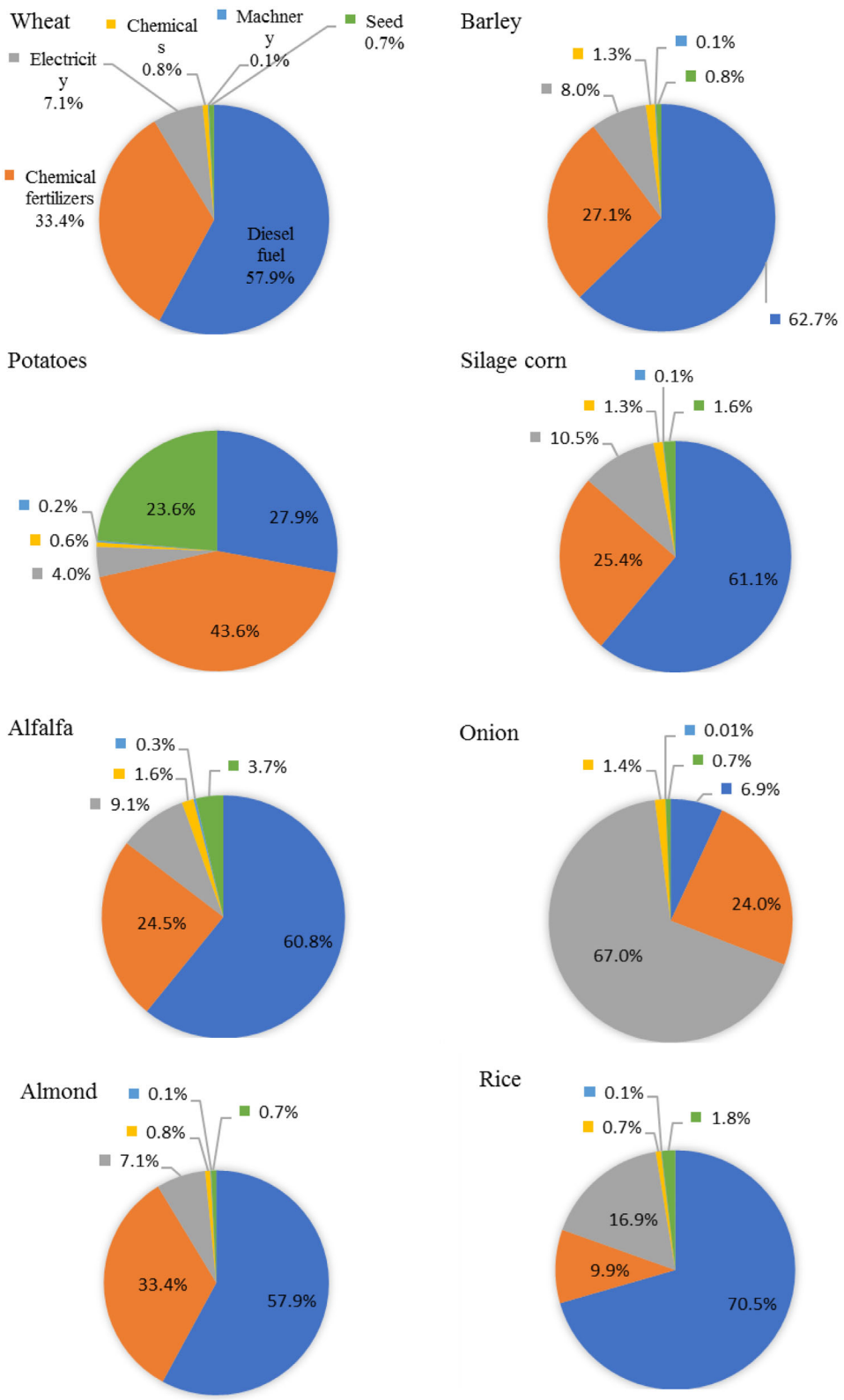

FIGURE 5 Share of agricultural inputs for greenhouse gas emissions for crop production in 2019. [Colour figure can be viewed at wileyonlinelibrary.com]

(555 kg) is more than rice (350 kg). The reason for this difference is related to the type of consumption. Since more nitrogen and micro fertilizers are used to produce rice.

Figure 4 shows the energy consumption inputs per crop in a hectare. The results indicated that the shares of fertilizer in energy consumption for rice and alfalfa were 10% and 17%, respectively, which has

TABLE 4 Values of the WEFG and WEFNI (El-Gafy, 2017) indices and the normalized values of different indicators applied in the WEFG nexus index for the selected crops.

Crop	EC	WC	CEE	CEP	EMP	WMP	CeP	CfP	EE	WE	CE	WEFG	WEFNI
Almond	0.997	0.687	1.000	0.811	0.000	0.000	0.914	0.000	1.000	0.716	1.000	0.658	0.520
Silage corn	0.920	0.839	0.525	0.887	1.000	1.000	0.026	1.000	0.077	1.000	0.043	0.526	0.806
Onion	0.732	0.492	0.768	0.628	0.709	0.683	0.357	0.664	0.297	0.202	0.306	0.436	0.519
Barley	1.000	1.000	0.657	0.984	0.064	0.078	0.033	0.074	0.007	0.733	0.004	0.399	0.480
Potatoes	0.000	0.667	0.757	0.000	0.136	0.416	1.000	0.162	0.060	0.165	0.122	0.361	0.241
Alfalfa	0.933	0.472	0.666	0.974	0.161	0.096	0.085	0.208	0.067	0.025	0.054	0.16	0.292
Wheat	0.908	0.873	0.577	0.807	0.043	0.059	0.054	0.042	0.005	0.014	0.000	0.297	0.317
Rice	0.662	0.000	0.000	1.000	0.029	0.023	0.000	0.110	0.000	0.000	0.001	0.162	0.119

more influence than other factors. In other words, even though rice consumes more energy through fertilizer than alfalfa, the leading share of rice energy consumption is related to irrigation water and direct energy.

According to Figures 4 and 3e, more agricultural machinery reduces human labor and energy equivalents. It should be noted that 1 h of machine work is equivalent to several hours of human labor, so these two parameters were significantly different in Figure 3e.

3.2 | Carbon dioxide emission

Different agricultural activities (i.e., fertilization and pesticide application) emit different amounts of greenhouse gases (Table 3). Fossil fuels, electricity, and chemical fertilizers significantly contribute to greenhouse gas emissions, which vary between different crop products (Figure 5). Fossil fuels for barley, wheat, silage corn, alfalfa, and rice have the most carbon-emission, while fertilizers in potatoes and electricity in onions and almonds are the leading causes of carbon emissions. Due to the lower consumption of chemicals compared to other cases, crop spraying had a minor effect on carbon emissions (Figure 5). According to the share of each crop in carbon emissions (Figure 3d), almond/ onion and rice have the lowest/most carbon emissions and contributions to global warming.

3.3 | WEFG nexus index

Each indicator of the WEFG nexus was calculated for eight main traditional staple crops (Table 4). Barley and wheat have the lowest water consumption; thus, their normalized water consumption and energy indices have high scores (close to 1), while potatoes have high energy consumption and the lowest score accordingly. Due to having high required water, rice's growing environment is different from the other crops. In addition to considerable water demand during the growing season, a significant amount of water is also required to prepare and flood the paddy land before transplanting (Pimentel et al., 1997). Therefore, the least score on the water consumption indicator belonged to rice.

Despite the high score of consumption indicator for almonds, the water and energy-mass productivity indices of this crop are the lowest. The water and energy-mass productivity indices are the highest for silage corn, related to the crop yield per hectare. The almonds' low water/energy mass productivity indices revealed low production per consumed water/energy unit.

The lowest and highest carbon emission values were calculated for almonds (low direct energy consumption) and potatoes and rice (high indirect and direct energy consumption). However, rice has the least carbon emissions than other crops through the lower consumption of agricultural inputs such as fertilizers, pesticides, and fungicides. In addition, the rice seed release low carbon compared to the other crops. In contrast, the high carbon emissions of potatoes are justified due to high indirect energy consumption through high fertilizer consumption and the need for a large number of seeds. According to Table 3, although potato seeds release low carbon, their overall carbon emission is high due to the high number of required seeds. However, due to the high potato production yield, potatoes' carbon-energy productivity is the highest, while rice has the lowest score on this indicator. Silage corn has a high yield, and the emitted carbon due to its indirect energy is also relatively low, so it has the highest carbon-food productivity indicator, and almond has the lowest score.

Selling almonds is more economically profitable than other crop products, and energy consumption and carbon emissions for its production are lower than other products, so the economic productivity of almonds in both carbon emissions and energy consumption compared to others is the highest.

The WEFG and WEFNI indices ranged from 0.162 (rice) to 0.658 (almond) and 0.119 (rice) to 0.806 (silage corn), respectively (Figure 6a). Among the eight crops, silage corn, almonds, and barley consume less water and energy than others (Table 4).

Although the yield of silage corn is higher, almonds had a higher score in the WEFG index due to less greenhouse gas emissions. In this study, almond and silage corn consume less water and energy, so their low greenhouse gas emission influenced their general ranking. Almond emits fewer greenhouse gases (Figure 5) because of low direct energy consumption in the growth stages. Additionally, the economic productivity of almonds in both carbon emissions and energy consumption is

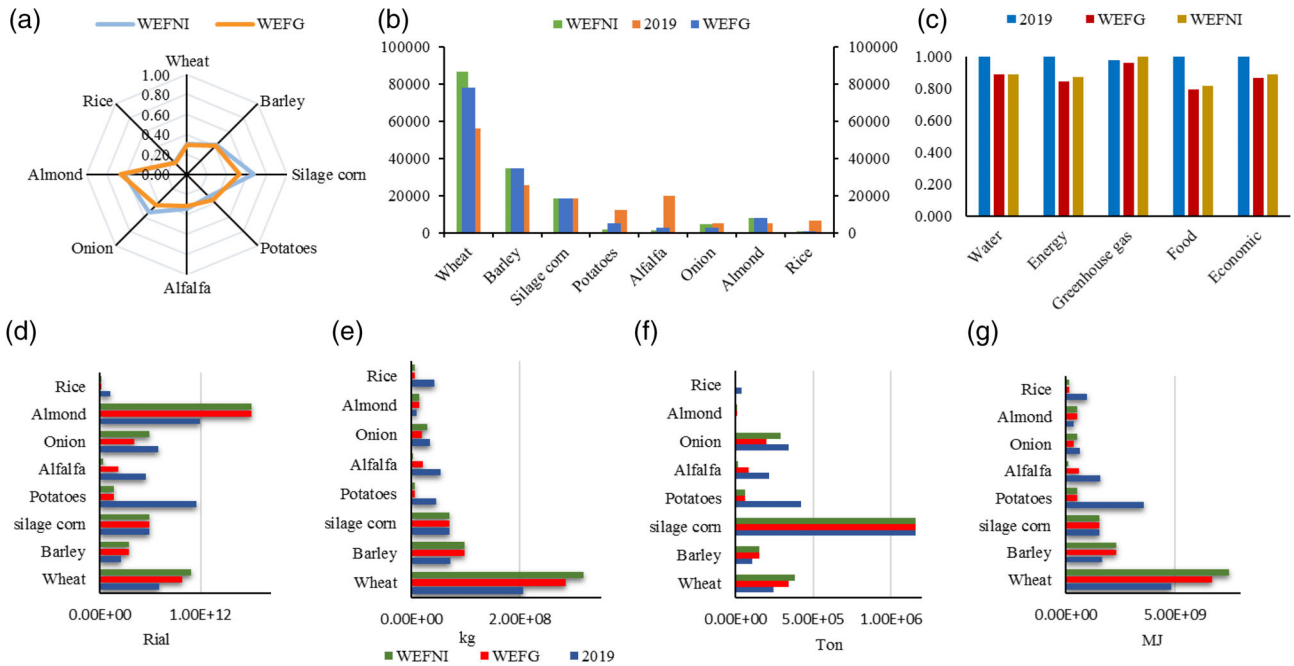

FIGURE 6 (a) Calculated WEFG and WEFG indices for the selected crops; (b) and comparison of the optimal crop patterns based on WEFNI and WEFG indices and the cultivated area for 2019; (c) Normalize crop inputs and outputs after optimizing the crop area; (d) Economic profit; (e) Greenhouse gas emissions; (f) Crop production; and (g) Energy consumption. [Colour figure can be viewed at wileyonlinelibrary.com]

high, leading to the highest score in the WEFG index (Figure 6a). Despite significant water and energy consumption, onion was placed in the third rank after almond and silage corn for WEFG and WEFNI indices due to higher yield (Table 4).

The almond was introduced as the most suitable plant in the present study due to the highest score in the WEFG index; this finding is consistent with Sadeghi et al., 2020 and Beigi et al., 2016. The emitted carbon from almond cultivation was less than the other crops as the major carbon emission from almond production is related to direct energy consumption (Figure 5). Likewise, (Salehi et al., 2016) confirmed that the main cause of carbon footprint in planting almonds in Iran is the age of agricultural machinery, which can be reduced by repairing and replacing machines.

Comparison of WEFG and WEFNI indices (Table 4) showed that despite a decrease in the score of each crop in the WEFG index compared to WEFNI due to the carbon footprint inclusion, the order of crops remained almost the same except for almond and silage corn as well as wheat and potato. Despite having a higher yield, potatoes ranked after wheat in the WEFNI index due to consuming more water and energy. However, in the WEFG index, potatoes score higher than wheat due to their high yield compared to their carbon footprint, especially in terms of direct energy consumption and higher economic value. Due to having higher carbon emissions and lower yield (WEFG index), wheat ranked last before rice (Table 4). According to the present results, Mohammadi et al., 2014 noted that wheat and barley cultivations had contributed significantly to greenhouse gas (especially N_2O) emissions and global warming.

3.4 | Optimized crop pattern

The crop patterns were optimized based on the WEFG and WEFNI indices for the study area (Figure 6b). Based on the maximum values of WEFG and WEFNI indices, the optimum cultivation areas for almond and silage corn were higher than their cultivated areas during 2019. Considering the low water consumption (Table 4), the allocated areas for wheat (86,675 and 77,856 ha based on WEFNI and WEFG indices) were also higher than its cultivated area during 2019 (56,261 ha). Therefore, the same amount of water consumption (1.016 km^3) has increased the allocated area for wheat cultivation area by 38.4% and 54% based on the WEFG and WEFNI indices, respectively.

The maximum differences between the allocated area in two indices were calculated for potatoes (Figure 6b). With WEFNI, the allocated areas to potatoes were lower, around 64.4% lower than WEFG. According to Table 4, silage corn is a valuable crop in agriculture due to its very high yield, but its value is slightly reduced by considering items such as carbon emission. In the present study, by considering the condition of not having zero cultivation level for crops, the allocated area for each crop was obtained to be greater or equal to its minimum cultivation level from 2005 to 2019.

Barley consumes little water and energy and is well compatible with the environment, so its cultivation level in the two indicators WEFG and WEFNI has reached a maximum of 34,925 ha which has increased by 37.3%. Compared to 2019. Having very high energy consumption, the cultivation level of potatoes has dropped significantly (85.2% in WEFNI and 58.4% in WEFG) in both indicators and has reached its minimum level (1838 ha) in the study period in WEFNI.

Alfalfa is consumed high water relatively with low economic value and yield; thus, the optimum cultivation area has decreased (by 85% in WEFG and 93.6% in WEFNI) compared to 2019. Based on the WEFG index, alfalfa's allocated cultivation area (7792 ha) was higher than WEFNI due to its low carbon footprint. Considering that almonds have a high score in both indices, their cultivation level has increased by 51.9% compared to the 2019 water year and reached its maximum level (8082 ha). Due to high water and energy consumption and high carbon emissions, rice has the lowest score in both indicators, so its cultivation area based on WEFG (1089 ha) has reduced by 83.96% compared to 2019.

The total crop production from the optimized crop pattern based on the WEFG index was (2,024,350 tons) was 2.73% less than WEFNI production (2,081,246.4 tons) due to the 2.4% reduction in the total allocated area (Figure 6b). Overall, the net profit of the optimized crop pattern based on the WEFG index was 2.4% lower than WEFNI (Figure 6c) because of the bigger allocated area to the onion with high economic values.

According to Figure 6g, despite the 2.3% increase in total cultivation area under optimization, the main reason for reducing energy consumption was minimizing the cultivation area for crops with high input energy, such as rice, compared to the cultivated area in 2019. In addition, the energy consumption in the WEFG index was slightly lower (3.1%) than in the WEFNI index due to more cultivation area for wheat and onion (Table 4 and Figure 6c).

As a result of optimizing the WEFNI index, increasing cultivation area (4.75%) increased the carbon dioxide emissions by 12,375,374 kg (2.3%), which would adversely affect the environment (according to Figure 6e, wheat was the most effective crop for carbon emissions in the WEFNI cultivation pattern). While optimized cultivation pattern based on the WEFG index has reduced the carbon emissions by 10,848,173.3 kg (2%) with a 2.3% increase in the total cultivation area (Figure 6c).

Increasing carbon dioxide emissions and greenhouse gas concentrations have an essential role in global warming and climate change. Therefore, applying the WEFG index effectively adapted the crop pattern to water shortage and mitigated greenhouse gas emissions in agricultural activities.

Optimized crop patterns based on WEFG index indicated 58.3%, 85%, 40.9%, and 84% reductions in the current cultivation areas of potatoes, alfalfa, onions, and rice, respectively. The cultivation areas of wheat, barley, and almond have also increased by 38.4%, 37.3%, and 51.9%, respectively, while the silage corn has not changed. The optimal cultivation pattern based on WEFG has led to 11% and 15.8% reductions in water and energy consumption, even with 2.3% rise in total cultivation area. Application of WEFG indicated 13.67% reduction in the current profit due to lower cultivation levels of high-yield crops such as onion and potatoes. However, greenhouse gas emission was reduced by 2% compared to the current situation in study area, leading to sustainable agricultural management.

4 | CONCLUSION

This study presented a comprehensive WEFG nexus index considering water, energy (human labor, machinery, fossil fuel, fertilizer, pesticides, and irrigated water inputs in the crop's production), crop yield, economic profit, and greenhouse gas emissions for long-term planning in the agriculture sector. This indicator will help managers make better decisions by considering the various impacts of cropping patterns. The developed WEFG index was applied to evaluate the main traditional staple irrigated crops in the Zayandeh-Rud River basin as a test case. The results showed that WEFG ranged from 0.162 to 0.658, calculated respectively for almond and rice due to high and less energy consumption and their consequent carbon emission levels. The index presented by El-Gafy et al. (WEFNI) was used to examine the differences between the developed index in this study (WEFG) and the indicators used in other studies, which do not consider carbon emissions and environmental issues. Using WEFNI for the Zayandeh River region showed that silage corn (0.806) and almond (0.52) had the highest score due to high yield and low water and energy consumption, and rice (0.119) had the lowest score with higher water and energy consumption.

The total production from the optimized crop pattern based on the WEFG index was calculated as about 2.73% less than WEFNI production due to the 2.4% reduction in cultivation area. Generally, the net profit of the optimized crop pattern based on the WEFG index was 2.4% lower than the proposed crop pattern for WEFNI because of allocating bigger cultivation areas to the onion with high economic values. The results indicated that with an increase of 2.32% in the cultivation area, we saw a decrease in water and energy consumption by 11% and 15.82% under the WEFG index. In addition, increasing cultivation area (4.7%) under the WEFNI index increased the carbon dioxide emissions by 2.3%, while optimized cultivation pattern (2.3% increase in cultivation area) based on the WEFG index has decreased the carbon emissions by 2%, mitigating the global warming impacts. Therefore, applying the WEFG index can effectively adapt the crop pattern to water shortage and combat climate change. While the study approach provides valuable insights into agricultural land management, the modeling method is associated with some limitations regarding greenhouse gases emission, which need to be considered when interpreting the results. Due to access to limited data of different greenhouse gas emissions during the selected crop production, the other greenhouse gases and air pollutants were converted to carbon equivalent using constant coefficients. The uncertainties introduced by this limitation can affect the final values of the developed nexus index and calculated land area for each crop. For future research, it is hence recommended to consider these gases separately and compare the final results with equivalent carbon.

AUTHOR CONTRIBUTIONS

All authors collaborated in the research presented in this publication by making the following contributions: research conceptualization:

Alireza Gohari and Ali Torabi Haghighi; Data curation and formal analysis: Hourieh Masaeli; result analysis and validation: Hourieh Masaeli, Alireza Gohari, Ali Torabi Haghighi, and Marzieh Hasanzadeh Saray, Writing –original draft: Hourieh Masaeli; Writing – review & editing: Alireza Gohari, Ali Torabi Haghighi, and Marzieh Hasanzadeh Saray; supervision, Alireza Gohari and Ali Torabi Haghighi.

ACKNOWLEDGMENTS

We acknowledge the Agricultural Jihad Organization of Isfahan Province for providing the input data in this study.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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How to cite this article: Masaeli, H., Gohari, A., Hasanzadeh Saray, M., & Torabi Haghighi, A. (2023). Developing a new water–energy–food-greenhouse gases nexus tool for sustainable agricultural landscape management. *Sustainable Development*, *31*(2), 877–892. https://doi.org/10.1002/sd.2427