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Decision-Making in the Water-Energy-Food-Environment Nexus: Pathways to Sustainable Agricultural Development

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Abstract

We have strived to present a fresh definition of the water-energy-food-environment-decision makers (WEFED) nexus through the creation of a comprehensive and interconnected system. In this study, we considered criteria for consumption, mass productivity, and economic productivity related to irrigation water, renewable and non-renewable energy, as well as the criteria of fertilizer and pesticide use, CO_2 emissions, and wetland conservation to elucidate the water-energy-food-environment (WEFE) nexus. We then assessed the impact of decision-makers' perspectives on the nexus criteria under seven different management scenarios: water consumption management (WCM), energy consumption management (ECM), water economic management (WEM), energy economic management (EEM), environmental management (ENM), management with equal weight given to criteria (WEFE), and management with weight based on the opinions of decision makers in the study area (WEFED), employing TOPSIS method. To explicitly integrate decision-makers' perspectives into this system (the WEFED approach), the weights assigned to each sustainability criterion in one scenario were determined directly based on a survey of local decision-makers using the Fuzzy Analytical Hierarchical Process (FAHP) method. The study findings revealed that in the WCM, ECM, and ENM scenarios, barley cultivation held the highest priority, yet despite improvements in environmental parameters, a decrease in water and energy economic productivity was observed compared to the current pattern. Conversely, in the WEM and EEM scenarios, tomato cultivation took precedence, and despite the deterioration of environmental conditions, enhanced mass and economic water and energy productivity were demonstrated compared to the current pattern. The discrepancy in results among the various sustainable scenario patterns underscored the substantial impact of decision-makers' perspectives on sustainable agricultural management. Finally, it was determined that the WEFE scenario returned the greatest number of improvements (11 out of 13 criteria) in sustainable management criteria compared to the current pattern. Therefore, the findings revealed that a holistic, equally-weighted nexus approach (WEFE), while increasing water consumption, delivers the most balanced sustainability outcomes, though its implementation must be coupled with robust water governance.

Keywords: CO_2 emission, Sustainability perspectives, Water and energy economic management, Wetland conservation

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Introduction

Achieving sustainable development goals (SDGs) is possible through sustainable food production and the efficient use of water and energy resources within food systems (UN, 2023; Mirzaei *et al*., 2024a). The agricultural sector, as the primary provider of food security, heavily relies on water and energy resources, with limited substitutability with other inputs in this sector (Sadeghi *et al*., 2020; Zuo *et al*., 2021; Radmehr *et al*., 2021). The expansion of agricultural production has exacerbated the strain on water resources, energy, the environment, and natural ecosystems like wetlands (Pastor *et al*., 2019; Abdelkader & Elshorbagy, 2021; Mirzaei & Zibaie, 2021; Mirzaei *et al*., 2022). In Iran, as a developing country, the agricultural sector contributes to approximately 10% of the GDP, over 20% of non-oil exports, and employs around 20% of the workforce (Farajian *et al*., 2018; Karamian *et al*., 2023).

Access to clean water and water management are at risk due to increasing climate-related disasters and the fact that several regions are facing severe water scarcity (UN, 2023). The agricultural sector is the dominant consumer of water in Iran. While many studies estimate its share of total water withdrawals in normal years to be between 80% and 90% (Keshavarz *et al*., 2021; Zad-Parsa *et al*., 2024), some research reports a higher figure of approximately 92% (Mohammad Jani & Yazdanian, 2014; Mirzaei *et al*., 2024b). It is important to note that this share can be significantly lower during drought periods. Despite this variability, Iran's agricultural water consumption remains substantially higher than regional and global averages-around 84% for the Middle East and 69% for the rest of the world (Mohammad Jani & Yazdanian, 2014; Mirzaei *et al*., 2024b). Research conducted by the International Water Management Institute predicts that many regions worldwide will face freshwater scarcity issues by 2025. Iran is among the countries grappling with a severe water crisis, which has been intensified by increasing demand, declining water quality, low prices, and inadequate water resource management (Madani *et al*., 2016; Saray & Haghighi, 2023). Moreover, over the past 23 years, Iran has experienced rising temperatures, reduced rainfall, and subsequent depletion of water resources, exacerbating the water crisis (National Climate Change Office, 2010).

The industrialization of agriculture and the excessive use of fertilizers, pesticides, and other high-energy inputs, such as fossil fuels, electricity, and machinery, have resulted in a growing consumption of non-renewable energy and the release of greenhouse gases (Li *et al*., 2016; Masaeli *et al*., 2023). In 2019, fossil fuels were identified by the International Energy Agency (IEA) as the primary source of energy worldwide, contributing to over 81% of global energy production (IEA, 2021). Developing countries are experiencing a 9.6% annual growth rate in renewable energy installation; however, despite substantial needs, international financial flows for clean energy continue to decline (UN, 2023). This heavy reliance on fossil fuels as a non-renewable energy source for Iran's energy supply will further worsen the energy crisis (Zolghadr-Asli *et al*., 2023). Additionally, in the agricultural sector alone, Iran consumes over 36 million kilowatt-hours of electricity, accounting for more than 15% of the country's total electricity consumption (Mirzaei *et al*., 2024b). Consequently, transitioning from fossil fuel-based energy systems to renewable sources and moving towards green growth are imperative to meet the objectives of the energy-food nexus (Mahdavian *et al*., 2022).

The review of literature highlights that previous studies have often taken a simplistic and sometimes incomplete approach when considering the interconnectedness of water, energy, and food resources (Martinez-Hernandez *et al*., 2017; Jalilov *et al*., 2018; Zhou *et al*., 2019). For instance, in the energy sector, there has been a predominant focus on hydropower generation, neglecting other forms of energy (Zhou *et al*., 2019). The examination of energy consumption types, including fossil fuel-based sources like coal, crude oil, natural gas, and renewable energies, has been insufficiently addressed within the context of the Water-Energy-Food (WEF) nexus in previous studies (Wu *et al.*, 2021). Furthermore, some studies have primarily concentrated on the water component, aiming to maximize gross margin and optimize water allocation in agricultural patterns (Garg & Dadhich, 2014; Zhang & Guo, 2016). Nevertheless, researchers now argue that all sustainability criteria pertaining to water, energy, and food resources should be quantified within the framework of the WEF nexus (Karamian *et al*., 2021; Radmehr *et al*., 2021).

The WEF nexus aims to achieve sustainable utilization of water, energy, and food resources while enhancing their security through integrated management and consideration of stakeholders' goals and interests in various sectors (Leck *et al*., 2015; Salam *et al*., 2017; Taguta *et al*., 2022). The conceptualization of the WEF nexus has shown significant variation in previous studies, depending on the industry being investigated and the objectives and methods employed (FAO, 2014; Nahidul Karim & Daher, 2021). Within the agricultural sector, the WEF nexus concept has been applied in various studies (El-Gafy, 2017; Li *et al*., 2019; Sadeghi *et al*., 2020; Jagadeesh & Sampath, 2022). Furthermore, studies related to the WEF nexus approach commonly utilize multi-objective optimization methods (Jalilov *et al*., 2016; Stamou & Rutschmann, 2018; Zhang *et al*., 2018; Si *et al*., 2019; Hu *et al.*, 2019; Sun *et al*., 2020; Ji *et al.*, 2020; Yu *et al.*, 2020).

In recent times, there has been a disregard for the environment and natural ecosystems within the WEF framework, resulting in insufficient attention being given to this crucial aspect. However, it is imperative to recognize the significance of environmental goals in order to effectively implement the WEF concept and measure sustainability in the agricultural sector (Mirzaei *et al*., 2022; Saray *et al.*, 2022). Disturbing statistics and information reveal the improper use of fertilizers and chemical pesticides, leading to their accumulation in agricultural products and positioning Iran at the 123rd rank out of 180 countries worldwide (Iran Food and Drug Administration, 2016). Furthermore, Iran's greenhouse gas emissions present an unfavorable situation, with a mere 0.52% contribution to the world's gross domestic product and an annual production of 1.65% of global greenhouse gas emissions, placing the country tenth on a global scale (World Resources Institute, 2015). Another critical aspect of environmental conservation involves the protection and restoration of wetlands. The condition of wetlands in Iran highlights a severe crisis characterized by their drying and the subsequent environmental ramifications resulting from conflicting water usage between the agricultural sector and wetlands (Mirzaei & Zibaie, 2021). Consequently, the lack of attention towards environmental issues poses numerous challenges to successfully implementing the WEF concept and maintaining the credibility of its outcomes. However, a review of the existing literature indicates limited research efforts addressing the weaknesses in the connection between WEF and environmental concerns. For example, Mirzaei *et al.* (2022) attempted to mitigate these weaknesses by incorporating the objective of minimizing the use of fertilizers and chemical pesticides alongside the WEF goals. Similarly, Saray *et al.* (2022) and Masaeli *et al.* (2023) have focused on reducing CO_2 emissions in the agricultural production process while aligning with the objectives of the WEF. Mirzaei *et al.* (2024b) added CO_2 emissions and water salinity as environmental criteria to the water-energy-food nexus and determined the relationships between these criteria and other components of the nexus.

Literature paid little attention to the divergent perspectives of regional decision-makers when it comes to implementing the WEF nexus, the complex quantification of nexus within mathematical programming models, and the inflexibility of these models in measuring qualitative criteria (Mirzaei *et al.*, 2023). In contrast, the use of multi-criteria decision-making methods, as opposed to multi-objective mathematical programming methods, allows for the easy formulation of complex issues and diverse objectives, while considering the opinions and perspectives of various experts and decision-makers, ultimately deriving appropriate solutions (Nehamo *et al*., 2020; Mirzaei *et al*., 2023). The use of multi-criteria decision-making methods such as TOPSIS addresses the critical gap in managing qualitative environmental criteria within the WEF nexus framework, fundamentally distinguishing it from the multi-objective optimization models prevalent in prior works (e.g., Radmehr *et al*., 2021). While optimization models excel at finding solutions based on quantitative constraints and objective functions, they often struggle to formally incorporate qualitative judgments and stakeholder preferences. In contrast, the TOPSIS method is uniquely suited for this task, as it enables the direct integration of both quantitative data and qualitative expert assessments into a unified analytical framework.

In general, in this study, we aim to utilize multi-criteria decision-making methods and consider the perspectives of various experts, as well as incorporate quantitative and qualitative environmental criteria, to determine sustainable resource allocation patterns for the WEF nexus. Thus far, no comprehensive research has been conducted that simultaneously takes into account all decision-makers' perspectives and all objectives of the WEF nexus index in conjunction with environmental goals, such as reducing non-renewable energy consumption, minimizing chemical pollution, decreasing CO_2 emissions, and protecting wetlands. Therefore, the conceptual framework of this study can be considered as a novel approach in the sustainable resource management of the agricultural sector. Consequently, the primary novelty of this work lies not merely in combining elements, but in creating a transparent, flexible, and stakeholder-informed decision-support tool that is specifically designed to elucidate and navigate the complex trade-offs between economic productivity, resource efficiency, and environmental conservation in contested landscape. The results of this study can address the fundamental question of how important it is to consider different objectives and perspectives in elucidating sustainable patterns in the agricultural sector, and what pattern can provide the most desirable sustainable management.

Methodology

We employed a five-step approach, based on a thorough literature review, to establish sustainable patterns in the agricultural sector of the study area (Fig. 1). Initially, we identified and evaluated six criteria pertaining to the interconnections of the WEF nexus index in agriculture. These criteria encompassed irrigation water consumption, energy consumption, water mass productivity, energy mass productivity, water economic productivity, and energy economic productivity. This assessment was conducted through an extensive review of literature and data extraction from the study area (El-Gafy *et al*., 2017; Nhamo *et al*., 2020; Mirzaei *et al*., 2023). To conduct a more comprehensive analysis of the WEF nexus, we categorized the energy-related criteria into renewable and non-renewable energy. In the third step, we established the interconnections between environmental objectives and nexus elements using three criteria: wetland conservation (water-environmental linkages) (Mirzaei & Zibaei, 2021), reduction of chemical pollution (food-environmental linkages) (Mirzaei *et al*., 2022), and reduction of CO_2 emissions (energy-environmental linkages) (Saray *et al*., 2022; Saray & Haghighi, 2023). The fourth step entailed determining and calculating the weights of different criteria of WEFE nexus index, based on the insights of regional decision-makers. Finally, we computed the closed index (new index) using the TOPSIS method and extracted sustainable patterns, considering diverse expert perspectives.

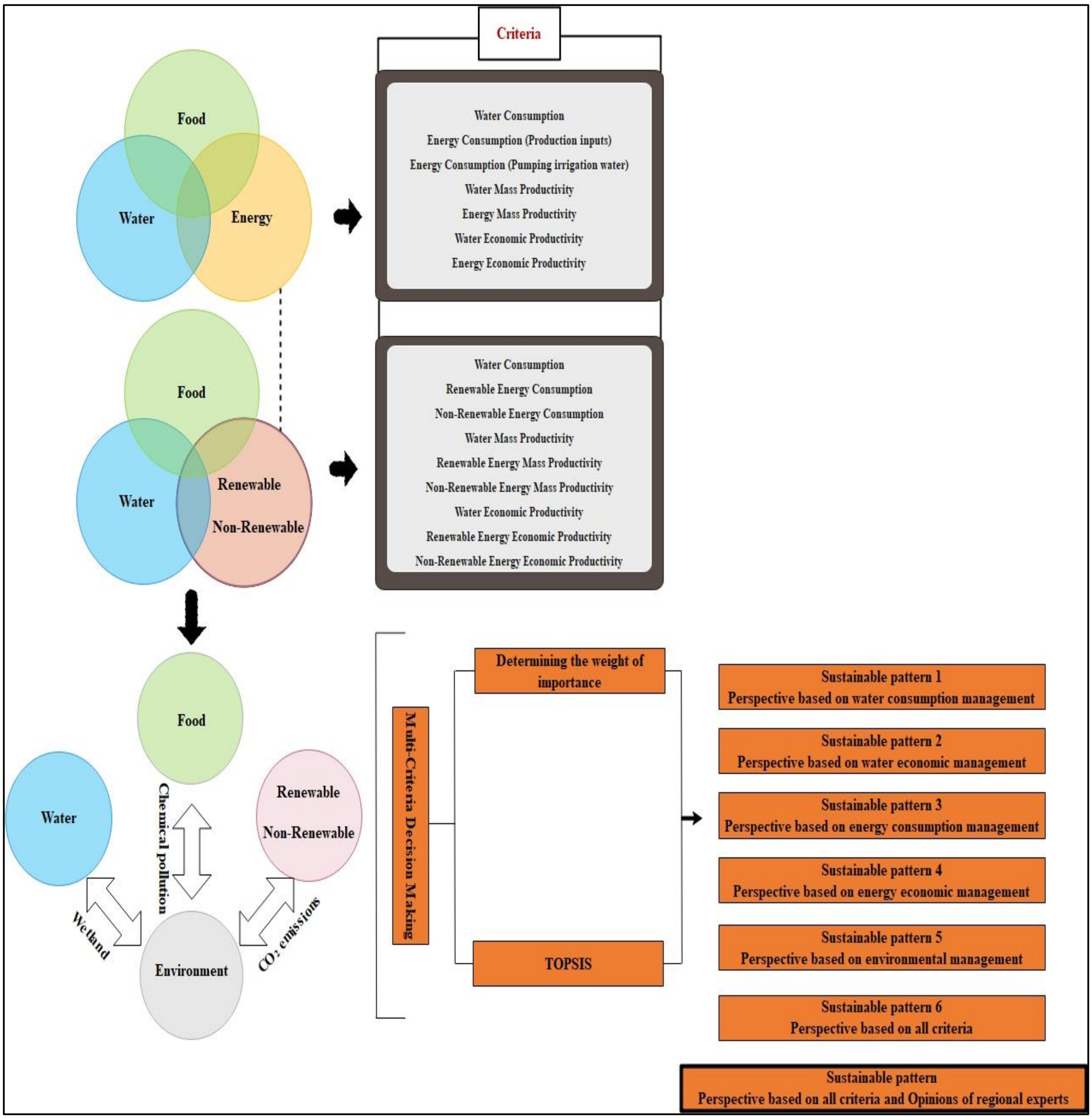

Figure 1- Proposed water-energy-food-environment-decision making nexus approach and assessment steps

Study Area

The study data was extracted from Shadegan Plain, located in Khuzestan Province, Iran (Fig. 2). Shadegan Plain is renowned as the largest plain in Khuzestan Province, spanning from 30° to 31° 33′ North, and 48° 17′ to 49° 49′ East. Wheat, barley, tomato, broad bean, and okra are among the main crops cultivated in this plain, with a significant portion of the land dedicated to wheat cultivation. Shadegan Wetland is situated in the southwest of Iran within this plain, approximately 60 kilometers south of Ahvaz, the capital of Khuzestan Province, and 5 kilometers south of Shadegan city.

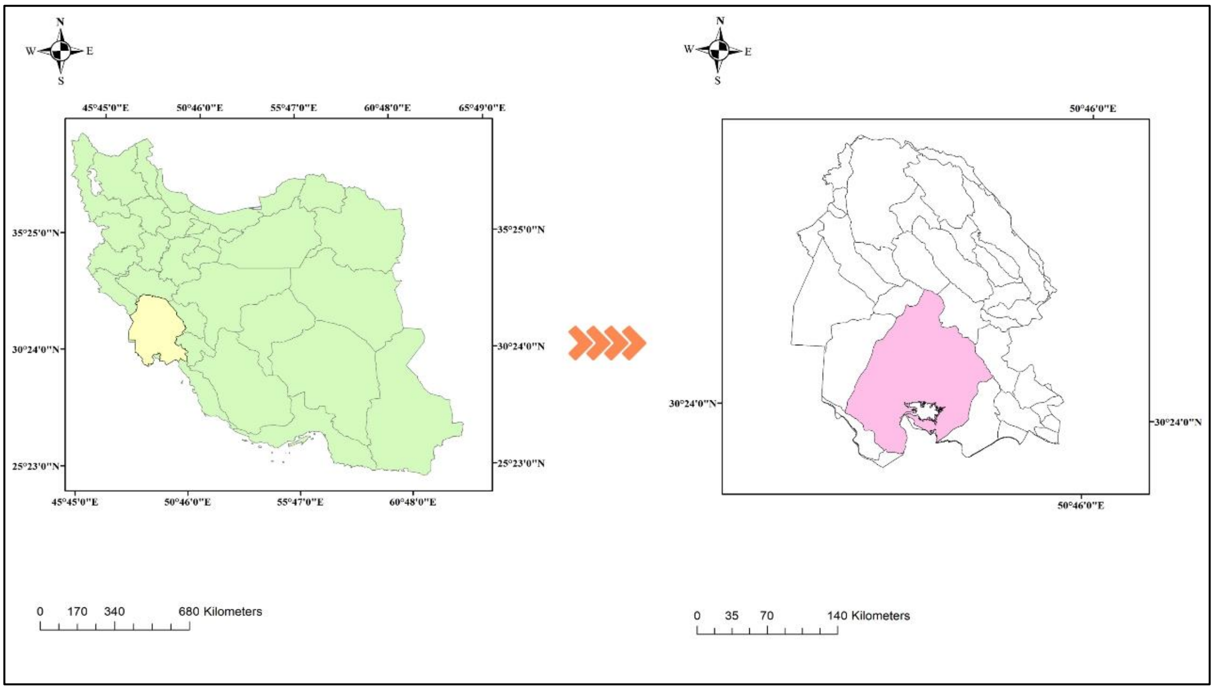

Figure 2- The geographical location of the studied area

Criteria of WEF Index

Water and food nexus indicators comprise irrigation water consumption, water mass productivity, and water economic productivity. A questionnaire was administered to the farmers, seeking details on the number of irrigation cycles, duration of each cycle, and the diameter or flow rate of the irrigation pipes. Utilizing their responses, the water consumption for each crop grown by the farmers was calculated. Consequently, the average water consumption per unit area (hectare) was determined for each crop in Shadegan Plain. The water mass productivity (WP) indicator, categorized by crop (C), was computed by dividing the crop yield (Y) per unit area (kilograms per hectare) by the water consumption of the crop (W) per unit area (cubic meters per hectare), based on equation (1) (El-Gafy, 2017):

$$WP_C = \frac{Y_C}{W_C} \quad (1)$$

To calculate the water economic productivity (WEP) indicator, it is necessary to compute the gross margin (GM) separately for each crop (C):

$$GM_C = (P_C.Y_C) - (\sum_{X=X1}^{Xn} P_X.X) \quad (2)$$

In equation (2), P_C and P_X represent the price per unit of the produced crop (dollars per kilogram) and the prices of input factors (*X=X1*, *X2*, ..., *Xn*) utilized in production. It is important to note that the prices of input factors vary depending on the type of input and may have different units. For instance, the price of seeds and fertilizers is measured in dollars per kilogram of input, while the price of machinery and labor is measured in dollars per hour of usage. Y and X indicate the yield of the crops per unit area (kilograms per hectare) and the consumption of different inputs per unit area, respectively. Therefore, the WEP is derived using equation (3). Equation (3) demonstrates that WEP (dollars per cubic meter) represents the ratio of the gross margin per unit area (dollars per hectare) to the water consumption per unit area (cubic meters per hectare).

$$WEP_C = \frac{GM_C}{W_C} \quad (3)$$

Energy-food nexus indicators encompass the utilization of renewable energy pertaining to labor, seeds, and animal manure, along with the utilization of non-renewable energy associated with chemical fertilizers, pesticides, fossil fuels, and machinery. Both the energy mass productivity of renewable and non-renewable energy sources, as well as the energy economic productivity, are taken into consideration. In order to compute the energy consumption in the production of diverse crops, the energy equivalent (ec) is considered for each unit of input consumption (Table 1). Subsequently, the renewable energy consumption (E1) and non-renewable energy consumption (E2) for the chosen sample farms per unit area (measured in MJ per hectare) are calculated by multiplying the coefficients in Table 1 with the quantities of input consumption (Kitani, 1999).

$$E1_c = (\text{labor}_c.\text{ec}_{\text{labor}}) + (seed_c.\text{ec}_{\text{seed}}) + (manure_c.\text{ec}_{\text{manure}}) \quad (4)$$

$$E2_c = (\text{fertilizer}_c.\text{ec}_{\text{fertilizer}}) + (pesticide_c.\text{ec}_{\text{pesticide}}) + (fuel_c.\text{ec}_{\text{fuel}}) + (machinary_c.ec_{machinary}) \quad (5)$$

Table 1- Energy equivalent (ec) to the inputs used in the production of crops

Inputs	Unit	Energy equivalent (MJ)	References
Labor	h	1.96	Khanali *et al.*, 2021; Sarbijan *et al.*, 2025
Nitrogen fertilizer	kg	78.1	Khoshnevisan *et al.*, 2013
Phosphate fertilizer	kg	17.4	Khoshnevisan *et al.*, 2013
Potassium fertilizer	kg	13.7	Khoshnevisan *et al.*, 2013
Micronutrient fertilizer	kg	120	Khoshnevisan *et al.*, 2013
Livestock manure	kg	0.3	Tabatabaei *et al.*, 2013
Insecticides	l	115	Khoshnevisan *et al.*, 2014
Herbicides	l	85	Khoshnevisan *et al.*, 2014
Fungicides	l	295	Khoshnevisan *et al.*, 2014
Disel fuel	l	47.8	Rajaiefar *et al.*, 2014
Electricity	kwh	11.93	Kaab *et al.*, 2019
Machinery	h	62.7	Sadeghi *et al.*, 2020; Sarbijan *et al.*, 2025
Wheat seed	kg	15.7	Soltani *et al.*, 2013
Barley seed	kg	14.7	Ozkan *et al.*, 2004
Broad bean seed	kg	14.7	Ozkan *et al.*, 2004
Okra seed	kg	0.8	Tuti *et al.*, 2012
Tomato seed	kg	1	Esengun *et al.*, 2007

The energy mass productivity indicators for renewable energy (E1P) and non-renewable energy (E2P), categorized by crops (C), express the relationship between crop yield (Y) per unit area (kilograms per hectare) and the consumption of renewable energy (E1) and non-renewable energy (E2) per unit area of the crop (MJ per hectare). These indicators can be computed using equations (6) and (7) (El-Gafy, 2017):

$$E1P_C = \frac{Y_C}{E1_C} \quad (6)$$

$$E2P_c = \frac{Y_C}{E2_C} \quad (7)$$

Moreover, the energy economic productivity indicators for renewable energy (E1EP) and non-renewable energy (E2EP) are calculated by dividing the GM per unit area (dollars per hectare) by the consumption of renewable energy (E1) and non-renewable energy (E2) per unit area of the crop (MJ per hectare). These indicators can be computed using equations (8) and (9).

$$E1EP_C = \frac{GM_C}{E1_C} \quad (8)$$

$$E2EP_C = \frac{GM_C}{E2_C} \quad (9)$$

Environmental criteria and WEF index

Four environmental indicators, including the fertilizers consumption, pesticides consumption, CO_2 emissions, and wetland conservation, have been identified to reflect the interconnectedness between the environment and food, energy, and water. Data on fertilizer and pesticide consumption, categorized by specific crops, were extracted from questionnaires completed by sampled farmers. The measurement of CO_2 emissions, also categorized by crops, was obtained by multiplying the input consumption by the corresponding CO_2 emission coefficient per unit of input (Table 2).

Table 2- CO_2 equivalent to the inputs used in the production of crops

Inputs	Unit	CO_2 equivalent (kg CO_2 eq)	References
Machinery	h	0.071	Dyer & Desjardins, 2007
Disel fuel	l	2.76	Dyer & Desjardins, 2007
Nitrogen fertilizer	kg	1.3	Lal, 2004
Phosphate fertilizer	kg	0.2	Lal, 2004
Pesticides	l	3.9	Lal, 2004
Electricity	kwh	0.608	Dyer & Desjardins, 2007

In order to evaluate the wetland conservation indicator, we employed expert-assessed data that was categorized according to specific crops. Experts assigned scores ranging from 1 to 9, based on the water consumption associated with each crop and the allocated water reserve for meeting the wetland's water rights. One crucial aspect to take into account is the intersection of two criteria irrigation water consumption and wetland conservation through water supply. It is evident that higher irrigation water consumption for a crop leads to a lower score for wetland conservation. This raises a potential concern regarding duplicated and redundant criteria in the calculations. However, if only irrigation water consumption is considered as a criterion, and the experts' perspective solely determines the weight of its importance, some respondents may solely focus on the concept of water consumption, time efficiency, and cost reduction, disregarding the impact of reducing water consumption on reserving more water to meet the wetland's water rights. Hence, to attain reliable results and minimize errors in the derived patterns, this criterion has also been incorporated in the analysis.

Table 3- Definition of scenarios

Scenarios	Perspectives	Allocated weights (definition of scenarios)
WCM	Water consumption management	The criterion of irrigation water consumption received the highest weight of importance (60%). The remaining weight (40%) was evenly distributed among the other 12 criteria (each criterion approximately 3.33%).
WEM	Water economic management	The criteria of water economic productivity, water mass productivity, and irrigation water consumption were given the highest weights of importance, in that order (30%, 20%, and 10% respectively). The remaining weight (40%) was evenly distributed among the other 10 criteria (each criterion accounting for 4%).
ECM	Energy consumption management	The criteria of renewable energy consumption (40%) and non-renewable energy consumption (20%) were given the highest weights of importance, in that order. The remaining weight (40%) was evenly distributed among the other 11 criteria (each criterion approximately 3.64%).
EEM	Energy economic management	The criteria of economic productivity of renewable energy (20%), economic productivity of non-renewable energy (20%), mass productivity of renewable energy (10%), and mass productivity of non-renewable energy (10%) were given the highest weights of importance, in that order. The remaining weight (40%) was evenly distributed among the other 9 criteria (each criterion approximately 4.44%).
ENM	Environmental management	The criteria of fertilizer consumption (15%), pesticide consumption (15%), CO_2 emissions (15%), and wetland conservation (15%) were given the highest weights of importance, in that order. The remaining weight (40%) was evenly distributed among the other 9 criteria (each criterion approximately 4.44%).
WEFE	Combination of perspectives with equal weights	All criteria are assigned equal weights (approximately 7.69% for each criterion).
WEFED	Decision-makers of the study area	The weights of all criteria be determined based on the opinions of regional decision-makers using the FAHP[1] method.

1- Fuzzy Analytical Hierarchical Process

TOPSIS Method and Extraction of Sustainable Patterns

In this study, we utilized the proposed WEFE (Water-Energy-Food-Environment) nexus criteria along with the TOPSIS method to extract sustainable patterns. The criteria encompassed 13 indicators, namely: irrigation water consumption, water mass productivity, water economic productivity, renewable energy consumption, non-renewable energy consumption, renewable energy mass productivity, non-renewable energy mass productivity, renewable energy economic productivity, non-renewable energy economic productivity, fertilizer consumption, pesticide consumption, CO_2 emissions, and wetland conservation. In the TOPSIS method, the initial step involved constructing a performance matrix and determining the weight assigned to each criterion. To establish these weights, we considered seven different scenarios (Table 3). Subsequently, we conducted a comparative analysis of the sustainable patterns obtained for different scenarios, thereby assessing the validity of the proposed approach.

In the TOPSIS method, we begin by normalizing the performance matrix without considering the units. Next, the normalized values of the performance matrix are multiplied by the weights assigned to each criterion, resulting in a weighted normalized performance matrix. Moving forward, the TOPSIS method, categorized as a compromise or consensus-based approach, chooses the option with the shortest distance from the ideal alternative as the best choice. The method follows these steps:

1) In the case of criteria aiming for maximum, the highest values are deemed the most favorable points for identification and ideal alternatives. Conversely, for criteria aiming for minimum, the lowest values are considered the best points for identification and ideal alternatives (A^+). This study considers water mass productivity, renewable and non-renewable energy mass productivity, water economic productivity, renewable and non-renewable energy economic productivity, and wetland conservation as positive performance criteria, where higher values are preferred. On the other hand, irrigation water consumption, renewable and non-renewable energy consumption, fertilizer and pesticide consumption, and CO_2 emissions are considered negative performance criteria, where lower values are preferred.

$$A^+ = \{A_1^+, A_2^+, \dots, A_j^+\} \quad (10)$$

2) For criteria that aim for maximum, the lowest value is considered the anti-ideal alternative (A^-). Conversely, for criteria that aim for minimum, the highest value is considered the anti-ideal alternative (A^-).

$$A^- = \{A_1^-, A_2^-, \dots, A_j^-\} \quad (11)$$

The closed index (CI) for each crop was calculated using equation (12).

$$CI = \frac{(R)^-}{(R)^+ + (R)^-} \quad (12)$$

Where R^- represents the distance of each alternative from the anti-ideal alternative, and R^+ represents the distance of each alternative from the ideal alternative. Subsequently, in order to assess the contribution of each crop to the sustainable cropping pattern, the standard CI will be employed. This involves dividing the CI of each crop by the sum of the CI_s of all pattern crops, and thereby calculating the proportionate share of each crop within the cropping pattern. It should be noted that the calculations for the TOPSIS method were performed using Microsoft Excel software.

Sampling

Using the Cochran formula, the sample size was estimated to be 68 farmers. These farmers were selected through a simple random sampling method, and the data were collected by completing face-to-face questionnaires with these farmers. To acquire the necessary data, 68 farmers from Shadegan Plain (selected randomly using the Cochran formula) were surveyed through questionnaires during the 2021-2022 cropping season. The collected data encompassed various aspects such as employed labor, machinery fuel, electricity, water pumping fuel, machinery, fertilizers, pesticides, water consumption, seeds, cost information of inputs, and product details (including crop yield, cultivated area, and price). To implement the FAHP and TOPSIS methods, a sample of 10 experts was also selected. The experts were selected using a purposive sampling method based on two main criteria: (1) their organizational affiliation and direct involvement in the management of water, agricultural, or environmental resources in the Shadegan Plain, and (2) a minimum of 10 years of relevant work experience in the region to ensure informed and reliable judgments.

Result and Discussion

Analysis of Water Component Criteria

Water consumption, water mass productivity, and water economic productivity were individually calculated for the production of five main crops in the region, namely wheat, barley, broad bean, okra, and tomato, as presented in Table 4. The findings reveal that barley, with an approximate water consumption of 4871 (M^3 per hectare) and okra, with approximately 45357 (M^3 per hectare), stand as the least and most water-intensive crops in terms of water resources, respectively. Tomato production exhibits the highest level of water mass productivity, with one cubic meter of water resulting in the production of 2.165 kilograms of tomato. Conversely, okra demonstrates the lowest water mass productivity, yielding an average of around 0.214 kilograms of okra per cubic meter of water. The calculated water economic productivity points out that tomato generate the highest economic profit, amounting to $0.379 per cubic meter of water. Conversely, barley exhibits the lowest water economic productivity, with an economic return of $0.151 per cubic meter of water. Overall, it can be concluded that tomato possess a more favorable status compared to other crops in terms of water productivity and economic efficiency. The significant water mass productivity of tomato has also been supported by other studies (El-Gafy *et al*., 2017; Mirzaei *et al*., 2022). As for barley, despite its low water consumption, it falls short in terms of economic viability compared to other crops in the pattern, resulting in the lowest water economic productivity. This finding aligns with previous studies conducted on Iranian farms (Sadeghi *et al*., 2020; Saray *et al*., 2022; Masaeli *et al*., 2023).

Table 4- Values of water component criteria in the proposed WEFE nexus

Crops	Irrigation water consumption (M^3/he)	Water mass productivity (Kg/M^3)	Water economic productivity ($\$/M^3$)
Wheat	7160.96	0.674	0.183
Barley	4871.34	0.821	0.151
Broad bean	7208	0.370	0.159
Okra	45356.57	0.214	0.203
Tomato	20418.63	2.165	0.379

Analysis of Energy Component Criteria

The energy consumption shares resulting from the use of various inputs for the production of the 5 main crops in the study area are presented in Fig. 3. The findings indicate that fertilizers and fuel for machinery have the highest energy consumption shares for wheat and barley, respectively. According to the obtained results, these two inputs account for over 65% of the total energy consumption. Specifically, the energy consumption share of fertilizers for wheat and barley production is approximately 36.60% and 34.51%, respectively, while the energy consumption share of fuel for machinery is approximately 31.28% and 29.90%, respectively. Moreover, the results reveal that fuel for water pumping and fertilizers have the highest energy consumption shares for the production of three crops: broad bean, okra, and tomato. The fuel share for water pumping accounts for roughly 51%, 51%, and 60% of the energy consumption in the production of broad bean, okra, and tomato, respectively. Similarly, the input share of fertilizers in energy consumption is approximately 26%, 25%, and 34% for the production of these crops, respectively. Previous studies have consistently demonstrated that fertilizers and diesel fuel are the primary contributors to energy consumption in agricultural production systems (Hülsbergen *et al.*, 2001; Saray *et al.*, 2022; Masaeli *et al.*, 2023). Diesel fuel has particularly been identified as the most significant energy-consuming factor in crop production within the agricultural sector across various studies (Erdal *et al.*, 2007; Pishgar-Komle *et al.*, 2012; Zahedi *et al.*, 2015; Saray & Haghighi, 2023).

The results demonstrate that the proportion of energy consumed from non-renewable sources for the production of all desired crops is significantly greater than the proportion derived from renewable energy (Fig. 4). For example, in the case of tomato and okra, renewable energy accounts for less than 2% of the total energy consumption, while non-renewable sources contribute to over 98% of the energy consumed. The barley exhibits the highest share of renewable energy consumption, making up approximately 12% of the total energy consumption. Consequently, it can be inferred that excessive reliance on non-renewable energy in the agricultural sector will exacerbate environmental challenges, a conclusion that aligns with findings from other studies (Asgharipour *et al.*, 2016; Hua *et al.*, 2016; Dimitrijević *et al.*, 2020; Saray & Haghighi, 2023).

According to the results in Table 5, the highest amount of renewable energy has been consumed in the production of two crops, barley (approximately 3834 MJ per hectare) and wheat (approximately 3580 MJ per hectare). Meanwhile, the lowest amount of renewable energy has been consumed in the production of two crops, tomato and okra, which are approximately 834 and 1265 MJ per hectare, respectively. The highest amount of non-renewable energy consumption is related to the production of okra and tomato, with approximately 87454 MJ per hectare for okra and approximately 56920 MJ per hectare for tomato. The total amount of renewable and non-renewable energy consumption also shows that the production of barley and wheat requires less energy consumption, while the production of okra and tomato requires more energy consumption. The low energy consumption for the production of barley and wheat compared to other agricultural crops has been proven in several studies (Zahedi *et al.*, 2015; Sadeghi *et al.*, 2020; Mirzaei *et al.*, 2022; Saray *et al.*, 2022).

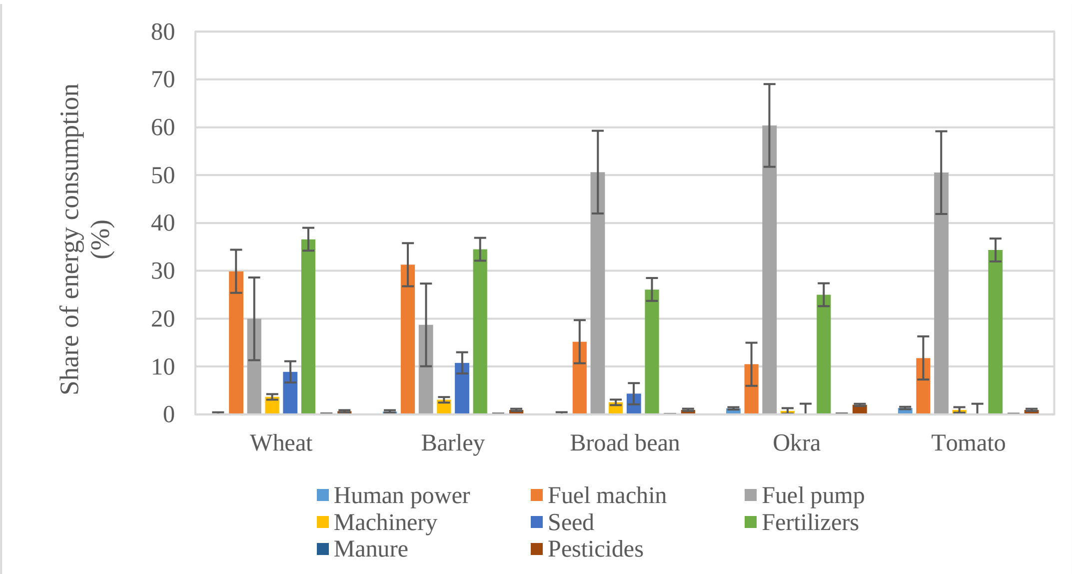

Figure 3- The distribution of energy consumption among different inputs

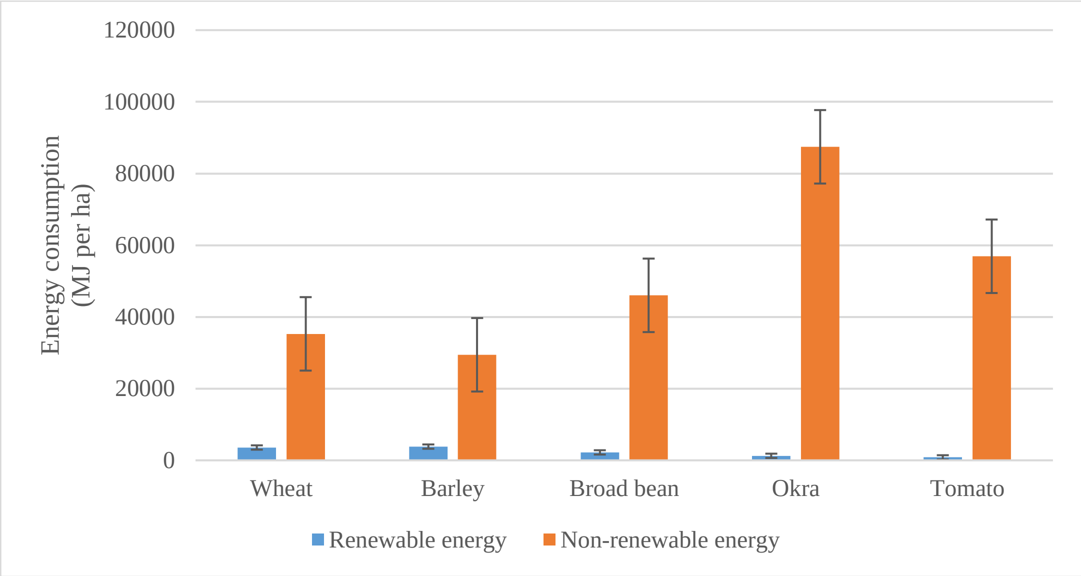

Figure 4- The distribution of energy consumption, into renewable and non-renewable energy sources

The comparison of the mass productivity of renewable energy reflects the fact that 1 MJ of renewable energy consumption can result in approximately 53 kilograms of tomato and 8 kilograms of okra, which is the highest amount among the desired crops. On the other hand, for barley and broad bean, the lowest mass productivity of renewable energy has been calculated, and 1 MJ of renewable energy consumption can only lead to the production of approximately 1 and 2.1 kilograms of barley and broad bean, respectively. Based on the obtained results, it can be concluded that the mass productivity of energy, especially non-renewable energy, for all crops is less than 1 MJ per hectare, which is consistent with the results of other studies (El-Gafy *et al*., 2017; Mirzaei *et al*., 2022). Among the examined crops, tomato has allocated the highest amount of approximately 0.78 kilograms, and broad bean has the lowest amount of approximately 0.06 kilograms of non-renewable energy mass productivity. The high mass productivity of tomato crop has been proven in the studies by El-Gafy *et al*. (2017) and Mirzaei *et al*. (2022). Finally, the results indicate that tomato and okra have the highest energy economic productivity for both types of renewable and non-renewable energy, which is consistent with the results of the study by El-Gafy *et al*. (2017).

Table 5- Values of energy component criteria in the proposed WEFE nexus

Crops	Energy consumption (MJ/he)		Energy mass productivity (Kg/MJ)		Energy economic productivity ($/MJ)	
	Renewable	Non-renewable	Renewable	Non-renewable	Renewable	Non-renewable
Wheat	3580	35280	1.35	0.137	0.366	0.037
Barley	3834	29443	1.04	0.136	0.192	0.025
Broad bean	2219	46024	1.20	0.058	0.515	0.025
Okra	1265	87454	7.68	0.111	7.270	0.105
Tomato	834	56920	53.02	0.777	9.273	0.136

Analysis of Environmental Component Criteria

The results presented in Table 6 reveal that okra and tomato exhibit the highest consumption of fertilizers and pesticides. okra is estimated to consume around 1321 kilograms, while tomato consumes approximately 1182 kilograms per hectare. As for pesticide consumption, okra utilizes about 18 liters per hectare, whereas tomato requires around 6 liters. Moreover, the findings indicate that okra and tomato production are associated with the highest levels of CO_2 emissions, approximately 4691 and 2987 kilograms per hectare, respectively. Conversely, wheat and barley production result in the lowest CO_2 emissions, approximately 1487 and 1766 kilograms per hectare, respectively. Saray *et al.* (2022) and Saray & Haghighi (2023) conducted an assessment of CO_2 emissions from wheat and barley production and discovered that these emissions were lower compared to other crops. Furthermore, Masaeli *et al.* (2023) demonstrated that barley production has the lowest CO_2 emissions. In terms of water conservation and subsequently ensuring wetland water rights, barley (approximately 6.3) and wheat (approximately 4.9) achieved the highest scores, while okra (approximately 1.2) and tomato (approximately 2.2) obtained the lowest scores (See Appendix A1). In the study conducted by Mirzaei and Zibaei (2021), which aimed to preserve the wetland, the cultivation pattern saw an increased contribution from barley, indicating its suitability in the agricultural sector for securing downstream water rights in the wetland.

Analysis of Sustainable Patterns Based on Index of WEFED Nexus

Before analyzing the TOPSIS results, the final weights of the criteria, derived from expert opinions using the FAHP method, are presented in Table 7.

Table 6- Values of environmental component criteria in the proposed WEFE nexus

Crops	Fertilizers consumption (Kg/he)	Pesticides consumption (L/he)	CO_2 emission (Kg/he)	Score of wetland conservation (1 to 9)
Wheat	847	2.58	1766	4.94
Barley	684	3.19	1487	6.27
Broad bean	750	4.67	2416	4.06
Okra	1321	17.79	4691	1.23
Tomato	1182	5.53	2987	2.19

Table 7- The importance weights of the criteria based on the FAHP method

Criteria	Weights
Water consumption	0.097
Renewable energy consumption	0.052
Non-renewable energy consumption	0.046
Water mass productivity	0.120
Renewable energy mass productivity	0.089
Non-renewable energy mass productivity	0.044
Water economic productivity	0.146
Renewable energy economic productivity	0.139
Non-renewable energy economic productivity	0.077
Fertilizers consumption	0.039
Pesticides consumption	0.037
CO_2 emission	0.061
Wetland conservation	0.054

The results of the TOPSIS closed index for different scenarios are shown in Table 8. These results indicate that tomato is given the highest priority for cultivation in scenarios WEM, EEM, WEFE, and WEFED. Following tomato, barley has the highest priority in various scenarios among the crops examined. Specifically, in scenarios WCM, ECM, and ENM, barley is given the first cultivation priority. On the other hand, okra consistently has the lowest cultivation priority among the studied crops in most scenarios, including WCM, WEM, ECM, ENM, and WEFE. Analyzing the obtained results reveals that despite its high-water consumption (ranked fourth in cultivation priority according to WCM) and relatively unfavorable environmental conditions (ranked third in cultivation priority according to ENM), tomato still has the highest cultivation priority from a holistic perspective, considering all proposed WEFE components. This is due to its ability to enhance the economic productivity of water and energy resources. Conversely, okra has a lower cultivation priority in the proposed WEFE pattern due to its poor performance in environmental criteria and its higher water and energy consumption. The sensitive analysis revealed a notable shift in the middle rankings. Specifically, when the "wetland conservation" criterion was removed, the ranking of okra increased, placing it in a higher priority position within the cropping pattern. This finding aligns perfectly with the theoretical expectation, as okra is a crop with high water consumption that was penalized in the original model due to its relatively lower score on the separate "wetland conservation" criterion. Its rise in ranking when that penalty is removed confirms that the model is logically capturing the interplay between these criteria.

Based on the findings of Table 8, it can be concluded that there is minimal disparity between the results of the WEFE and WEFED scenarios. This suggests that the sustainable pattern derived from the WEFED scenario (the importance weight of the criteria based on the opinions of regional decision-makers) is almost comparable to the sustainable pattern obtained from the WEFE scenario (equal importance weights for the criteria). Nonetheless, distinct variations exist in cultivation priorities between the proposed WEFE patterns and sustainable patterns from different perspectives. For instance, the cultivation priority outcomes of different scenarios, where environmental criteria are disregarded, differ completely from the cultivation priority outcomes based on environmental management. When factors such as fertilizer and pesticide consumption, CO_2 emissions, wetland conservation, and water and energy resource management are given greater significance, crops such as barley and wheat receive the highest cultivation priority. Conversely, when the economic productivity of water and energy resources holds greater importance, the cultivation priority is higher for tomato. Finally, the results of the sustainability criteria for each pattern are presented in Table 9.

In scenarios WCM, ECM, and ENM, despite reducing the use of water and non-renewable energy and improving environmental factors, there is a decrease in the economic productivity of water and energy compared to the current pattern. Consequently, sustainable agricultural management, which emphasizes reducing water and energy consumption and addressing environmental concerns, cannot achieve satisfactory economic efficiency. This implies that we cannot be optimistic about implementing these patterns in the region. The results also show that in scenarios WEM and EEM, there will be improvements in the mass and economic productivity of water and energy. However, we cannot expect significant improvements in environmental parameters, particularly in reducing water and energy consumption, from these perspectives.

Table 8- prioritizing crop cultivation under different scenarios

Scenarios		Wheat	Barley	Broad bean	okra	tomato
WCM	Score	0.88	0.89	0.87	0.05	0.62
	Rank	2	1	3	5	4
WEM	Score	0.36	0.37	0.30	0.18	0.82
	Rank	3	2	4	5	1
ECM	Score	0.76	0.78	0.48	0.16	0.3
	Rank	2	1	3	5	4
EEM	Score	0.22	0.23	0.19	0.5	0.87
	Rank	4	3	5	2	1
ENM	Score	0.66	0.69	0.59	0.16	0.6
	Rank	2	1	4	5	3
WEFE	Score	0.45	0.47	0.39	0.27	0.71
	Rank	3	2	4	5	1
WEFED	Score	0.35	0.37	0.31	0.35	0.8
	Rank	3	2	5	4	1

The blue, green, yellow, orange, and red cells represent the first to fifth priority order of crop cultivation, respectively.

Table 9- Value of criteria under different scenarios

Criteria	Base	WCM	ECM	WEM	EEM	ENM	WEFE	WEFED
Water consumption	13347	9627	10511	15468	22225	11780	15280	17771
Renewable energy consumption	2346	2741	2915	2114	1714	2599	2277	2053
Non-renewable energy consumption	51024	41582	41500	49113	58067	44015	48735	52136
Water mass productivity	0.85	0.91	0.81	1.22	1.19	0.95	1.06	1.13
Renewable energy mass productivity	12.86	11.01	7.86	22.71	25.23	13.16	18.03	21.15
Non-renewable energy mass productivity	0.24	0.23	0.20	0.38	0.40	0.26	0.32	0.35
Water economic productivity	0.22	0.21	0.19	0.25	0.27	0.21	0.24	0.25
Renewable energy economic productivity	3.53	2.14	1.86	4.57	5.96	2.75	3.93	4.73
Non-renewable energy economic productivity	0.07	0.05	0.05	0.08	0.09	0.06	0.07	0.08
Fertilizers consumption	957	848	848	980	1083	887	956	1004
Pesticides consumption	6.75	4.08	4.51	5.53	7.93	4.74	5.75	6.51
CO_2 emission	2669	2135	2140	2560	3056	2280	2540	2729
Wetland conservation	3.74	4.50	4.62	3.62	2.89	4.26	3.78	3.44

The green and red colors of the cells indicate a better and worse situation, respectively, compared to the current pattern.

Therefore, a narrow focus on the economic aspect could potentially undermine the regional environmental conditions. The WEFE scenario demonstrates the highest number of improvements in sustainable management criteria compared to the current pattern (11 cells marked in green). Hence, considering all perspectives and giving equal importance to them in sustainable agricultural management can help achieve most sustainability goals. The positive impact of the WEFE nexus on achieving sustainable agricultural patterns has been demonstrated in various studies (Saray *et al*., 2022; Mirzaei *et al*., 2022; Mirzaei *et al*., 2024b).

It is worth noting that the WEFE scenario shows an increase in water consumption compared to the current pattern. This highlights the fact that patterns aiming to reduce water consumption may not necessarily be sustainable (Sarbijan *et al*., 2025). The results of the WEFED scenario align with those of the WEM and EEM scenarios, indicating that economic criteria hold greater importance according to the decision-makers in the studied region. Thus, in this scenario, there are improvements in the mass and economic productivity of water and energy resources compared to the current pattern, while water and energy consumption and other environmental factors face an undesirable situation.

Conclusion and Recommendations

The aim of the present study is to achieve the objectives of sustainable management in the agricultural sector by designing a comprehensive system based on decision-makers' opinions. The study focuses on the interrelationships between water, energy, food, and the environment, using the WEFE nexus concept. Sustainable patterns for the agricultural sector are derived from this nexus, taking into account decision-makers' opinions from various research areas. The study area selected for this research is the Shadegan plain in Khuzestan province, Iran. Sustainable patterns are obtained under 7 different scenarios, including water consumption management (WCM), energy consumption management (ECM), water economic management (WEM), energy economic management (EEM), environmental management (ENV), comprehensive management with equal importance to all criteria (WEFE), and comprehensive management with importance based on the opinions of regional decision-makers (WEFED). The results of the different sustainable scenarios highlight the significant role of decision-makers' and managers' perspectives in sustainable agricultural management. For example, if decision-makers' prioritize water consumption management, energy consumption, and other environmental dimensions such as chemical pollutants, CO_2 emissions, and wetland conservation, the cultivation priority will be given to barley and wheat. However, despite the improvement in environmental conditions, the economic situation of farmers will worsen compared to the current pattern in the region. On the other hand, if economic components are given greater importance, tomato cultivation becomes the first priority. Although this improves economic water and energy productivity indicators, it leads to increased consumption of water and non-renewable energy resources and environmental degradation. The WEFE scenario demonstrates that giving equal importance to all dimensions can result in simultaneous economic and environmental management. However, it is important to note that water consumption will increase compared to the current pattern in the region. This contradicts the viewpoint of most policy-makers and decision-makers who prioritize reducing water consumption for sustainable agricultural development. Decision-makers in this field need to develop suitable patterns that improve economic resource efficiency through a comprehensive and systemic approach. When these patterns result in increased water consumption, it is crucial to manage water consumption through effective water resource management policies while implementing sustainable patterns. The results of the WEFED scenario indicate that the prevailing perspective in the region aligns closely with the WCM, ECM, and ENV scenarios, with less emphasis on economic productivity components compared to resource consumption management. Based on the findings, while the WEFE scenario offers a more balanced sustainability performance, its implementation would lead to increased water consumption compared to the current pattern-a critical challenge in water-scarce regions. To enable the adoption of such sustainable cropping patterns, it is essential to complement them with water-saving strategies. These include promoting modern irrigation technologies, improving water conveyance efficiency, implementing incentive-based policies to encourage farmers to adopt water conservation practices, and Incentive programs to shift cultivation towards increased tomato production while adhering to water consumption quotas and utilizing irrigation technologies. Effective monitoring and governance mechanisms will also be crucial to ensure that sustainability objectives are met without exacerbating water scarcity.

Appendix A1: Expert Scoring Rubric for Wetland Conservation Criterion

This appendix outlines the rationale and scoring methodology for the qualitative "Wetland Conservation" criterion presented in Table 6. The scores (on a scale of 1 to 9) were assigned by a panel of regional agricultural and environmental experts based on the combined impact of two primary factors: 1) Crop Water Consumption and 2) Alignment with Environmental Water Rights.

The scoring rubric used by the experts is summarized in the table below. A higher score indicates a cropping pattern that is more compatible with the goal of preserving water for the Shadegan Wetland's ecological needs.

Table A1: Expert Scoring Rubric for Wetland Conservation

Score	Description / Justification
1-2 (Very Low)	Assigned to crops with very high-water consumption (e.g., >20,000 m³/he). Cultivation of these crops significantly reduces the water volume available for downstream environmental flow, posing a severe threat to the wetland's health and water rights.
3-4 (Low)	Applied to crops with high water consumption. These crops substantially compete with the wetland for water resources, leading to a significant negative impact on the potential for meeting its water rights.
5 (Medium)	Represents crops with moderate water consumption. Their cultivation has a discernible but moderate impact on the water available for the wetland, representing a neutral to slightly negative influence.
6-7 (High)	Assigned to crops with low to moderate water consumption. These crops are considered more compatible with wetland conservation, as their water use allows for a better balance between agricultural needs and environmental water allocation.
8-9 (Very High)	Reserved for crops with very low water consumption (e.g., <5,000 m³/he). These crops are highly favorable for wetland conservation, as they minimize competition for water resources, thereby preserving a greater share for fulfilling the wetland's environmental water rights and promoting its ecological sustainability.

Justification for the Approach: This expert-based scoring system allows for the integration of a critical qualitative environmental indicator into the quantitative WEFE nexus framework. It directly links agricultural water use decisions to their downstream ecological consequences, a relationship that is crucial for sustainable resource management but difficult to capture with purely quantitative metrics alone.

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تصمیم‌گیری در پیوند آب، انرژی، غذا و محیط زیست: مسیرهایی به سوی توسعه‌ی پایدار کشاورزی

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چکیده

ما کوشیده‌ایم تا با ایجاد یک سیستم جامع و به‌هم‌پیوسته، تعریف تازه‌ای از پیوند آب-انرژی-غذا-محیط‌زیست-تصمیم‌گیرندگان (WEFED) ارائه دهیم. در این مطالعه، معیارهای مصرف، بهره‌وری فیزیکی و بهره‌وری اقتصادی مربوط به آب آبیاری، انرژی تجدیدپذیر و تجدیدناپذیر، همچنین معیارهای مصرف کود و آفت‌کش، انتشار CO_2 و حفاظت از تالاب‌ها را برای تبیین پیوند آب-انرژی-غذا-محیط‌زیست (WEFE) در نظر گرفتیم. سپس تأثیر دیدگاه‌های تصمیم‌گیرندگان را بر معیارهای این پیوند، در قالب هفت سناریوی مدیریتی متفاوت شامل مدیریت مصرف آب (WCM)، مدیریت مصرف انرژی (ECM)، مدیریت اقتصادی آب (WEM)، مدیریت اقتصادی انرژی (EEM)، مدیریت زیست‌محیطی (ENM)، مدیریت با وزن‌دهی مساوی به معیارها (WEFE)، و مدیریت با وزن‌دهی بر اساس نظرات تصمیم‌گیرندگان منطقه مورد مطالعه (WEFED) با استفاده از روش TOPSIS ارزیابی کردیم. به‌منظور ادغام صریح دیدگاه‌های تصمیم‌گیرندگان در این سیستم (رویکرد WEFED)، وزن اختصاص‌یافته به هر معیار پایداری در یکی از سناریوها، مستقیماً بر اساس نظرسنجی از تصمیم‌گیرندگان محلی و با استفاده از روش فرآیند تحلیل سلسله‌مراتبی فازی (FAHP) تعیین شد. یافته‌های مطالعه نشان داد که در سناریوهای WCM، ECM و ENM، کشت جو بالاترین اولویت را داشت، با این حال، علی‌رغم بهبود پارامترهای زیست‌محیطی، کاهش بهره‌وری اقتصادی آب و انرژی نسبت به الگوی فعلی مشاهده شد. در مقابل، در سناریوهای WEM و EEM، کشت گوجه‌فرنگی در اولویت قرار گرفت و علی‌رغم بدتر شدن شرایط زیست‌محیطی، بهبود بهره‌وری فیزیکی و اقتصادی آب و انرژی نسبت به الگوی فعلی نشان داده شد. اختلاف نتایج میان الگوهای سناریوی پایدار مختلف، تأثیر قابل‌توجه دیدگاه‌های تصمیم‌گیرندگان را بر مدیریت پایدار کشاورزی برجسته ساخت. در نهایت مشخص شد که سناریوی WEFE بیشترین تعداد بهبود (۱۱ مورد از ۱۳ معیار) را در معیارهای مدیریت پایدار نسبت به الگوی فعلی به همراه دارد. بنابراین، یافته‌ها نشان داد که رویکرد کل‌نگر و مبتنی بر وزن‌دهی مساوی در پیوند (WEFE)، ضمن افزایش مصرف آب، متعادل‌ترین نتایج پایداری را ارائه می‌دهد، هرچند که اجرای آن باید با حاکمیت قوی بر آب همراه باشد.

واژه‌های کلیدی: انتشار CO_2، حفاظت از تالاب‌ها، دیدگاه‌های پایداری، مدیریت اقتصادی آب و انرژی

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