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Research Article

Proposing a Conceptual Model of the Water-Energy-Food-Environment Nexus in the Agricultural Sector

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Abstract

Regarding natural resources, Iran possesses a rich biodiversity that provides a foundation for biological security, prosperity, and economic development, as well as supporting sustainable production. Accordingly, wise management and sustainable utilization of these invaluable resources are crucial. Sustainability strategies, protection of natural resources, and pollution control have introduced complexities and challenges due to the existing interdependencies among resources. Therefore, focusing on one aspect without considering others can lead to serious consequences for the region or the entire system. Consequently, this research presents a conceptual model for managing the climate Water-Energy-Food Nexus (WEFN) in the Mashhad study area for the years 2018-2019. The results indicated that by applying the nexus approach, farmers' gross profits increased by 40%, total consumption costs decreased by 40%, and environmental impacts were reduced by 21%. Overall, the findings suggest that utilizing the Optimal integrated model allows farmers to balance environmental considerations, optimal consumption, and resource sustainability while selecting and implementing policies that sustain economic income.

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1.Introduction

The growing population and its diverse dietary needs have led to shifts in food demand, resulting in a corresponding change in the requirements for water and energy needed for food production. Water, food, and energy are essential for human sustenance, and the intricate, interwoven relationship between these systems highlights their interdependence and mutual impact on one another within the production cycle (Obsi et al., 2023; Fu et al., 2018). Agriculture, the most significant sector in food production, is a consumer of water and energy and the primary supplier of these resources. Food production relies on water and energy, while energy generation requires water, and access to water is contingent upon energy availability. Moreover, the food system also contributes to energy production. Therefore, a balance must be established between the extraction and consumption of production resources and the level of agricultural output (Karabulut et al., 2018; Eslami et al., 2019). According to predictions from the United Nations, the population of developing countries, including Iran, is expected to increase by approximately 50% by the year 2050 (OECD, 2014).

The agricultural sector is estimated to account for approximately 90% of freshwater and 30% of energy consumption related to food production and its supply chain (FAO, 2018). Consequently, the anticipated increase in the global population, along with ongoing economic development and the rising demand for 50% more food, 40% more energy, and 30% more water by the year 2030, has led to numerous challenges, culminating in potential water and energy shortages (OECD, 2014). Iran will be added to the list of countries facing water scarcity by 2025. Environmental and water crises threaten the country's food and energy security, necessitating urgent measures to optimize limited water resources. Without such action, achieving sustainable development in Iran will be hindered (Ahani et al., 2024; Emamzadeh et al., 2016).

The Asia region has identified the security of water, food, energy, and the preservation of natural resources as significant challenges. In response, the United Nations (UN) has established a series of Sustainable Development Goals (SDGs) since 2015 to achieve the long-term sustainable development of human societies and ensure the availability of water, food, and energy for future generations (Hoff, 2011).

Recognizing the intricate interconnection between these systems and their collective influences, a novel concept, termed the nexus approach, has been put forth. The Water-Energy-Food Nexus (WEFN) is a proposed framework for creating a governance system that aims to facilitate intersectoral participation and strengthen coherent policies for sustainable resource management. The WEFN approach was first introduced at the Bonn Conference in 2011 at the World Economic Forum in Germany. Its objective is to address issues such as resource scarcity. This approach provides a transparent, intelligent, and logical framework to examine the interconnections. By conducting an integrated analysis, the approach aspires to offer a more profound understanding of the interactions between the environment and human activities (Hoff, 2011). More comprehensive programs, decisions, and policies can be achieved by identifying the connections between the resources in these domains. Ultimately, this ensures the security of water, food, and energy, driving the country towards overcoming obstacles and achieving long-term sustainability (Ding et al., 2023; Ikram et al., 2020). The primary challenges confronting the nation in implementing developmental programs have been associated with the sectoral approach to resource management. Approaches such as the nexus have been instrumental in addressing this planning gap by offering an integrated perspective of energy, water, and climate systems. This integrated approach has yielded comprehensive solutions that address and improve challenges while minimizing development impacts (Chen et al., 2020; Forni et al., 2016). Consequently, the nexus approach is imperative for confronting Iran's triple challenges (water, energy, and food). This approach allows the country's resources to be allocated with minimal environmental impact and maximum socio-economic benefits.

The nexus approach is a comprehensive framework that considers the interrelated impacts of various drivers, including climate change, socio-economic developments, population growth, and excessive resource consumption. Fig. 1 illustrates the interconnection between the diverse components of intricate social and environmental systems.

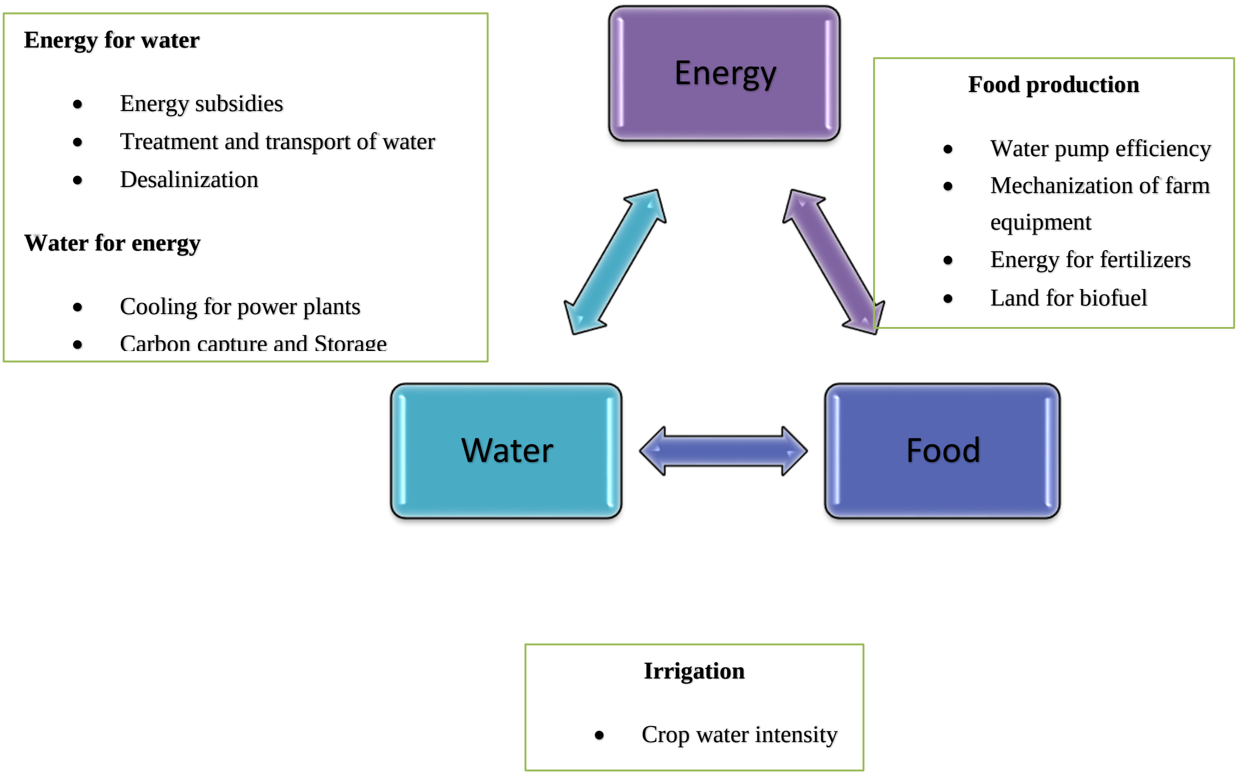

Figure 1. Components of the Water-Energy-Food- Environment nexus

1.1 Benefits of the Water-Energy-Food Nexus (WEFN)

The allocation of resources is founded on the principles of sustainability. Adopting nexus thinking has been demonstrated to engender improved resource use efficiency and forestall adverse effects emanating from single-sector development policies (Mirabi & Krabi, 2020). This implies that WEFN's elements, water, energy, and food, are pivotal to poverty alleviation, as they ensure the equitable provision and distribution of resources to sustain and enhance livelihoods. Given the global limitations in natural resources, this relationship will have newer and more advanced dimensions (Monem et al., 2019).

Implementing policies that prioritize a single aspect of Sustainability while disregarding their inherent interconnectedness is likely to be ineffective and unsuccessful. This approach entails many risks, including those that jeopardize economic security, the fulfillment of human needs, and, ultimately, human health. Iran has a profound absence of discourse on sustainable development and its indicators. Integrating these indicators into policy formulation across various sectors and implementing them in development programs is imperative (Marzban et al., 2020). The WEFN, a concept of paramount importance in Iran, is a crucial element in achieving sustainable development. Consequently, emphasis must be placed on sustainable resource management in the country. To this end, a Sustainable approach must be disseminated among researchers, experts, and policymakers to reveal its capabilities and form a consensus among public and private stakeholders to commit to such an approach (Layani & Bakhshoodeh, 2022).

A one-dimensional approach to solving water resource issues generally leads to "sectoral conflict," signifying a partial perspective in problem-solving. This approach overlooks the necessity of a holistic approach as a fundamental principle in the management of water resources. For instance, an exclusive emphasis on reducing water consumption, without consideration for its interconnection with food production and energy consumption, may yield beneficial outcomes in certain sectors. However, this approach disregards the ramifications on the production and consumption sectors (Safaee et al., 2021).

A primary benefit of this approach is enhancing resource use efficiency, thereby circumventing the deleterious effects often accompanying single-sector development policies. The absence of coordination and the inadequacy of interaction among economic, social, and environmental sectors have resulted in the unsustainable exploitation of other resources, including water, energy, and land. Consequently, these factors threaten water and food security and achieve sustainable development goals. Consequently, implementing a single policy for managing each resource in isolation will likely engender many issues with other resources (Bagheri, 2018; Emamzadeh et al., 2016).

Researchers believe that the water, energy, and food crisis in Iran's future is serious and alarming. Therefore, creating a nexus network to provide new knowledge for planning and policymaking in the country's water, energy, and food sectors is essential. This network will facilitate the exchange of ideas and collaboration, especially through developing technical knowledge and interactions among researchers and scholars (Safaee et al., 2021). In this regard, a few domestic and international studies have examined the water-food-energy nexus through mathematical planning models, some of which are discussed below.

Concurrently a study conducted by Kerman, Emamzadeh et al. (2016), province revealed a notable limitation in economic analyses, namely, an exclusive emphasis on augmenting farmers' economic profits without considering the environmental ramifications. Consequently, to achieve more comprehensive results, mathematical planning models should concurrently examine the economic and environmental objectives of agricultural products and other goals in an integrated manner. Furthermore, Peng et al. (2022) compared the importance of agricultural resources and the diversity of farmers' cropping patterns in agricultural sustainability from the perspective of the food-energy-water nexus. The findings indicated that agricultural diversity exerts a favorable influence on economic profitability and resource sustainability. Conversely, agricultural diversity has been shown to enhance crop performance, as measured by the Linkage approach. However, this enhancement may come at the expense of economic and environmental costs. In a study by Samadi-Foroushani et al. (2022), the dynamic policies of sustainable water resource management based on the Linkage model were analyzed. This analysis considered the demand changes resulting from population and economic growth over a 20-year horizon using a system dynamics approach. The findings indicated that Sustainability nexus, along with simulations and proposed solutions, was identified as the optimal approach within an ideal system. Ahani et al. (2024) employed an innovative mathematical planning approach to evaluate the repercussions of climate change on the water-food-energy nexus. This approach was implemented across multiple climatic, hydrological, economic, and environmental sectors within the Kashafrud basin. The findings indicated that, by 2040, climate change is projected to result in a decline in crop yields, irrigation water consumption, energy consumption, and farmers' net profit, accompanied by increased water demand.

A review of the existing literature revealed a lack of research in the country on the water-food-energy nexus approach. This approach evaluates environmental issues alongside economic dimensions through a mathematical planning model in the agricultural sector. Consequently, the objective of this study is to propose a multi-objective mathematical planning model employing the Systemic approach in the Mashhad study area. The primary goal of this model is to maximize farmers' gross profit while minimizing greenhouse gas emissions. This is accomplished by considering constraints such as water, land, and fertilizer, leading to the sustainable use of water resources in agriculture to increase production. This study utilizes a mathematical planning method to investigate the potential trade-offs between maximization and minimization objectives in the water-food-energy nexus within the region. It is anticipated that the findings will provide actionable insights to formulate effective strategies that address environmental concerns while augmenting farmers' income within the study area.

2.Methodology

2.1 Integrated mathematical programming model for the agricultural sector

The conceptual framework of the Systemic model in the agricultural sector of the Kashaf Rood

Basin consists of two steps. Step one: A hydrological simulation of the basin was performed using the Water Evaluation and Planning (WEAP) model. WEAP is one of the most important tools for water resource planning based on the principle of water balance. It links different sub-basins, water demand nodes, infrastructure, water flows, and water transfer channels. The WEAP model calculates components of the hydrological cycle by simulating precipitation-runoff processes over the entire basin, using time series data of climate parameters. Therefore, each sub-basin unit is divided into different land use classes, and the water balance is calculated under the climatic conditions of that sub-basin. In this model, empirical functions are applied for each agricultural unit to describe and simulate evaporation and transpiration, runoff and surface flows, soil moisture changes, streamflow to rivers, and deep infiltration to groundwater.

In the second part, based on the study by Mo Li et al. (2019), an optimized management model is developed, which includes economic and environmental dimensions. This model can simulate the interactions and interrelationships among the three systems of water, food, and energy, including water supply and demand, energy supply and demand, land requirements, crop performance, and water and energy allocation. The hypothetical model under consideration includes land used for crop production within the basin. In this model, water required for crop irrigation is supplied from surface and groundwater resources. Electricity (consumed energy) is used to collect and pump the water needed for power plants, food production, and supply to the residential and industrial sectors. In addition, food production and processing processes require water resources (surface and groundwater) and energy. Electricity generation, food production, crop irrigation, and the use of fertilizers and chemical pesticides emit greenhouse gases, especially CO2. Therefore, this study aims to introduce a model for the water-food-energy nexus using multi-objective programming (MOP) techniques, which is capable of handling management decisions. In addition to economic considerations, the model also examines greenhouse gas emissions and environmental control.

The conceptual framework of the Water-Food-Energy-Environment Nexus is illustrated in Fig. 2.

The main structure of mathematical programming for determining the cropping pattern of agricultural products based on the integrated model is as follows. In this study, the objectives of maximizing gross profit and minimizing greenhouse gas emissions have been examined (Li et al., 2019). The objectives are analyzed considering the constraints of electricity consumption for water allocation, electricity consumption for food production and processing, available energy, surface water supply, groundwater supply, water required for food production, maximum water allocation (crop water requirement), land constraints, and maximum and minimum production constraints based on the Systemic approach.

The algebraic relationships between these objectives are expressed through Eqs 1 and 2. As previously mentioned, the primary objective of agricultural policymakers and economists is to support and stabilize farmers' incomes while adhering to minimum environmental standards. Consequently, the primary objective is to enhance farmers' gross profit, which is calculated based on Eq. (1).

This assertion is supported by the findings outlined in Eq. (1): Max Profit_V: The goal is to maximize the gross profit of farmers, Price_p_k The selling price of the product (Rial/Kg), yield _P_{ik}: Production yield of each region, Area_V_{ik}: Cultivated area allocated for food production to crops of each region (hectares), Cost $\text{sw\_}_{P_{ik}}$: Cost of exploiting surface water for irrigation for crops in each region, Cost $\text{Gw\_}_{P_{ik}}$: The cost of using groundwater for irrigation for crops in each area, costs euw__{P_i}: costs Electricity for water collection and transmission in each area, Elect $\text{sw\_}_{V_{ik}}$: Amount of electricity allocated to surface water for crops in each area (kWh), Elect $\text{gw\_}_{V_{ik}}$: Amount of electricity for groundwater extraction for crops in each area (kWh), consum euf__{P_i}: consumption Electricity costs for food processing in each region, Elect $\text{fp\_}_{V_{ik}}$: Amount of electricity consumed for food production and processing of crops in each region (kWh), Cost Fertil_P_{ik}: Fertilizer consumption costs per unit for crops in each region, Cost Pesti_p_{ik}:

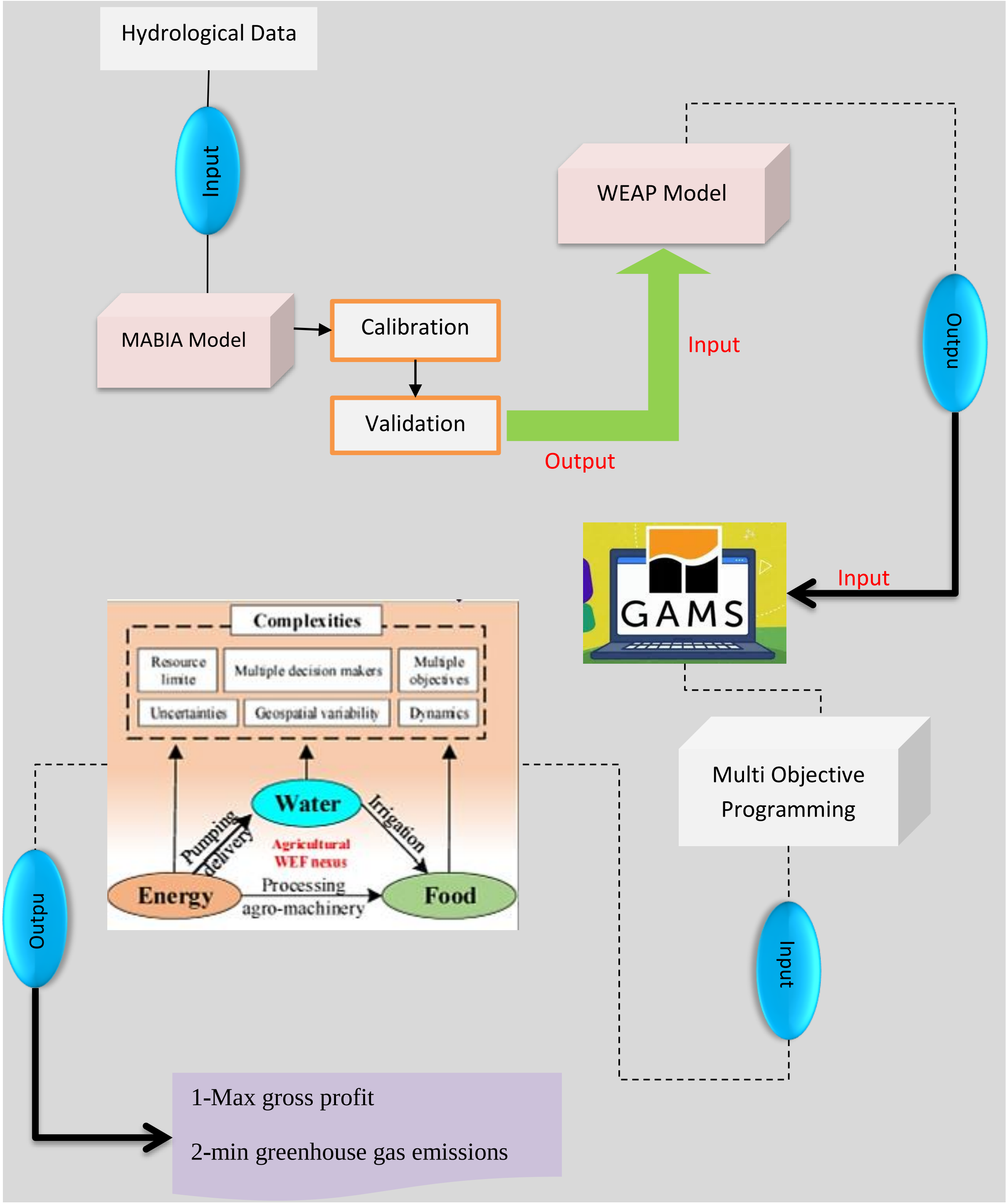

Figure 2. Conceptual Framework of the Water-Energy-Food-Environment Nexus.

Costs of pesticides per hectare of crops in each region, Cost agri machin_P_{ik}: Cost of operating agricultural machinery per unit for crops in Area, Cost_p_{ik}: Total Costs (Milio Rial/ha), Cost agri film_P_k: Cost of agricultural Film per hectare of crops (million rials/hectare).

The reduction of greenhouse gas emissions, which is referred to as the environmental objective in this study, was calculated based on (Eq. 2).

$$Max\ Profit\_V = \sum_{i=1}^{I} \left[\begin{array}{l} Price\_Pk.yield\_Pik.Area\_Pik)\ - \\ (Costsw\_Pik.(\frac{\sum_{k=1}^{k} swat\_Vik}{swatco\_Pi}) + CostGw\_Pik.(\frac{\sum_{k=1}^{k} Gwat\_Vik}{Gwatco\_Pi}) + \\ \sum_{k=1}^{k} \left(\begin{array}{l} Costew\_Pi \left(\sum_{k=1}^{k} Elesw\_Pik + Elegw\_Vik \right) + Costef\_Pi\,(\sum_{k=1}^{k} \begin{array}{l} Elefp\_Vik) + \\ \sum_{k=1}^{k} CostFe\_Pik + CostPe\_Pik \end{array} + CostAM\_Pik) + \\ (Cost\_Pik + Costfi\_Pik).(\sum_{k=1}^{k} Area\_Vik)) \end{array} \right) \end{array} \right] \quad (1)$$

$$MinCo2\_V = \sum_{i=1}^{I} (Co2diesel\_p.DieselCon\_pik \sum_{k=1}^{k} Area\_Vik + Co2film\_p.film\_pi \sum_{k=1}^{k} Area\_Vik + \\ Co2Pesti\_p.Pesti\_pik \sum_{k=1}^{k} Area\_Vik + Co2elect\_p.Eleccon\_Pik \\ \sum_{k=1}^{k} Area\_Vik + Co2ferti\_P.Ferti\_Pik \sum_{k=1}^{k} Area\_Vik) \quad (2)$$

This assertion is supported by the findings outlined in Eq. (2): Min CO2_V: Minimize greenhouse gas emissions, Carbon diesel_p: Carbon emission coefficient in the use of diesel fuel (kg/ co2 liters), . Diesel Consum_p$_{ik}$: Diesel fuel consumption per hectare per area (liters/hectare), Carbon emiss film_p: Carbon emission coefficient in the use of agricultural Film (kg/ co2 kg), Agri film_P$_i$: Consumption of agricultural Film (kg/ha), Carbon emiss pesti_p: Carbon emission coefficient in the use of pesticides (kg/ co2 kg), Pesti$_{\_p_{ik}}$: Amount of pesticides per hectare (kg/ha), Carbon emiss elect_p: Carbon emission coefficient from electricity for irrigation (kg/ co2 kWh), Elect consum_p$_{ik}$: Amount of electricity consumed per hectare per area (kWh/ hectare), Carbon emiss fertil_p: Carbon emission coefficient in the use of fertilizers (kg/ co2 kg), Fertil consum_p$_{ik}$: Fertilizer consumption per hectare per area (kg/hectare).

The most salient limitations of the study objectives are presented as follows. The quantity of electricity utilized for the allocation and distribution of surface water and the extraction of groundwater should not exceed the permissible limit established for each region. This restriction is incorporated within Eq. (3).

$$Eusw\_pi \left[\left(\frac{\sum_{k=1}^{k} Swat\_Vik}{Swatco\_Pi} \right) + Eugw\_pi \left[\left(\frac{\sum_{k=1}^{k} Gwat\_Vik}{Gwatco\_Pi} \right) \right] \right] \leq Enalloc\_Vik \quad (3)$$

This assertion is supported by the findings outlined in Eq. (3): Elect sw_P$_i$: Electricity consumption per unit of surface water pumping in each area (kWh/ cubic meter), Surwatfood_V$_{ik}$: Net allocation of surface water for food production to crops in each region (cubic meters), utilizcoeffisur wate_P$_i$: Surface water utilization coefficient, Groun wat food_V$_{ik}$: Net amount of groundwater allocation for food production to crops in each area (cubic meters), utilizcoeffi groun wat_P$_i$: Groundwater utilization coefficient, Energy allocate wter_V$_{ik}$: The amount of energy allocated to water resources in each area (kWh).

The amount of energy consumed in the process of food production and processing should not exceed the allocated energy for food production and processing in the region. This limitation is expressed in (Eq. 4).

$$\sum_{k=1}^{k} (Eleprod\_Pik.yield\_Pik).Area\_Vik \le Alloprod\_Vik \qquad (4)$$

This assertion is supported by the findings outlined in Eq. (4): Elect consum food produ_P_{ik} : Electricity consumption per unit of food production for crops in each region (kWh/ kg), Energy allocat food Product_V_{ik}: Amount of energy allocated for food production and processing in each region (kWh).

It is imperative to ensure that the availability of energy for various agricultural activities, including the allocation and transfer of surface water, groundwater pumping, and food production and processing, does not exceed the total energy available for agricultural purposes within a specific region. This calculation should exclude the energy consumption of the household and industrial sectors. This limitation is incorporated within (Eq. 5).

$$Enalloc\_Vik + Enprod\_Vik \le Enavail\_pi - Enih\_pik \qquad (5)$$

This assertion is supported by the findings outlined in Eq. (5): Energy Available_P_i: Available amount of energy for the region (kWh), Energy indust and home _P_{ik}: Energy consumption of industry and home sector in each region (kWh).

The allocation of surface water for all crops in each region should not exceed the water supplied through water supply projects, such as water transfer projects, water storage projects, and water intake projects. This limitation is incorporated within Eq. (6).

$$\frac{\sum_{k=1}^{k} Swat\_Vik}{Swatco\_Pi} \le sw\sup\_Pi.Rsw\_Pi \qquad (6)$$

This assertion is supported by the findings outlined in Eq. (6): Surf wate supply_P_i: Surfacewater supply in each area (cubic meters), Rsw_P_i: Ratio utilization ratio of agricultural surface waters in each region.

In a manner analogous to surface water, the allocation of groundwater for all crops in the region should not exceed the amount of groundwater pumped Eq. (7).

$$\frac{\sum_{k=1}^{k} Gwat\_Vik}{Gwatco\_Pi} \le Gw\sup\_Pi.Rgw\_Pi \qquad (7)$$

This assertion is supported by the findings outlined in Eq. (7): roun wat supply _P_i: Groundwater supply in the form of groundwater pumping in each area (cubic meters), Rgw_P_i: Agricultural groundwater utilization ratio of each region.

The maximum and minimum amount of arable land for all crops is determined by Eq. (8).

$$Area\_p_{ik}^{\min} \le Area\_Vik \le Area\_p_{ik}^{\max} \qquad (8)$$

This assertion is supported by the findings outlined in Eq. (8): $Area\_P_{ik}^{min}$: Minimum land allocated to crops in each area (hectares), $Area\_P_{ik}^{max}$: Maximum land for crops in the area (h).

The production amount of each product should not deviate from its maximum and minimum demand. This limitation is incorporated within (Eqs. 9 and 10).

$$\sum_{i=1}^{I} Area\_Vik.yield\_Pik \ge Demand\_p_{ik}^{Max} \qquad (9)$$

$$\sum_{i=1}^{I} Area\_Vik.yield\_Pik \ge Demand\_p_{ik}^{Min} \qquad (10)$$

This assertion is supported by Eqs 9 and 10.

$Deman\_P_{ik}^{Max}$: max demand of each region for the product, $Demand\_P_{ik}^{Min}$: min demand of each region for the product.

The determination of the non-negative set of model variables is finally achieved through the application of Eq. (11).

$$\begin{aligned} & Swat\_Vik \geq 0 \forall i,k \\ & Gwat\_Vik \geq 0 \forall i,k \\ & Area\_Vik \geq 0 \forall i,k \\ & Elesw\_Vik \geq 0 \forall i,k \\ & Elegw\_Vik \geq 0 \forall i,k \\ & Elefp\_Vik \geq 0 \forall i,k \\ & Enavail\_Pi \geq 0 \forall i,k \\ & Eleprod\_Vik \geq 0 \forall i,k \end{aligned} \tag{11}$$

It should be noted that the data required for this study were collected through the review of publications, reports, and agricultural statistical yearbooks for 2019-2020, as well as through interviews with relevant experts and consulting engineering firms. All stages of modeling, calculations, and coding were carried out using the GAMS software.

2.5. Study Area

The Kashafrud Basin, a second-degree sub-basin located in the western region of the Qaraqum Basin, serves as the primary focus of this study. The study area, encompassing the city of Mashhad, is situated in the northern portion of Khorasan Razavi Province, extending across an area of 9,908 square kilometers. A notable aspect of the Mashhad study area is its topographical diversity, with approximately 66% of its area situated within the highlands and the remaining 34% occupying the plains. The basin is characterized by a paucity of surface water resources, a circumstance attributable to the preponderance of vast, fertile terrain and substantial population centers. Consequently, the management of these limited surface water resources has emerged as a pivotal objective in the context of water resource planning and utilization within the basin. The surface water resources of the Mashhad study area encompass dams, rivers, waterways, and streams, which are predominantly influenced by a snow-rain regime. Fig. 3 provides a visual representation of the study area's geographical location within the broader context of the country and the province.

3. Results and Discussion

Table 1 presents the initial data for modeling the water-energy-food-environment nexus. The performance evaluation of agricultural products demonstrated that forage corn exhibited the highest yield at 55 tons per hectare, while barley exhibited the lowest yield at 3.6 tons per hectare. Sugar beets exhibited the highest electricity consumption at 9,057 kilowatt-hours, while barley demonstrated the lowest at 2,492 kilowatt-hours per hectare. Consequently, wheat, barley, alfalfa, and corn exhibited the most economical utilization of other inputs, namely fertilizers and pesticides.

Table 2 presents a comparison of the cultivated area of crops in the multi-objective model and the current level. According to the observations, the cultivated area in the multi-objective model for cucumber, wheat, onion, sugar beet, potato, and tomato decreases by 21%, 23%, 34%, 42%, and 43%, respectively. Furthermore, the highest and lowest reductions in cultivated area among the crops are for other products such as forage corn and alfalfa, with reductions of 51% and 21%, respectively. Conversely, the cultivated area dedicated to barley exhibits a 50% increase.

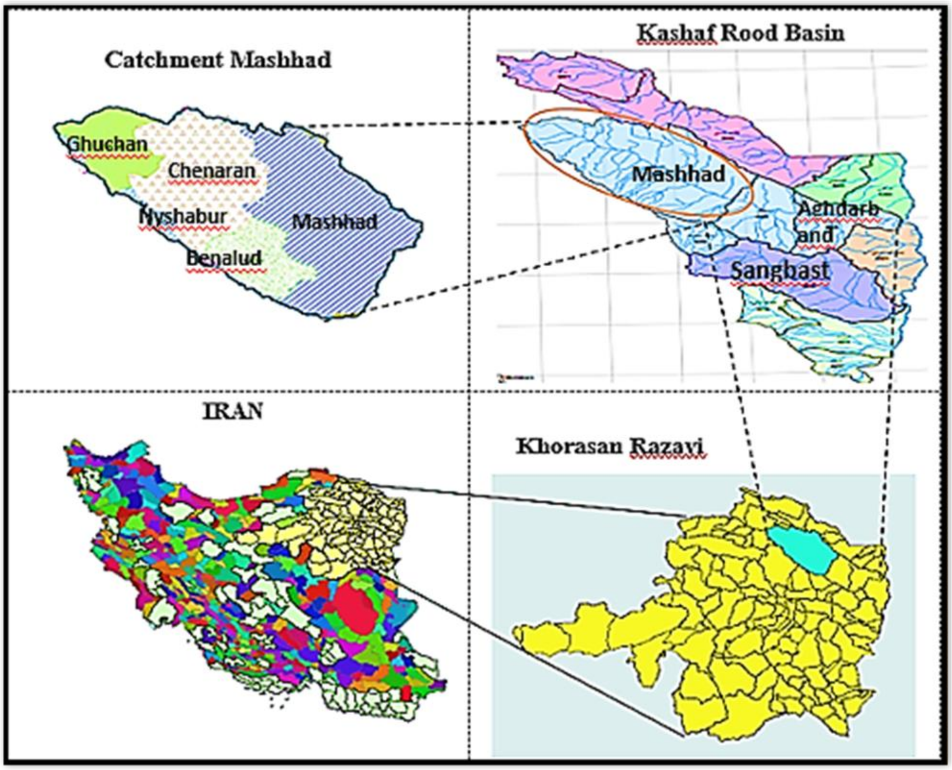

Figure 3. Location of study srea: province of Razavi Khorasan, Kashaf Rood basin, and Mashhad city.

Table 1. List of basic crop data

pesticides (Kg/ha)	Fertilizer consumption (tons/ha)	Yield (Ton/ ha)	Gross water requirement (MCM/ha)	Electricity consumption (kw.h/ ha)	product
1.391	392	4/2	6644	2969	Wheat
0.962	364	3/6	5577	2492	Barley
4.38	572	35	20266	9057	SugarBeet
4.18	606	50	1511	6842	Onion
3.64	706	35	19600	8759	Potato
2.97	641	40	18022	8054	Tomato
0.957	253	11	18511	8272	Alfalfa
2.13	543	55	13600	6078	Maize
4.18	456	25	13111	5859	Cucumber

Source: Khorasan Razavi Agricultural Jihad Organization, 2019-2020.

Table 2. Cultivation area of agricultural products in Mashhad (ha)

Perc	MOP	MinCO2	MaxProfit	Current	products
-51	2637	2637.05	2637.05	5385	Alfalfa
50	31861	10417.89	23936.89	21261	Barley
-51	2185	2185.4	2193.86	4460	Maize
-21	731	730.92	1127.45	920	Cucumber
-34	762	761.91	1426.26	1149	Onion
-42	187	187.20	394.68	323	Potato
-40	1436	1435.72	2096.89	2385	Sugarbeet
-43	3333	3332.65	7271.71	5869	tomato
-23	17057	10904.46	19624.96	22254	Wheat
-29	187710	126853.20	189540.70	256024	Total

A comprehensive analysis of the total cultivated area for crops is presented in Table 2. This analysis revealed a 26% decrease in the cultivated area for the profit maximization objective, from 189,540.70 hectares in the current model to 256,024 hectares.

In the multi-objective model, the total

cultivated area for the greenhouse gas emission minimization objective (the environmental objective) decreased by 50%, from 126,853.20 hectares to 256,024 hectares. Moreover, greenhouse gas emissions for all crops based on the WEF nexus approach underwent a 50% reduction.

Fig. 4 shows the environmental and economic impacts in the optimal pattern and the current level in the adaptation scenario to changes in cultivated areas. According to the observations, the amount of greenhouse gas emissions, referred to as environmental impacts in this study, increases at the current level, which, based on the adaptation scenario of the nexus approach in the multi-objective model, decreases by 162 million tons, equivalent to 21%. The total cost reduction for the entire basin in the current pattern is 10,419 million rials, and in the multi-objective pattern, it is 6,232 million rials, a decrease of 40%. In addition, the gross profit of farmers (economic dimension) in the scenario of adaptation to changes in cultivated area in the multi-objective model increased by 3,982 billion rials, which is 40%. This indicates that applying the nexus approach in studies and policy-making, in addition to sustainability and proper resource management to control environmental impacts, also brings significant economic benefits to farmers.

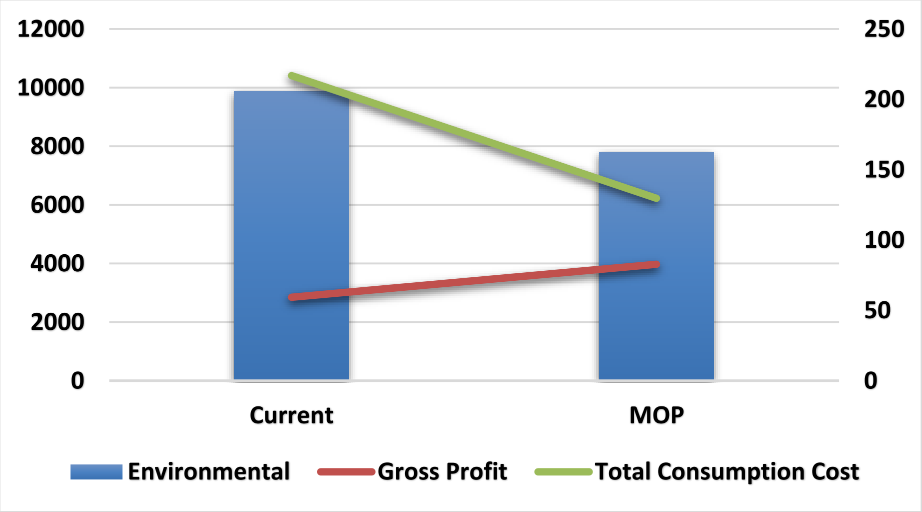

Figure 4. Comparison of environmental and economic impacts based on the nexus approach

The reduction of the cultivated area due to the nexus has been observed not only in the catchment areas of eastern Iran but also in the northern (Kalbali et al., 2021) and central (Layani & Bakhshoodeh, 2022; Eslami et al., 2019) regions of Iran. In addition, studies (Ikram et al., 2020; Lee et al., 2020) indicate that due to the decline in groundwater levels and the intensification of global warming in regions of China (Li et al., 2019; Peng et al., 2022), a reduction in the area under crops has also been observed. This calls for wise measures at both the national and global levels to manage resources in an integrated approach in line with the principles of sustainable development.

It should be noted that according to the results of studies (Kalbali et al., 2021; Safaee et al., 2021), the reduction in the cultivated area aimed at profit maximization for some crops in eastern and northeastern Iran including onions (24%), tomatoes (23%), potatoes and cucumbers (22%), and barley (12%). Conversely, based on the results of studies (Li et al., 2019; Emamzadeh et al., 2016; Ding et al., 2023), a significant decrease in the area cultivated for profit maximization of fodder crops in eastern Iran and northern China is observed as follows: alfalfa and maize silage (50%) and sugar beet (12%). In addition, the slightest change in area for profit maximization is calculated for wheat in the northeastern basin of Iran, which is 11%. In contrast, there has been a significant decrease in other basins in Iran (Safaee et al., 2021; Bagheri, 2018) and different countries (Karabulut et al., 2018; Obsi et al., 2023).

Therefore, optimizing cropping patterns based on the Sustainability approach, as observed in studies (Lee et al., 2023; Ahani et al., 2024; Li et al., 2019), will result in optimal use of chemical fertilizers, cost reduction, and ultimately a reduction in greenhouse gas emissions. Overall, the proposed comprehensive solution for optimizing cropping patterns based on the Linkage model allows farmers to simultaneously experience proper resource management, cost reduction, and environmental impact mitigation, in line with the results of various studies (Esteve et al., 2015; Fu et al., 2018).

In general, it is necessary to allocate more area to forage crops such as alfalfa, barley, corn silage, and wheat than to other crops such as tomatoes, sugar beets, potatoes, and onions in the irrigated cropping pattern to achieve higher profits and reduce environmental impacts. The results of the studies (Eslami et al., 2019; Al-Saidi & Elagib, 2017) also showed that the objectives of the producer play a crucial role in the design of the cropping pattern in selecting the type and area of crops. In other words, a cropping pattern designed based on economic objectives, such as the current pattern in the region, will primarily focus on profit-oriented objectives. However, by implementing the proposed cropping pattern based on the WEF nexus, the adverse effects of pollutants on water, soil, and air and production costs will be reduced in the long term.

According to the results of Fig. 4, the application of the Integrated approach in the agricultural sector, in addition to reducing agricultural costs as shown in studies (Li et al., 2019; Esteve et al., 2015; Safaee et al., 2021), leads to the reduction of the use of chemical fertilizers and pesticides, reduction of energy costs, increased water productivity, reduced waste, increased production, and ultimately increased profitability through the production of sustainable products in the long run. Moreover, it leads to sustainability and improved environmental conditions as observed in the study (Eslami et al.,2019; Marzban et al., 2020) in central regions of Iran.

4. Conclusion

The study evaluated the optimal cropping pattern for irrigated crops in the Kashafrud watershed based on the nexus approach. The results showed that considering the MOP model based on economic and environmental issues, there was a significant reduction in the cultivated area of alfalfa, barley, and corn silage. In other words, to achieve the goals of maximizing profit and minimizing environmental impact, the area planted to forage crops, including barley and alfalfa, decreases while the area planted to onions, tomatoes, potatoes, and cucumbers in irrigated systems increases. The study of the economic and environmental dimensions in selecting the cropping pattern of the basin showed that the emphasis on different criteria leads to different results. Therefore, the decision and the use of different indices must be based on the importance of each option in the area studied. Thus, considering the optimal cropping pattern obtained in this study based on the Integrated model allows farmers to simultaneously maintain economic income while following environmental considerations to reduce negative environmental impacts in their cropping pattern. Overall, determining the optimal cropping pattern by integrating WEAP and MOP in the region can be proposed as a sustainable approach to managing environmental impacts, reducing economic and environmental risks, and providing favorable and comprehensive economic outcomes for the region. Finally, recommendations based on the results of the study were presented:

Considering the reduction in the area of some crops such as wheat, alfalfa, sugar beet, onion, and cucumber in the multiobjective model, steps should be taken to ensure food security through overseas cultivation or land use planning and its precise implementation. Solutions such as implementing optimal cropping patterns based on water, energy, and food security constraints should be considered.

Another result was the increase in the cultivated area of crops to maximize profit for onions, tomatoes, and potatoes in the multiobjective planning model. Considering that the area of these crops has decreased intending to minimize greenhouse gas emissions, it is recommended that the current pattern be changed to produce crops with less environmental impact, such as wheat, alfalfa, and onions. In this way, to increasing the gross profit of farmers, environmental damage and destructive consequences will also be prevented.

Since the Integrated approach integrates all the different economic, social, technical, and environmental components and considers them concerning each other, the use of multi-objective mathematical planning models is very important in this regard. It is suggested to use other multi-objective problem-solving algorithms, such as metaheuristic algorithms, in future studies.

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Competing interest

This expression states that there is no conflict of interest to disclose

Authors contribution statement

E.A. and S.Z. conceived of the presented idea. M.M. developed the theory and performed the computations. E.A. verified the analytical methods. Also, S.Z. and M.M. investigated the computational results of this work. All authors discussed the results and contributed to the final manuscript

5. References

Ahani, Elahe ; Ziaee, Saman ; Mohammadi, Hamid ; Mardani Najafabadi, Mostafa ; Mirzaei, A. (2024). An Investigation into the Effects of Climate Change on Water-Energy-Food Nexus: A New Mathematical Programming Approach. *International Journal of Environmental Research, 18*(2). https://doi.org/10.1007/s41742-024-00567-9

Al-Saidi, M., & Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy, and food nexus. *Science of The Total Environment, 574,* 1131–1139. https://doi.org/https://doi.org/10.1016/j.scitotenv.2016.09.046

Bagheri A. (2018). Water resources management with water, energy, and food linkage approach. *The First International Conference on Water Consumption Management*.

Chen, L., Huang, K., Zhou, J., Duan, H.-F., Zhang, J., Wang, D., & Qiu, H. (2020). Multiple-risk assessment of water supply, hydropower, and environment nexus in the water resources system. *Journal of Cleaner Production, 268,* 122057. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.122057

Ding, T., Fang, L., Chen, J., Ji, J., & Fang, Z. (2023). Exploring the relationship between water-energy-food nexus sustainability and multiple ecosystem services at the urban agglomeration scale. *Sustainable Production and Consumption, 35*(12), 184–200. https://doi.org/10.1016/j.spc.2022.10.028

Emamzadeh, S. M., Forghani, M. A., Karnema, A., & Darbandi, S. (2016). Determining an optimum pattern of mixed planting from organic and non-organic crops about economic and environmental indicators: A case study of cucumber in Kerman, Iran. *Information Processing in Agriculture, 3*(4), 207–214. https://doi.org/https://doi.org/10.1016/j.inpa.2016.08.001

Eslami Z., janatrostami S., A. A. (2019). Application of Modeling in Management of Water, Energy, and Food Nexus. *Journal of Water and Sustainable Development, 6*(2), 1–8.

Esteve, P., Varela-Ortega, C., Blanco-Gutiérrez, I., & Downing, T. E. (2015). A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture. *Ecological Economics, 120,* 49–58. https://doi.org/https://doi.org/10.1016/j.ecolecon.2015.09.017

FAO. (2018). United Nations climate change conference. *FAO's Work on Climate Change*, 5–19.

Forni, L. G., Medellín-Azuara, J., Tansey, M., Young, C., Purkey, D., & Howitt, R. (2016). Integrating complex economic and hydrologic planning models: An application for drought under climate change analysis. *Water Resources and Economics, 16,* 15–27. https://doi.org/https://doi.org/10.1016/j.wre.2016.10.002

Fu, Y., Zhao, J., Wang, C., Peng, W., & Wang, Q., and Zhang, C. (2018). The virtual Water flow of crops between intraregional and interregional in mainland China. *Agricultural Water Management, 208,* 204–213.

Hoff, H. (2011). Understanding the NEXUS. Background paper for the Bonn, nexus conference: The water, energy, and food security nexus solutions for the green economy. *The Water, Energy, and Food Security Nexus.* https://doi.org/https://www.sei.org/publications/understanding-the-nexus/

Ikram, M., Zhang, Q., Sroufe, R., & Shah, S. Z. A. (2020). Towards a sustainable environment: The nexus between ISO 14001, renewable energy consumption, access to electricity, agriculture and CO2 emissions in SAARC countries. *Sustainable Production and Consumption, 22,* 218–230. https://doi.org/https://doi.org/10.1016/j.spc.2020.03.011

Kalbali, E., Ziaee, S., Najafabadi, M. M., & Zakerinia, M. (2021). Approaches to adapting to impacts of climate change in northern Iran: The application of a Hydrogy-Economics model. *Journal of Cleaner Production*, *280*, 124067. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124067

Karabulut, A. A., Crenna, E., Sala, S., & Udias, A. (2018). A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. *Journal of Cleaner Production*, *172*, 3874–3889. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.05.092

Layani, G., & Bakhshoodeh, M. (2022). Effects of climate change on the agricultural sector in the Kheirabad River Basin: Application of WEAP Software. *Agricultural Economics Research*, *13*(4), 208–223. https://doi.org/10.30495/JAE.2021.21701.2030

Lee, S.-H., Choi, J.-Y., Hur, S.-O., Taniguchi, M., Masuhara, N., Kim, K. S., Hyun, S., Choi, E., Sung, J., & Yoo, S.-H. (2020). Food-centric interlinkages in agricultural food-energy-water nexus under climate change and irrigation management. *Resources, Conservation and Recycling*, *163*, 105099. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105099

Li, M., Fu, Q., Singh, V. P., Ji, Y., Liu, D., Zhang, C., & Li, T. (2019). An optimal modeling approach for managing agricultural water-energy-food nexus under uncertainty. *Science of The Total Environment*, *651*, 1416–1434. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.09.291

Marzban Z., Asghare Pour M. R., Ghanbari A., N. A. . (2020). Ramroudi M., and seyd Abadi E. 2020. Reducing environmental effects by redesigning the cultivation pattern with the approach of using cycle assessment Life and Multipurpose Planning (Case Study: East of Lorestan Province). *Scientific Knowledge of Agricultural Knowledge and Sustainable Production*, *30*(3), 311–330.

Mirabi M, & Krabi M. (2020). Integrated modeling in the optimal management of water, energy, and food resources with a correlated approach. *11th National Congress of Civil Engineering*.

Monem M.J., Delavar M., & Hosseini S.M. (2019). Application and Evaluation of Water, Food, and Energy (NEXUS) in Irrigation Networks Management: Case Study of Zayandehrud Irrigation Network. *Journal: IRANIAN JOURNAL OF IRRIGATION AND DRAINAGE*, *14*(1), 275–285.

Obsi Gemeda, D., Korecha, D., & Garedew, W. (2023). Determinants of climate change adaptation strategies and existing barriers in Southwestern parts of Ethiopia. *Climate Services*, *30*, 100376. https://doi.org/https://doi.org/10.1016/j.cliser.2023.100376

OECD. (2014). *OECD Environmental Performance Reviews*. OECD Publishing. https://doi.org/doi.org/10.1787/9789264213715-en.

Peng, W., Zheng, H., Robinson, B. E., Li, C., & Li, R. (2022). Comparing the importance of farming resource endowments and agricultural livelihood diversification for agricultural sustainability from the perspective of the food-energy-water nexus. *Journal of Cleaner Production*, *380*, 135193. https://doi.org/10.1016/J.JCLEPRO.2022.135193

Safaee, V., Pourmohamad, Y., & Davari, K. (2021). Integrated Approach of Water, Energy, and Food in Water Resources Management (Case Study: Mashhad Catchment). *Iranian Journal of Irrigation and Drainage*, *14*(5), 1708–1721. https://doi.org/20.1001.1.20087942.1399.14.5.18.9

Samadi-Foroushani, M., Keyhanpour, M. J., Musavi-Jahromi, S. H., & Ebrahimi, H. (2022). Integrated Water Resources Management Based on Water Governance and Water-food-energy Nexus through System Dynamics and Social Network Analyzing Approaches. *Water Resources Management*, *36*(15), 6093–6113. https://doi.org/10.1007/s11269-022-03343-6