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Mathematical approaches to enhancing crop efficiency in water-limited environments

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Abstract

Due to the extensive border areas and varied climates across the country, establishing an effective cultivation pattern is essential for maximizing the use of production factors and resources. This is particularly important in addressing the significant issue of water scarcity. In recent decades, mathematical planning models have become increasingly popular for crafting agricultural policies, optimizing cultivation strategies, and managing agricultural resources. A study conducted in Mazandaran province utilized a two-stage simple random sampling technique, which is known for its reliability, allowing results to be generalized to the entire population when principles are correctly applied. This method aligns with the Iranian Statistics Center's practices, ensuring consistency in statistical methodologies. The study utilized an ideal planning model, specifically goal programming, to integrate diverse and sometimes conflicting objectives, guiding decision-makers toward optimal outcomes. The findings suggest that adopting sustainable practices could streamline crop cultivation in the region, potentially phasing out certain products from the current agricultural system. This transition is projected to boost gross revenue by 775,000 $ compared to existing models. Additionally, the research indicates that the use of fertilizers could decrease: phosphate by 102.12 tons, nitrogen by 65.02 tons, and potash by 38.5 tons, alongside significant reductions in chemical substances like herbicides, insecticides, and fungicides.

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Introduction

Iran boasts a rich agricultural heritage, with Mazandaran province frequently recognized for its agricultural productivity, especially in horticultural crop cultivation. However, traditional farming techniques are increasingly proving inadequate to meet the surging demand for these crops. To confront this challenge effectively, there is a pressing need to enhance productivity through the optimization of horticultural crop cultivation in Mazandaran by integrating mechanization practices (Moir and Valenzuela, 2024). The integration of mechanization into farming has shown considerable promise in improving efficiency, curtailing labor costs, and elevating crop yields. Employing modern machinery and technology in the cultivation process enables farmers to achieve higher production levels and greater profitability. This case study focuses on exploring the impact of mechanization indicators on horticultural crop cultivation in Mazandaran. By examining data regarding the implementation of mechanization practices—including tractors, sophisticated irrigation systems, and advanced harvesting equipment—we aim to pinpoint the crucial factors that drive successful crop cultivation in this region (Saadi et al., 2025; Taherzadeh-Shalmaei et al., 2021). Ultimately, the goal is to provide insights that help farmers in Mazandaran enhance their horticultural practices, fostering a more sustainable and economically viable agricultural sector in Iran (Mostashari-Rad et al., 2021). Agriculture is a pivotal component of economic growth and development, playing a significant role in the financial progress of nations. Today, the vital challenge of fulfilling the world's food demands has catalyzed food security into a primary objective on governmental agendas (◌a. Kaab et al., 2023; Vogel et al., 2019). With societal expansion and the relentless march of globalization, resource management has become increasingly complex. Simultaneously, population growth and economic development have escalated food demand, necessitating the adoption of modern agricultural methods and innovations, including fertilizers and pesticides. Unfortunately, the overuse and mismanagement of these chemicals have led to adverse health impacts for consumers and significant environmental degradation (Nabavi-Pelesaraei et al., 2021). The geographic diversity of Iran, characterized by its expansive borders and varying climates, underscores the need for tailored cultivation strategies. These strategies should maximize the utilization of vital production resources, particularly water, in an efficient manner (Ghasemi-Mobtaker et al., 2024). An effective cultivation strategy involves crafting an agricultural system that delivers sustainable economic benefits, aligns with national policies, leverages localized agricultural knowledge, and respects ecophysiological principles to protect the environment (Engler and Krarti, 2021). Consequently, the Ministry of Agricultural Jihad is tasked with determining agricultural land allocation and creating cultivation plans for each region. These plans must be informed by a comprehensive analysis of factors such as resource availability, market demand, production costs, crop yields, and strategic policy objectives. Decisions on whether to grow agricultural or horticultural crops should be rooted in an assessment of infrastructure, social factors, economic viability, and technological capabilities, aiming to ensure essential resources are secured to meet national needs (de Carvalho et al., 2016; Loveimi et al., 2025). Often, economic analyses emphasize the enhancement of farmers' economic conditions, often at the expense of environmental considerations. Therefore, it becomes critical for agricultural managers to simultaneously weigh a range of economic and environmental goals when planning agricultural activities (Ma et al., 2018). Contemporary agricultural management recognizes that while economic profitability remains essential, the environmental footprint of agricultural practices must also be taken into account (Kaab et al., 2023; Verma et al., 2016). Considering that the overarching aim of agricultural management and mechanization science is the efficient allocation of scarce resources among competing needs, the implementation of innovative methods and techniques is essential. One effective approach for resource optimization is the application of mathematical programming models (Wu et al., 2018). These models have become increasingly popular in the agricultural sector, aiding in tasks like policymaking, optimizing crop rotation, and managing inputs. This study proposes utilizing a multi-objective planning model to identify optimal crop rotation patterns in Mazandaran province. By addressing multiple conflicting objectives faced by managers, this method provides a practical alternative to conventional economic planning practices. We anticipate that systematic implementation of this model will not only yield significant benefits for producers but also attract the interest of agricultural planners (Fathollahi-Fard et al., 2023). With the global population projected to reach 9 billion by 2050, current agricultural practices may not suffice to sustain food production, signaling an urgent need for transformative change. Leveraging and adapting existing agricultural technologies is a promising pathway toward achieving sustainable food production goals (Behnia et al., 2025; Nyanga et al., 2016). Establishing a knowledge base to support these adaptations is critical for the success of these efforts. Key strategies for enhancing agricultural productivity include improving yield outcomes, investing in sustainable land management, and optimizing the utilization of resources such as organic fertilizers, resilient crop varieties, and soil and water conservation measures (Probst, 2018). A related study aims to optimize energy usage and minimize greenhouse gas (GHG) emissions in horticultural crop production in Guilan Province, Iran. Data collected from producers of various crops, including eggplant, garlic, tea, hazelnut, kiwifruit, and tangerine, was analyzed through surveys. The research examines GHG emissions from both on-farm and off-farm activities using data envelopment analysis to optimize energy usage and emissions reduction. Findings revealed that tea production exhibited the highest energy consumption, whereas kiwifruit recorded the least energy usage. Notably, kiwifruit and eggplant demonstrated high technical efficiency, while tangerine and tea achieved strong scores in pure technical efficiency. Kiwifruit orchards were particularly efficient in energy savings, consuming 8,316.29 MJ ha^{-1}, with potential energy savings identified for nitrogen fertilizers and diesel fuel across most crops. Furthermore, kiwifruit production presented the highest potential for reducing GHG emissions, indicating that optimal fertilizer management could lead to significant reductions in both emissions and energy consumption (Mostashari-Rad et al., 2019).

The exploration of novelty in mathematical approaches to enhancing crop efficiency in water-limited environments primarily revolves around developing innovative models and analytical techniques that optimize water use. Advanced mathematical frameworks, such as systems of differential equations, optimization algorithms, and machine learning methods, are employed to simulate plant growth, water uptake dynamics, and soil-plant interactions. These models enable precise prediction and management of irrigation schedules, seed selection, and nutrient application tailored to specific climatic and soil conditions, thereby reducing water wastage. Additionally, they facilitate the design of resilient crop varieties through data-driven insights by analyzing genetic and environmental interactions. Integrating remote sensing data with mathematical models further enhances the ability to monitor crop health and water status in real time, empowering farmers to make informed decisions that maximize yield under water constraints. Overall, these novel mathematical strategies are crucial in advancing sustainable agriculture by improving water efficiency, increasing resilience to drought, and ensuring food security amidst increasing climate variability.

Materials and methods

Case study and data collection

The current research employed questionnaires, interviews, and official statistics from the Ministry of Jihad Agriculture over the past decade as data collection methods. The questionnaire consisted of two main sections: the first explored the personal and professional characteristics of farmers in the region, while the second assessed the impact of appropriate technology and mechanization on agricultural development, focusing on technical, economic, and social indicators of agricultural mechanization. To ensure the questionnaire's validity, feedback was collected from university professors, graduate students, and experts from Jihad Keshavarzi and research centers in Mazandaran province (Nejad et al., 2023). This study utilized a two-stage simple random sampling method, which is considered the most straightforward sampling technique and yields reliable results that can be generalized to the larger population, provided the sampling principles are adhered to. The choice of this method was influenced by its consistency with the standards set by the Iranian Statistics Center and the Management and Planning Organization. In this method, every unit in the population has an equal chance of being selected at each stage (Ahmadbeyki et al., 2023). The research focused on farmers in the central region of Mazandaran province, including cities such as Amol, Babol, Ramsar, Sari, and Behshahr. The sample size was determined using Equation 1 (Cochran, 1977), and the farmers were randomly selected with a confidence level of 95%.

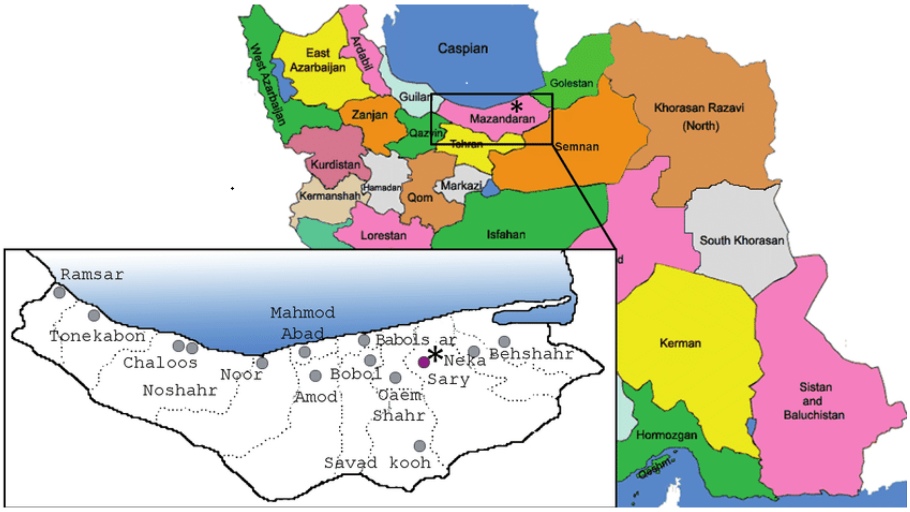

Figure 1. The location of the study about Mazandaran province of Iran.

$$n = \frac{Nt^2S^2}{Nd^2 + t^2S^2} \quad (1)$$

N represents the total population size in the area, while t indicates the confidence coefficient, which is obtained from the Student's t table, assuming a normal distribution of the targeted trait. S^2 refers to the estimated variance of the trait being investigated, d signifies the desired level of probability accuracy, and n is the sample size. For this research, the statistical population comprised 448 individuals, leading to an estimated sample size of 89 individuals based on equation (1). To identify the optimal cultivation pattern, collected data on farmers' income and expenses separately. This information was obtained from the Jihad Keshavarzi organization's statistics for Mazandaran province and through interviews with farmers in the selected cities.

In this study, the preferred approach to planning is employed. Among various planning models, a notable and adaptable one for this purpose is the goal programming or multi-objective programming model. This model is capable of accommodating diverse and at times conflicting objectives within a single system, thereby assisting the manager in attaining optimal goals. The modeling principles in linear ideal programming closely resemble those of linear programming. The key difference lies in how goals, ideals, their priorities, and constraints are defined and formulated. This method is commonly used in multi-objective decision-making, where an ideal value is established for each objective. The final ideal planning model involves four decision variables for the entire region.

Functional constraints in this model encompass factors like cultivated land area, types of fertilizers (phosphate, nitrogen, and potash), types of pesticides (herbicide, insecticide, and fungicide), labor, water usage, machinery services, and financial resources. Machinery services, water consumption, and human labor are individually factored in for four stages: preparation, planting, growth, and harvesting over a span of 12 months. Regarding the capital limitation, the coefficients of cultivation variables (products) are linked to the variable costs of those products, and the total available capital is set as equivalent to all the variable costs within the current model.

Ideal planning method

In planning pattern development programs, the optimal mix of production factors is determined based on the ideal combination of goals for each time period. Additionally, it is crucial to prioritize goals in alignment with the production system within the deterministic multi-objective model framework (Mosadeghi et al., 2015).

$$\begin{aligned} &Min \quad D = \sum_j \omega_j h_j (d^+, d^-) \\ &s.t: \quad g_i(x) \le 0, \\ &\qquad f_l(x) + d_l^- - d_l^+ = b_l \qquad l = 1,...,k. \\ &\qquad x, d^+, d^- \ge 0 \\ &\qquad d_l^+ . d_l^- = 0 \qquad l = 1,...,k. \end{aligned} \tag{2}$$

In defining the optimal cultivation pattern, we consider a vector Z representing weighted objectives, a vector of decision variables indicating positive and negative deviations from the i-th ideal, and a linear function incorporating the significance of ideals in the model using w elements (weights). This function delineates the relationships among decision variables, constraints, and coefficients in the model.

Table 1. Decision-making variables, limitations and coefficients related to the model in the design of optimal cultivation pattern.

Variable	Definition	Unit
A_{CS}	Land area available for planting different crops in S season	ha
Ls	The total amount of water estimated and available during the S season	m³
EWS	Total cash capital available for resources during the year	$
ETC	Estimated and available labor force throughout the year in terms of person-days	person-days
EMD	Total working hours of available machines throughout the year in hours	hours
EMH	The total amount of chemical fertilizers used throughout the year in kilograms	kg
EMN	The total amount of chemical poisons consumed during the year in liters	liters
EMP	The number of labor required for each hectare of product C in season S	man per day
MD_{CS}	Working hours of machines required for each hectare of product C in season S	hours
MN_{cs}	Chemical fertilizers used per hectare of product C in season S (kg)	kg
MPO_{cs}	Chemical pesticides used per hectare of product C in season S (liters)	liters
MH_{CS}	The volume of water required per hectare of product C in season S	m³
W_{CS}	Average cost of different resources per hectare of crop C in season S	$\$ ha^{-1}$
AVC_{CS}	Yield per hectare of product C in season S	kg
EP_{CS}	Desired level of production (optimal target) for product c in kilograms	kg
ATP_{CS}	Market price at harvest time of crop c in season s in $ per kilogram	$\$ kg^{-1}$
MP_{CS}	Total expected (desired) market value of different products	$
EMP	The ratio of annual product production between u and w of the product,	ratio
$R_{u,w}$	Estimated gross income per unit of crop level c in season s in $ per hectare	$\$ ha^{-1}$
PR_{cs}	The optimal level of gross income desired by the manager for product c in season s in $	$
PRT_{cs}	Deviation in a positive direction from desirable (ideal) goals.	deviation
d_i^+	Deviation in a negative direction from desired (ideal) goals.	deviation
d_i^-	Land area available for planting different crops in S season	ha

Now, according to the variables defined above, the organic structure of ideals considered in the model can be shown as below.

Objectives of land use

The key issue for area management is determining the optimal cropping pattern for various crops. This involves deciding the allocation of land for each crop to align with the manager's objectives. Therefore, equations pertaining to land constraints have been incorporated into the model (Amos et al., 2018).

$$\sum_{c=1}^{c} A_{cs} + d_i^- - d_i^+ = L_s, \quad s = 1,2,3 \quad i = 1,2,\dots,n \tag{3}$$

where n is the number of land constraints.

Ideal goals of production

The equations regarding production constraints, considering the allocation of planting different crops over the course of the year, are inputted into the model in the following manner (Shisanya and Mafongoya, 2016):

$$\sum_{c=1}^{C} A_{CS} + d_s^- - d_s^+ = L_s \qquad for\ \ s = 1,2,3$$
$$for\ \ c = 1,2,\dots,c \tag{4}$$
$$\sum_{S=1}^{C} A_{CS}.EP_{CS} + d_{s+c}^- - d_{s+c}^+ \tilde{\leq} ATP_C$$

Water consumption goals

One critical aspect of economic sustainability is the preservation of water resources. Given Iran's arid climate, it is crucial to focus on sustainability in the country, emphasizing the sustainable use of natural resources with future interests in mind. Preserving water reserves is a key objective for sustainable development authorities. The National Environmental Document of Iran outlines the organization's vision up to 1404 AH, including a target to reduce water consumption in the agricultural sector by 13% from the 2010 baseline to 1404, equivalent to an annual decrease of 0.93%. This target is distributed across 12 months based on seasonal water requirements, aiming for a consistent reduction in water usage. The equations detailing water consumption objectives for various levels of seasonal crop production are incorporated into the model as follows (Garcia et al., 2021).

$$\sum_{c=1}^{c} A_{cs}.W_{cs} + d_i^- - d_i^+ = EW_s, \quad s = 1,2,3 \tag{5}$$

Results and Discussion

Cultivation pattern of garden crops

Due to the special features of the cropping pattern, cropping frequency, cropping operations calendar and irrigation of various common crops in the regions, a very wide range of cropping combinations, the existence of arable land limitations and the serious competition of crops in obtaining the required water (which is caused by of different periodic types common in the regions) the most important model containing the above information is mathematical planning models. The first stage model of the first prioritization structure Eq. (11):

$$\begin{aligned}
&Minimize\ (d_1^+ + d_2^+ + d_3^+)\\
&S.T.:\\
&X_1 + X_2 + X_3 + d_1^- - d_1^+ = 2150\\
&X_4 + X_5 + X_6 \qquad + d_2^- - d_2^+ = 3140\\
&X_7 + X_8 \qquad + d_3^- - d_3^+ = 1550\\
&A_{cs} \geq 0, \quad d_i^+.d_i^- = 0
\end{aligned} \tag{11}$$

The unsaid aspect of this model lies in the coefficients assigned to deviations in the objective function. These coefficients reflect the relative importance of each deviation compared to others, often determined subjectively by the manager. They represent the opportunity cost associated with each deviation. For instance, when a coefficient of 2 is assigned to one deviation and a coefficient of 1.5 to another, it indicates their importance relative to other deviations within the same priority level. The next step is to select the optimal prioritization structure among the available options.

The findings presented in Table 2 reveal a shift in cultivation patterns. Specifically, the cultivation of oranges, persimmons, and Japanese parsnips is being reduced, while the areas dedicated to oranges, tangerines, and blue kiwis are expanding. Additionally, introducing pomegranate and olive cultivation is recommended to align with this new pattern. The optimized planning model highlights that moving toward sustainability will require a reduction in crop variety, leading to the elimination of certain products. This transition involves specializing in crops that are best suited to the region's resources. Furthermore, the research projects an increase in gross returns to $1 billion compared to the current model. It also estimates reductions in the use of fertilizers: 102.12 tons of phosphate, 65.02 tons of nitrogen, and 38.5 tons of potash. Additionally, it is anticipated that consumption of chemical pesticides—including herbicides, insecticides, and fungicides—will decrease by 850.27 liters, 1,052.85 liters, and 9,400.23 liters, respectively.

This city lies in the Tehran province, bordering coastal cities like Babolsar and Faridunknar to the north, Simorgh city to the northeast, Qaimshahr and Northern Swadkoh to the east, Swadkoh city to the southeast, Amol city to the west, and the Alborz mountain range and Firozkoh city to the south.

Table 2. The results of the pattern of horticulture in Amol city.

Product Name	Variable	Pattern		
		Area under cultivation available (ha)	Area under cultivation Optimum (ha) ideal	Deviations
Orange	X1	1694.70	2400.00	$d_1^- = 96.15$
Tangerine	X2	774.00	820.00	$d_2^- = 614.77$
Orange	X3	38.80	0.00	$d_3^- = 1140.90$
Pomegranate	X4	68.11	48.00	$d_{11}^- = 908.14$
Persimmon	X5	33.00	0.00	$d_{12}^- = 1487.60$
Kiwi	X6	159.43	486.00	$d_{13}^- = 2638$
Japanese Parsley	X7	15.80	0.00	$d_{14}^+ = 436.86$
Olive	X8	481.00	450.00	$d_{15}^- = 4871.40$

The findings presented in Table 3 reveal that the proposed cultivation plan will phase out pomegranate, olive, and Japanese parsnip crops, while expanding the cultivation of orange, persimmon, olive, and kiwi. It also recommends incorporating mandarins and oranges into the current cultivation pattern. The optimal planning model suggests that transitioning toward sustainability will streamline crop varieties in the region, eliminating certain products from the existing model.

To ensure sustainable progress in this area, it is crucial to specialize in cultivating select products that align with the region's resources. The research forecasts a rise in gross revenue to $5 billion compared to the current model, along with anticipated reductions in fertilizer usage: phosphate by 25.88 tons, nitrogen by 55.00 tons, and potash by 41.5 tons. Additionally, the use of chemical pesticides— herbicides, insecticides, and fungicides—is expected to decrease by 640.12 liters, 950.2 liters, and 8,400.32 liters, respectively.

Sari City, located in the eastern part of Mazandaran province, Iran, consists of six central districts: Rudpi North, Rudpi, Chahardangeh, Dodangeh, and Kalijan Rastaq. It is bordered by the Mazandaran Sea to the north, Miandrod and Neka cities to the east and south, and Semnan province to the south, with Qaemshahr, Swadkoh, and Joibar to the west. As the second most populous city in Mazandaran province, after Babol, Sari serves as a central hub for both the city and the province.

The study also provides a bibliometric review of water sustainability disclosures in agriculture, analyzing 257 publications from 2015 to 2024 using the PRISMA 2020 methodology. It highlights an increase in research driven by sustainability regulations, identifies key themes such as corporate practices, and emphasizes the need for better integration and standardization in disclosures (Wahyuningrum et al., 2025).

Moreover, commercialization and collaboration are essential for sustainable applied research. This study explores the perspectives of 32 leaders from 24 research institutes in Sri Lanka regarding the management of these aspects in R&D. The findings offer optimal models for commercialization and collaboration, fostering synergies to enhance innovation, and propose a decision-making model for effective integration into performance management systems.

Table 3. The results of the pattern of horticulture in Amol city.

Products name	Variable	Pattern		
		Area under cultivation available (ha)	Area under cultivation Optimum (ha) ideal	Deviations
Orange	X1	16423.9	1824.00	$d_1^- = 81.43$
Tangerine	X2	2032.3	2010.00	$d_2^- = 609.77$
Orange	X3	278.5	2456.00	$d_3^- = 1148.09$
Pomegranate	X4	142.2	0.00	$d_{11}^- = 943.15$
Persimmon	X5	148	505.00	$d_{12}^- = 487.60$
Kiwi	X6	448.41	740.00	$d_{13}^- = 1788$
Japanese Parsley	X7	15.5	0.00	$d_{14}^+ = 315.86$
Olive	X8	22	0.00	$d_{15}^- = 734.15$
Lemon	X9	55	120.00	$d_{15}^- = 461.40$

The findings presented in Table 4 reveal that the revised cultivation plan phases out orange, pomegranate, kiwi, and Japanese parsnip crops. In contrast, the cultivation areas for orange, sweet lemon, and figs will be expanded. Additionally, the introduction of persimmons, mandarins, and olives is recommended to align with this new strategy.

This shift toward sustainability in cultivation practices results in a more focused product range for the region, requiring the removal of certain crops from the current model. Essentially, to achieve sustainability, it's crucial to specialize in growing products that are well-suited to the region's resources.

The optimized planning model forecasts a gross return of $1.5 billion and a reduction in the use of phosphate, nitrogen, and potash fertilizers by 0.123, 21.68, and 41.5 tons, respectively. It also projects a decrease in the consumption of various chemical pesticides, including herbicides, insecticides, and fungicides, by 1,025.6 liters, 1,850.5 liters, and 12,400.8 liters, respectively.

Ramsar, located in Mazandaran province, northern Iran, was historically known as Sars-e-Sar. It is the westernmost city in Mazandaran, bordered to the east by Shiroud, to the west by Chabaksar in the Oshian district of Gilan, with the Alborz Mountains to the south and the Caspian Sea to the north.

Table 4. The results of the horticulture pattern of Sari city.

Products name	Variable	Pattern		
		Area under cultivation available (ha)	Area under cultivation Optimum (ha) ideal	Deviations
Orange	X1	9968.84	14254.00	$d_1^- = 102.15$
Tangerine	X2	8984.58	9200.00	$d_2^- = 895.77$
Orange	X3	319.41	0.00	$d_3^- = 3014.80$
Pomegranate	X4	84.4	0.00	$d_{11}^- = 1048.20$
Persimmon	X5	26	50.00	$d_{12}^- = 807.50$
Kiwi	X6	21.99	0.00	$d_{13}^- = 1407$
Japanese Parsley	X7	17.8	0.00	$d_{14}^+ = 640.25$
Olive	X8	489	2100.00	$d_{15}^- = 1750.50$
Lemon	X9	55	250.00	$d_1^- = 245.23$
Fig	X10	10	90.00	$d_{16}^- = 960.50$

The findings in Table 5 indicate that figs and Japanese parsnips have been removed from the new cultivation strategy, while the production of oranges, mandarins, and mulberries has increased. Additionally, current agricultural trends suggest introducing kiwi, persimmon, tangerine, and orange cultivation. Consequently, the optimal planning model shows that transitioning to sustainable practices will streamline the region's crop variety by phasing out certain products. This strategy highlights the need to focus on crops that leverage the region's resources for improved sustainability. The research also forecasts a total revenue increase of $0.6 billion compared to the current model. Moreover, expected declines in fertilizer use include reductions of 98.5 tons of phosphate, 58.1 tons of nitrogen, and 32.5 tons of potash. There will also be a significant decrease in the use of chemical pesticides, with reductions of 980.70 liters of herbicides, 1,403.20 liters of insecticides, and 8,700.31 liters of fungicides.

Table 5. The results of the horticulture pattern of Ramsar city.

Products name	Variable	Pattern		
		Area under cultivation available (ha)	Area under cultivation Optimum (ha) ideal	Deviations
Orange	X1	6046.13	7240.00	$d_1^- = 58.12$
Tangerine	X2	350.09	490.00	$d_2^- = 841.33$
Orange	X3	55.62	35.00	$d_3^- = 588.12$
Persimmon	X4	47	67.00	$d_{12} = 3541.40$
Kiwi	X5	244.14	315.00	$d_{13} = 641.20$
Japanese Parsley	X6	14.3	0.00	$d_{14}^- = 1045.14$
Mulberry	X7	37	150.00	$d_{15}^- = 769.70$
Fig	X8	5.5	0.00	$d_{16}^- = 478$

The proposed model for shifting cultivation patterns presents promising opportunities for enhancing sustainability and profitability in agriculture. However, several challenges may discourage farmers from adopting these changes.

One major challenge is the significant cost associated with transitioning to new crops, such as pomegranates and olives. Farmers may face high initial investments for seeds, land preparation, irrigation systems, and other necessary infrastructure. This financial burden can deter adoption, especially when farmers are uncertain about future returns. Additionally, reallocating funds from existing operations to invest in new crops might negatively impact their immediate income and cash flow.

Knowledge Gaps

Another obstacle is the lack of training and knowledge regarding new crops and farming practices. Successfully transitioning requires adequate education on optimal methods, including pest management and nutrient needs. However, access to resources and extension services for this training is often limited, making it essential to bridge these gaps for successful adoption.

Market Access and Demand

Market dynamics also pose challenges. Farmers may hesitate to switch to new crops without guaranteed demand or stable prices. An understanding of market trends and the establishment of reliable supply chains are crucial to ensure the viability of new products. Shifts in consumer preferences can also affect crop sustainability, leading to potential financial losses if market responses are unfavorable.

Infrastructure and Technology

Infrastructure and logistical issues further complicate the transition. Adapting supply chains for perishable goods like fruits can be difficult, and depending on the new crop requirements, farmers may need to invest in specialized equipment or modify their irrigation systems, serving as additional barriers to entry.

Environmental Considerations

Environmental and climatic factors are significant as well. While the proposed model may offer benefits, local conditions—such as soil type, water availability, and climate—must align with the chosen crops for successful cultivation. Additionally, farmers may need training in sustainable practices to reduce the use of fertilizers and pesticides, which can challenge established routines.

Policy and Support Mechanisms

Finally, policy and incentives are critical for facilitating this transition. Effective government support measures, including subsidies or financial incentives for sustainable practices, can help instill the confidence necessary for change. However, existing land use regulations may hinder those looking to alter their cultivation patterns, underscoring the need for policy reform.

In summary, a comprehensive strategy that includes education, support, and infrastructure development is essential to overcome these challenges. Collaboration among government bodies, agricultural organizations, and the farming community will help facilitate smoother transitions to the proposed model. Engaging farmers throughout this process is vital to address their concerns and uncertainties regarding this significant shift in cultivation practices.

Water Management Insights

Water scarcity presents a critical global challenge, particularly in agriculture. The review highlights sustainable practices and linear programming (LP) for optimizing water use, including crop selection, land allocation, irrigation, and management strategies. Findings underscore the role of LP in enhancing water efficiency, maximizing yields, and encouraging sustainable systems amid water scarcity (Mizyed, 2025).

Policymakers face difficulties in managing water supply and demand. This study proposes a framework that integrates ANFIS, multi-objective ε-constraint models, and TOPSIS to improve efficiency. Using hydrological data from 2001 to 2017, the model was applied in the Karkheh basin, demonstrating reduced irrigation water use and enhanced economic productivity (Mardani et al., 2022).

Deteriorating water resources significantly impact global food production, especially under self-sufficiency policies. This study connects intra-country trade networks, food security, and water footprints (WFs) in Iran, indicating a potential water saving of 781 × 10^6 m³ and offering 400 management scenarios to boost food security while effectively reducing WFs (Maroufpoor et al., 2021).

Conclusions

The research conclusions stemmed from a model designed to optimize cultivation patterns for specific economic and environmental outcomes. The methodology began with this optimization model, which simulated the effects of various agricultural practices on input usage, including fertilizers and pesticides, as well as environmental factors like water consumption. A crucial aspect of the model was the feedback from local farmers, ensuring that the objectives were relevant and practical.

Key targets included a 7% reduction in chemical fertilizers, with specific goals of 9.5% for phosphate and potash fertilizers and 4% for nitrogen fertilizers. The research also aimed to decrease pesticide use, targeting reductions of 4.5% for herbicides, 6% for insecticides, and 9% for fungicides. Environmental considerations played a significant role, particularly given the area's ample water resources, which permitted a 1% monthly reduction in water consumption while maintaining agricultural productivity.

Effective water management strategies were integral to achieving these reductions and enhancing resource management. Performance evaluations indicated that the model surpassed existing cultivation practices by successfully combining economic and environmental goals, contrasting with traditional linear optimization methods. The outcome metrics demonstrated that the ideal planning approach not only achieved the initial targets but also provided a framework for lead farmers and decision-makers to apply these practices effectively.

This research underscored the need to address resource deficits, such as capital and labor, to enhance productivity and increase income per hectare. The reductions of 9.5% in phosphate and potash fertilizers, 4% in nitrogen, and similar pesticide reductions were calculated through modeling scenarios that integrated local farmer input, current agricultural methods, and regional resource availability. This comprehensive, multi-objective approach evaluated the trade-offs and synergies between agricultural output and sustainable practices, supporting the adoption of optimized cultivation strategies in areas facing resource constraints or environmental issues. Ultimately, the findings highlight the importance of strategic planning in modern agriculture to balance profitability with sustainability.

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