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RESEARCH PAPER

Sustainable Urban Development through Optimizing Urban Agriculture: A Comprehensive Study on Location, Technology, and Gender Equality in Kermanshah, Iran

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Abstract

Rapid urban growth, driven by urbanization and agglomeration of goods and services in metropolitan cities, jeopardizes land conversion for agriculture and challenges traditional models of urban development. The traditional urban growth models emit carbon, destroy the environment, and create food deserts, thereby compromising food security and health for urban residents. Sustainable urban agriculture can be an alternative solution since it provides food security and access to fresh and affordable food. The present research employs a two-stage model: regional ranking with an integrated ANP-TOPSIS method, and best allocation of resources, such as location selection, cultivation technology, and gender-balanced human resource deployment, with the mixed integer programming methodology. Implemented in Iran, Kermanshah, the proposed model recommends vertical hydroponic production of cauliflower and tomatoes to reduce water and land use. It also promotes gender balance in working opportunities, thus lessening the disparity among men and women in job activities. Economic evaluation using the net present value method reaffirms the economic viability of urban farming, with a mention of the effect of land price and return on investment. Analysis of the ANP-TOPSIS model establishes that increasing the level of sustainability raises the farm's sustainability, albeit non-linearly in all the dimensions and sub-criteria. This approach supports observations regarding effective urban agriculture practices towards sustainable urban development.

Keywords:
Food Security,
Multi-Criteria Decision Making,
Net Present Value,
Sustainable Development,
Urban Agriculture.

1. Introduction

Urban agriculture has been the leading paradigm shift in urban planning with the theme of feeding urban populations at its center. Urban agriculture is a complex practice with an extensive variety of activities ranging from crop and animal production to horticultural production in cities. Its basic function is improving urban food security, making healthy food available for the urban populace. Further, urban agriculture plays a significant role in rendering cities more resilient to food supply chain disruption in the form of labor disputes, natural

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disasters, war, and economic downturn, which have crippling impacts on food production and distribution. As documented by Hoornweg and Munro-Faure (2008) and Montgomery (2008), rapid urbanization strains various elements of the food supply chain, including the main resources like land and water, and the food production, transportation, and distribution processes. Similarly, Rashid et al. (2018) observe the contribution of burgeoning urban populations towards guaranteeing food insecurity, together with increasing demand for main resources like land, water, and food itself. Food security, as defined by the Food and Agricultural Organization (2006), is the physical and economic access of an individual to sufficient, safe, and nutritious food to meet their dietary needs for a healthy life. This is aligned with one of the basic principles of the United Nations' 2030 Sustainable Development Goals (SDGs), which is to achieve global food security (Breene 2016).

Urban food production offers tremendous potential for enhanced food security, but its attainment should be based on diligent planning taking into consideration labor allocation, efficient management of water resources, land utilization, energy issues, and addressing relevant social and environmental issues in cities. The United Nations World Commission on Environment and Development advocates for sustainable development and recognizes the crucial factor of constructing sustainable cities. The primary role of the UNWCED is to satisfy present needs without compromising the potential for future generations to satisfy their (Monroe et al. 2017). The adoption of innovative agric practices has brought about a paradigm shift in the movement of sustainable farming, with increased focus on city space. Metropolitan agriculture has been a strategic response to traditional rural agriculture, such as farming, processing, and marketing food within or near metropolitan cities. According to the Food and Agriculture Organization (2020), urban agriculture not only enhances productivity and employment opportunities but also encourages environmental care, enhances urban climate change resilience, and offers access to fresh produce for city consumers. Urban agriculture is a key provider of food production for sustainable cities, and its expansion is included in sustainable urban planning. Urban agriculture, which started as a hobby, has become a money-making business fueled by technological progress, according to Shamshiri et al. (2018). Despite important developments, however, the majority of towns still face the problem of "food deserts" in which healthy diet is lacking, a problem referred to by Slade et al. (2016).

As the key purpose of this research, incorporating urban farms within limited urban spaces involves the strategic selection of best sites, employing appropriate cultivation technology, and considering various dimensions of sustainability. The general purpose of integration is to enhance the resilience of urban spaces and food security and to guarantee that urban agriculture provides a positive impact on the development of future cities. Thus, urban farms must be carefully evaluated in various dimensions of sustainability.

In the environmental context, urban farms need to prove compatibility with limited urban resources such as water, land, and energy, allowing food production without over-tapping these resources. Environmental pollution in terms of groundwater and land degradation caused by poisons and pesticides needs to be addressed through proper choice of cultivation technology and tight product control at all levels. Economically, urban farms need stability and financial effectiveness to be viable urban enterprises and be invested in. Economically, land and equipment costs, local regulations, product prices, efficiency, and investment risks are key determinants of the economic viability of urban farms. Urban farms can do a great deal to benefit society by contributing significantly to ensuring food availability, reducing poverty, adherence to just and fair labor practices, gender empowerment, and job creation, thereby assuming critical social functions.

Valuing the complexity, character, and difficulty of urban farming requires creating a strong intellectual foundation. The foundation should highlight the important role that urban farms play in changing the future of cities, properly managing the complications and difficulties about urban farming. Meanwhile, it should highlight the distinguishing characteristics of urban farming and its worthwhile contribution to food security, environmental and social emergencies, and the overall trajectory of urban progress. This intellectual framework needs increased sensitivity in disciplines such as management, agriculture, economics, and engineering.

This study makes an important contribution to encouraging sustainable urban agriculture by providing a two-stage procedure. The first stage involves determining the sustainability of cities through a multi-criteria decision approach. This step ranks cities based on economic, social, and environmental criteria, and provides policymakers with information about the nature and problems of each region for the establishment of urban farms. The second phase makes use of mathematical programming to schedule major factors, including location, technology selection, production scheduling, and the promotion of gender empowerment. The selection of farm sites considers sustainability decisions in addition to cost minimization. Technology choice, as well as the identification of best cultivation patterns, is also determined on cost and demand considerations. Balanced employment division between men and women finally encompasses the social importance of this profession.

In the subsequent sections, the paper continues as follows: Section 2 presents an introduction to the topic and correlated research, setting a context for discussion. Section 3 explains the mathematical model and problems. Section 4 presents a complete case study and analysis to present the model's efficacy. Sections 5 and 6 summarize the outcome.

2. Literature Review

The primary aim of this literature review is to investigate the role of urban agriculture in advancing sustainable urban planning and its wide-ranging impacts on economic, environmental, and social dimensions. Building on this foundation, the review delves into research initiatives focused on mathematical optimization and multi-criteria decision-making in urban farm planning and local food supply. This comprehensive analysis also serves to identify gaps in the existing body of research within this field.

2.1. Urban Agriculture and Dimensions of Sustainability

Urban agriculture is a significant source of job creation, with examples like jasmine cultivation in Manila employing thousands, as noted by Barker et al. (2007). Azunre et al. (2019) highlights over 11 million urban farmers in South Asia, along with 6 million in other regions, emphasizing its global employment impact. While affluent cities traditionally focused on ecological and recreational aspects, recent studies indicate a shift toward urban agriculture incorporating economic and sustainable dimensions (Lovell 2010). For instance, as highlighted by Keraita et al. (2008), urban farmers in Ghana earn double the income of their rural counterparts. Furthermore, urban agriculture contributes to sustainability by increasing household incomes and the GDP. In Shanghai, the 2.7 million urban farmers generate 2.7% of the city's GDP, according to research by Yi-zhong and Zhangen (2000). Pena et al. (2022) conducted a life cycle economic analysis on an urban tomato farm, revealing that workforce, greenhouse infrastructure, pest control, and rainwater collection significantly impact costs. Increasing production levels enhances farm economic viability.

Urban agriculture, highlighted by Golden, n.d. (2013), emerges as a potent tool for cultivating agricultural skills and generating employment. Studies by Bradley and Galt (2014) show several agricultural initiatives in California and Philadelphia that emphasize the economic and educational role of urban farms. Urban farms extend beyond economic benefits, playing a pivotal role in public education about food origins, as advocated by Prain et al. (2010). Research by in Sri Lanka (Gamhewage et al. 2015) shows that urban farmers allocate a significant portion of income to education, where 22% of women invest a portion of their income in education. Urban agriculture plays a pivotal role in diminishing gender disparities and fostering social justice by providing employment opportunities for individuals of all genders, as advocated by the International Labour Office (2013). Eigenbrod and Gruda (2015) emphasize the role of women in mitigating gender disparities along the agricultural supply chain. global statistics Azunre et al. (2019) suggest an 80:20 male-to-female ratio in urban agriculture. The findings by Kutiwa et al. (2010) shows that urban agriculture empowers women economically and in household decision-making and helps reduce gender inequality. Despite its positive effect, women's rights organizations are concerned about imposing additional responsibilities on women , policy makers must address these concerns to ensure that urban agriculture remains a force for gender equality and social justice (Van 2014).

But with the advent of the Industrial Revolution and significant advances in agricultural technologies, many farm activities were facilitated, and consequently, dependence on heavy human labor was reduced. For example, the use of machinery such as tractors significantly simplified the processes of plowing and cultivating crops and reduced the need for animal power and physical labor. In addition, the mechanization of crop harvesting caused human labor to assume the role of operator and supervisor of agricultural machinery. This reduction in dependence on physical strength in agriculture has increased the opportunities for success for women in this field. Women who, in the modern era, instead of relying on physical strength, use technical, managerial, scientific and academic skills to optimize agricultural processes. Ultimately, it can be concluded) that the creation of gender-equal opportunities in work environments leads to positive outcomes such as increased income for women, improved family economic status, and the strengthening of their social participation prospects. Considering the relatively understated importance given to the social dimension of sustainability and the role of women in previous agricultural studies, this research addresses human resource planning based on gender equality to draw attention to the vital issue of gender parity within the framework of the social dimension of sustainable development. Urban agriculture, as highlighted by Cristiano (2021), not only boosts food production but also fosters social responsibility by aiding the needy and engaging volunteers. Innovative cooperative model in Italy prioritizes produce distribution to participants or those in need, emphasizing key inputs in their life-cycle assessment: fertilizer, seedlings, machinery, and fuel.

Urban residents often worry about air quality and pollution from industrial and transportation activities, leading urban planners to explore strategies such as public transit development, traffic management, carbon emissions taxes, urban gardens, and agriculture. While trees play a vital role in removing pollutants, tree planting alone falls short, necessitating innovative approaches like utilizing rooftops and vacant lots for agriculture (Yang et al. 2008). Developed cities globally are actively expanding green infrastructures, allocating substantial land for initiatives like agriculture, as seen in Canada's Ottawa Green Belt Program (Pearson et al. 2011). The urban heat island effect, resulting from heat and greenhouse gas release, leads to temperature differentials between cities and suburbs. Urban agriculture, with shade provision, increased moisture, and carbon dioxide absorption, mitigates these effects, with a 10% increase in green space reducing temperatures by up to 4 degrees Celsius (Gill et al. 2007). The World Bank (Santos et al. 2015) emphasizes the role of urban farms in reducing the need for extensive transportation, minimizing energy consumption. However, certain agricultural technologies, like hydroponics, may increase energy consumption (Lages et al. 2015). As a result, focusing on renewable energy sources and advances in agricultural technology is necessary to manage greenhouse gas emissions in urban agriculture.

Notably, irrigated agriculture presently accounts for a significant portion, over 70%, of the world's freshwater consumption (Rosegrant et al. 2009). Urban agriculture complements strategies such as wastewater reuse and drip irrigation to contribute to water sustainability, although challenges in economically disadvantaged cities persist and require international organizations and government investment in urban agriculture (Ensink et al. 2002), (Nolasco 2020). Rufí-Salís et al. (2020) examined water recycling in closed-loop hydroponic farms, finding significantly reduced water consumption. The closed-loop system fully met farm needs through rainwater harvesting.

2.2. Mathematical models in urban agriculture

Urban agriculture must be approached with sustainability in mind, necessitating meticulous planning to optimize available land and production resources. Researchers have explored a wide array of topics within the academic literature, including production planning, demand modeling, and efficient utilization of water, land, and energy. For instance, Xu et al. (2020) formulated a mathematical model to equitably distribute water consumption among various users in both agricultural and non-agricultural sectors. Their model effectively balanced waste emissions, leading to a reduction by incorporating industrial wastes into agricultural processes. Dundar et al. (2017) introduced a robust optimization model to efficiently supply food and calories to the local population while minimizing land use. Despite uncertainties in land yield, the model provided a suitable solution for residents' food supply. Research by Peters et al. (2009) and Zumkehr Campbell. (2015) in cities like New York and Los Angeles indicates a substantial urban population can meet caloric needs with local foods within a 100-mile radius. Monaco et al. (2016) investigated food production capacity in the Milan metropolitan area, presenting three scenarios. The first balanced land use for animal fodder and crops. The second prioritized animal fodder self-sufficiency, reducing crop capacity. The third achieved crop self-sufficiency, significantly reducing animal fodder while substituting vegetable protein with meat protein.

Liao et al. (2019) employed linear programming and Geographic Information System (GIS) to optimize farm locations in Idaho, addressing supply and demand gaps and considering production facility capacities. In a correlated study Mack et al. (2017) classified urban sites and created an orchard placement optimization model, prioritizing food availability while incorporating constraints on orchard numbers and maximum coverage distance. Jing et al. (2020) introduced a mathematical model aimed at reducing costs and greenhouse gas emissions in diverse farms, allowing flexibility in energy source selection and farm types. In a related study, Tong et al. (2020) presented an optimization model maximizing vegetable production while addressing water resource constraints, incorporating decisions on cultivated land and optimal water allocation to crops.

Li et al. (2020) devised an environmental-economic model aiming to maximize profits while minimizing resource consumption in advanced urban farming systems. Their work, exemplified in Singapore, optimized factors like temperature, lighting, radiation, and CO2. In a related work, Pimentel et al. (2023) using a MILP model, achieved a 31% reduction in annual electricity costs through optimized operational plans and the P-Graph method. proposed a mathematical model for water and land allocation in agriculture, optimizing import/export decisions and transportation planning, resulting in increased profits and minimized use of fertilizers, water, and energy. Zhang et al. (2022) introduced an integer programming model, evaluated in Arizona, maximizing community and food garden coverage with benefits like increased population coverage, resilience to temperature fluctuations, and improved food access. Mosadeghi et al. (2015) utilized fuzzy hierarchical multi-criteria decision-making methods for diverse urban land planning, including agriculture, offering a comprehensive approach.

This study underscores the insufficient exploration of key aspects in sustainable urban agriculture, including diverse sustainability factors in farm site selection, cultivation technology significance, and gender equality in employment. These critical dimensions have not been adequately integrated into the optimization processes of urban farms, revealing a notable gap in understanding the holistic dynamics of sustainable urban agriculture. The research advocates for future endeavors to bridge this gap by incorporating these nuanced elements into decision-making and optimization frameworks. The study utilizes a two-step framework, linking sustainability assessments of urban areas with mathematical optimization. It explores gender equality and environmental impacts, scrutinizing cultivation technologies, and irrigation systems for more sustainable practices. Notably, the research stands out for its comprehensive approach, combining location selection, technology assessment, and production planning to address real-world complexities. By filling these gaps, the study aims to provide valuable insights for advancing sustainable urban agriculture practices. Table 1 presents a structured comparison between the current research and prior studies.

Table 1. A Structured Comparison Between the Current Research and Prior Studies

Paper	Model	Sustainability			Objective	Location	Technology choice	Production planning	Resource management	Human resources	Description
		EC	EN	SO							
Xu, Yao, and Chen 2020	LP	*			Max Benefit			*			case study of India
Dundar, Costello, and McGarvey 2017	LP	*			Min Land			*			case study Missouri
Liao et al. 2019	LP			*	Min Distance	*					case study Northern Idaho
Mack, Tong, and Credit 2017	MIP	*			Max Population coverage	*					
Jing, Hastings, and Guo 2020	MIP	*	*		Min Cost / GH gas		*				
Tong et al. 2020	MIP	*			Max Production			*	*		case study Arizona
Li et al. 2020	MIP	*	*		Max Value Min Water and Land use		*		*		case study Singapore
Najafabadi et al. 2019	MIP	*	*		Max Profit / Manpower Min Water / Energy	*			*	*	case study Isfahan
Zhang et al. 2022	MIP	*		*	Max Benefit of food and heat	*					Case study Phoenix
This study		*	*	*	Min Cost	*	*	*	*	*	Case study Kermanshah

3. Statement of the Problem

In response to the risk of urban food deserts caused by rapid urbanization, this study advocates for urban agriculture as a solution. It emphasizes the need for a meticulous approach considering economic, environmental, and social factors for successful integration into densely populated areas. As illustrated in Figure 1, this study introduces a two-stage optimization framework. In the first stage, a Multi Criteria Decision Making (MCDM) model of the ANP-TOPSIS type is employed, which assigns a sustainability score to each urban area based on the three main sustainability criteria (economic, social, and environmental) and 16 sub-criteria.

These assigned scores are then used in the second stage as input parameters for a Mixed Integer Programming (MIP) model. Finally, this mathematical model determines the optimal location for urban farms, the cultivation technology (M), and the water supply system (W) across various urban zones. Overall, this framework presents a comprehensive approach to align research analyses with the complexities of real-world decision making.

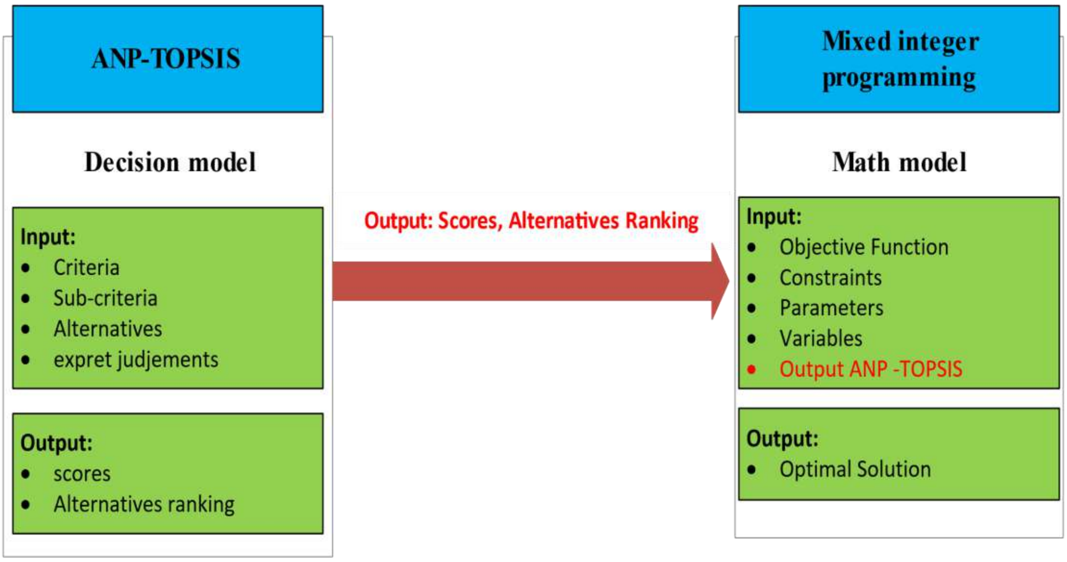

Figure 1. two-stage optimization framework

The research uniquely addresses the dual challenges of selecting appropriate agricultural technologies and establishing optimal cultivation patterns Traditional cultivation, heavily reliant on land and water, despite environmental impact and vulnerabilities, contrasts with greenhouse farming offering better control yet hindered by costs, while advanced methods like vertical farming, though yielding more, grapple with high setup expenses and energy use. Water supply systems, considering fresh water (W^1) from wells or urban supply and urban sewage treatment water (W^2), present varying setup costs and per-liter purchase prices. The subsequent crucial step involves determining the optimal cultivation plan for each product (P= {p^1, p^2}), considering required land and water resources across time periods (T= {t^1, t^2, t^3}). This requires specifying water and land allocations for each crop. Tax amounts for each farm are calculated based on the cultivated crop, chosen cultivation technology, and water supply system. The research emphasizes decisions on gender equality and human resource planning. Man-hours for maintaining each hectare vary by product and cultivation technology, calculated based on expected workers for 8 hours a day over 120 days in each period. The associated costs of hiring and training new employees or releasing existing personnel fluctuate as the number of employees varies over time. By embracing gender equality between men and women, this model sheds light on this crucial social issue and strives to emphasize and strengthen the social and economic contributions of women in the community.

Ultimately, the important assumptions of the problem are as follows:

- It is assumed that the demand for agricultural products (tomatoes and cauliflower) within each time period (3 periods of 120 days) is known and mandatory, and the total production must meet this demand.
- The land yield for each product, under every type of technology, and per hectare of cultivated area is specified.
- It is assumed that the primary resources (arable land, available water, energy) and the

existing labor force in each region and time period are limited and possess a known value (parameter), which must be optimally allocated by the model.

- The human resource cost, including hiring, termination , and hourly wages, is specified.
- The costs for land acquisition, farm construction, implementation of cultivation technology, and water supply system setup are specified per hectare of the farm.
- The amount of tax is specified based on the cultivated area.

3.1. Multi-Criteria Decision Making with ANP-TOPSIS Method

Multi-Criteria Decision-Making (MCDM) is a comprehensive methodology encompassing objective definition, criteria selection, alternative identification, criteria weighting, and subsequent ranking. This unbiased approach integrates planning objectives, as illustrated by Mosadeghi et al. (2015) and Elaalem (2013). Utilizing a combination of Analytic Network Process (ANP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), this methodology unfolds in distinct stages. Initially, objectives, criteria, and alternatives are defined, emphasizing sustainability rates and urban organization for potential farm establishment. The subsequent stage involves establishing correlations and criteria interconnectedness, followed by weighting using ANP. Integrating ANP-derived weights into TOPSIS forms a weighted matrix in the third stage. Moving to the fourth stage, positive and negative ideal alternatives are determined, leading to the fifth stage, which assesses alternative proximity to these ideals, ultimately resulting in the final ranking. Table 2 presents 16 sub-criteria classified into three primary categories: economic, social, and environmental. The interconnections among these sub-criteria are visualized in Figure 2.

Table 2. Criteria and Sub-Criteria for Urban Agriculture Sustainability

Criterion code	Sign	Criteria	Data collection and valuation	Categories
$e1$	+	Average income of the area	The average salary data were obtained from the Kermanshah Provincial Management and Planning Organization.	Economic
$e2$	+	Arable land in the area	Kermanshah has allocated specific parcels of land in each district for future development as parks, gardens, green spaces, and for non-residential and non-commercial uses	
$e3$	+	Investment interest in the region	A survey was conducted among investor groups to assess their interest in investing in the agriculture and food industries.	
$e4$	-	Distance from major markets	The distance from the center of each region to the closest market serves as a key evaluation criterion.	
$e5$	+	Effective transportation network	The quality of public transportation access to the regional center and traffic levels in each area were assessed through field observations and analysis of Kermanshah's public transportation network maps.	
$s1$	+	Population size of the area	Population data for each region were obtained from the Kermanshah City Management Organization.	Social
$s2$	+	Civic engagement	The study measured civic engagement by examining respondents' willingness to participate in activities such as water conservation, waste reduction, and agricultural training.	
$s3$	+	Security of the area	Data sourced from annual police reports	
$s4$	+	Satisfaction with job and life	A questionnaire was used to assess job satisfaction and quality of life	

$s5$	+	Access to education	The survey was administered to individuals aged 20 and older who had completed at least high school.	
$s6$	+	Food hygiene	A questionnaire was used to assess individuals' food styles.	
$en1$	+	Access to water resources	Data on water resources, including rivers, springs, and sewage systems, were obtained from natural resource maps and the Kermanshah Water and Wastewater Organization.	
$en2$	-	Environmental pollution impact	To assess the environmental impact, the distance of each area to waste disposal sites, construction waste disposal sites, and other pollution sources is calculated.	
$en3$	+	Green space	To assess the distribution of urban green spaces, data was compiled from city maps and green space inventories.	Environmental
$en4$	+	Access to energy resources	The entire city is uniformly covered by the electricity grid.	
$en5$	+	Wastewater management	Data for this study was acquired from the records of the Kermanshah Water and Wastewater Organization.	

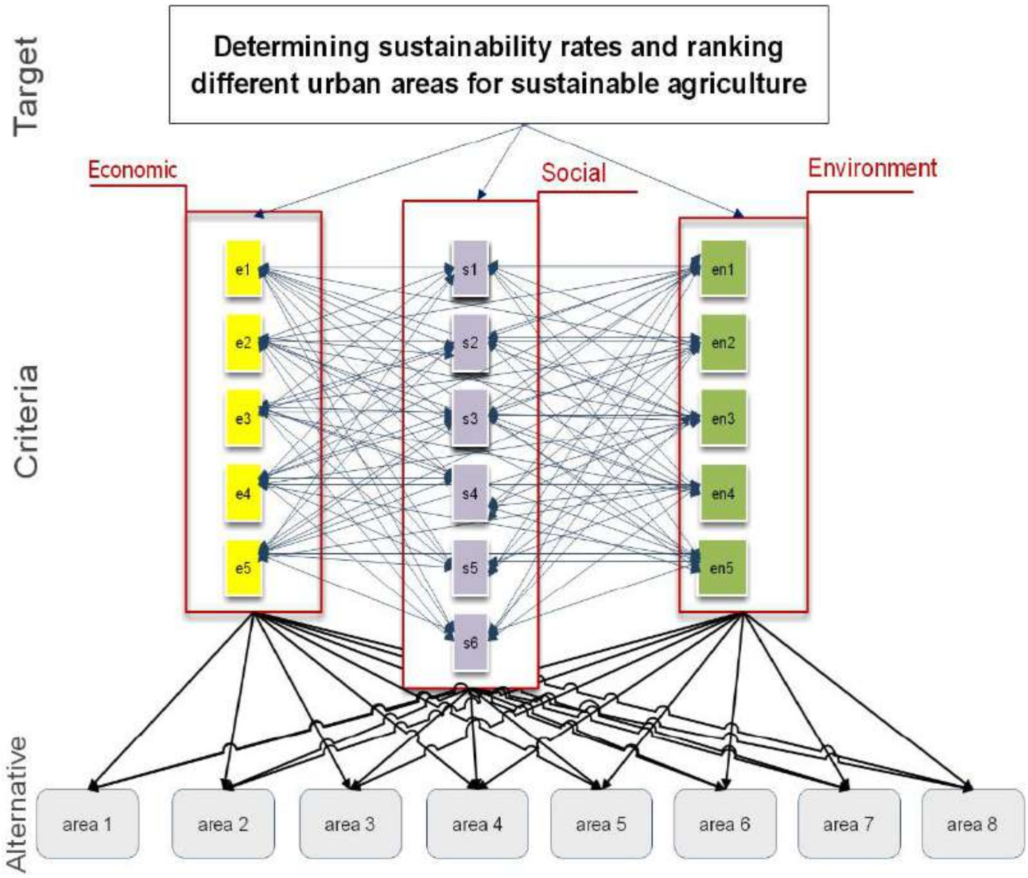

Figure 2. Relationship Between Objective Criteria and Decision-Making Model Options

The ANP results, including sustainability rates of urban areas and their ranking based on established criteria, feed into the mathematical model. Decision-makers set a minimum acceptable sustainability threshold based on stakeholder interests. Higher thresholds exclude more urban areas, while lower thresholds increase decision risks.

3.2. Mathematical Model

A mathematical model is employed to plan production and make location-based decisions for urban agricultural facilities, encompassing sewage treatment and cultivation technology selection. The sets, parameters, and variables used in this model are described below.

Sets

i	Set of urban areas $i = \{1,2,3, \dots, I\}$
p	Collection of products $p = \{p^1, p^2, \dots p^p\}$
m	Type of cultivation technology $m = \{m^1, m^2, m^3\}$
w	Water supply system $w = \{w^1, w^2\}$
t	Time period $t = \{t^1, t^2, t^3\}$

Parameters

rev_p	Price per kilogram of product p
d_{pt}	Demand for product p during period t
ss_i	Sustainability score of the area i derived from the decision model (Output ANP-TOPSIS)
Δ_{pm}	Volume of water required per hectare for cultivating product p using technology m
α_{pm}	Man-hours needed for labor per one hectare for cultivating product p using technology m
γ_{it}^1	Number of available male laborers during period t in area i
γ_{it}^2	Number of available female laborers during period t in area i
π_{itm}	Equipment working hours available for cultivation technology of type m during period t in area i
θ_{pm}	Man-hours of equipment needed to cultivate one hectare of product p with technology m
ω_{itw}	Volume of available water (fresh or wastewater) w in liters in area i and time period t
wr_i	Cost of hiring each worker in area i
wk_i	Cost of terminating each worker in area i
ch_{im}	Hourly wage for a worker specializing in cultivation technology m in area i
mr_{im}	Cost per working hour of machines with technology m in area i
g_i	Available land for urban agriculture in area i
TAX_i	Production tax in area i (percentage of revenue)
$TAXW_{iw}$	Tax related to the water supply system in area i per hectare (with a discount on sewage treatment tax)
$TAXM_{im}$	Tax related to the use of different levels of technology m in area i per hectare
cog_i	Cost of purchasing each hectare of land in area i
o_w^1	Cost of constructing an irrigation system of type w per one hectare
o_m^2	Cost of construction for cultivation technology of type m per one hectare
cw_w	Cost for each liter of water provided by the method w
ce	Cost for each unit of energy
sus	Minimum acceptable sustainability rate for decision-makers
RT	Percentage difference between the number of male and female employees determined by decision-makers
te_{Pm}	Yield coefficient per hectare for product p in cultivation method m
ea_{it}	The quantity of energy available in area i during period t
es_{pm}	Energy requirements per hectare for cultivating product p using method m
dt	Daily working hours
tw	Duration of the cultivation period in terms of day
$fixcost$	Fixed costs associated with farm construction
mo	A large number

Variables

Q_{pimt}	The allocation of land per hectare for cultivating product p in area i using method m during period t
MQ_i	The size of farmland in area i in terms of hectare
NWM_{it}	Number of male workers employed in area i during period t
NWW_{it}	Number of female workers employed in area i during period t
$NWMh_{it}$	Number of newly hired male workers in area i during period t
$NWWh_{it}$	Number of newly hired female workers in area i during period t
$NWMk_{it}$	Number of male workers laid off in area i during period t
$NWWk_{it}$	Number of female workers laid off in area i during period t

$VTAX_i$	Tax imposed on urban farms in area i
Y_{iw}^1	Binary variable: 1 if system w is selected for irrigation in area i, 0 otherwise
Y_{im}^2	Binary variable: 1 if technology level m is selected in area i, 0 otherwise
X_i	Binary variable: 1 if a farm is constructed in area i, 0 otherwise

The mathematical model for the problem under consideration is presented below:

$$\begin{aligned} min\, z = & \sum_i \sum_t (wr_i \times (NWWh_{it} + NWMh_{it}) + wk_i \times (NWWk_{it} + NWMk_{it})) \\ & + \sum_p \sum_i \sum_m \sum_t ch_{im} \times \alpha_{pm} \times Q_{pimt} \\ & + \sum_p \sum_i \sum_m \sum_t mr_{im} \times \theta_{pm} \times Q_{pimt} \\ & + \sum_p \sum_i \sum_m \sum_t \sum_w cw_w \times \Delta_{pm} \times Y_{iw}^1 \times Q_{pimt} \\ & + \sum_p \sum_i \sum_m \sum_t ce \times es_{pm} \times Q_{pimt} \\ & + \sum_i cog_i \times MQ_i + \sum_i VTAX_i \\ & + \sum_i \sum_w Y_{iw}^1 \times o_w^1 \times MQ_i + \sum_i \sum_m Y_{im}^2 \times o_m^2 \times MQ_i \\ & + \sum_i fixcost \times X_i \end{aligned} \tag{1}$$

$$\sum_p \sum_m \Delta_{pm} \times Q_{pimt} \leq \sum_w \omega_{itw} \times Y_{iw}^1 \quad \forall\, i,t \quad \forall\, i,t \tag{2}$$

$$\sum_p \sum_m \alpha_{pm} \times Q_{pimt} \leq (NWM_{it} + NWW_{it}) \times dt \times tw \quad \forall\, i,t \tag{3}$$

$$NWW_{it} = NWW_{i(t-1)} + NWWh_{it} - NWWk_{it} \quad \forall\, i,t \tag{4}$$

$$NWM_{it} = NWM_{i(t-1)} + NWMh_{it} - NWMk_{it} \quad \forall\, i,t \tag{5}$$

$$NWM_{it} \leq \gamma_{it}^1 \quad \forall\, i,t \tag{6}$$

$$NWW_{it} \leq \gamma_{it}^2 \quad \forall\, i,t \tag{7}$$

$$|NWM_{it} - NWW_{it}| \leq rt \times (NWM_{it} + NWW_{it}) \quad \forall\, i,t \tag{8}$$

$$\sum_p \sum_m \theta_{pm} \times Q_{pimt} \leq \sum_m \pi_{itm} \times Y_{im}^2 \quad \forall i,t \tag{9}$$

$$\begin{aligned} VTAX_i = & \sum_t \sum_p \sum_m TAX_i \times Q_{pimt} \times te_{Pm} \times rev_p \\ & + \sum_t \sum_p \sum_w \sum_m TAXW_{iw} \times Y_{iw}^1 \times Q_{pimt} \\ & + \sum_t \sum_p \sum_m TAXM_{im} \times Y_{im}^2 \times Q_{pimt} \quad \forall\, i \end{aligned} \tag{10}$$

$$MQ_i \leq g_i \times X_i \quad \forall i \tag{11}$$

$$\sum_m Y_{im}^2 \leq X_i \quad \forall\, i \tag{12}$$

$$\sum_w Y_{iw}^1 \leq X_i \quad \forall\, i \tag{13}$$

$$\sum_p Q_{pimt} \leq Y_{im}^2 \times MQ_i \quad \forall\, i,m,t \tag{14}$$

$$\sum_m \sum_i Q_{pimt} \times te_{pm} \geq d_{pt} \quad \forall\, p,t \tag{15}$$

$$SS_i \times X_i \geq sus \quad \forall i \tag{16}$$

$$\sum_{p}\sum_{m} es_{pm} \times Q_{pimt} \leq ea_{it} \quad \forall\, i,t \tag{17}$$

$$MQ_i = \max_{t}\{\sum_{p}\sum_{m} Q_{pimt}\} \quad \forall\, i \tag{18}$$

$$Q_{pimt} \geq 0 \tag{19}$$

$$NWM_{it}\,, NWW_{it}\,, NWWh_{it}, NWMh_{it}\,\,, NWWk_{it}\,, NWMk_{it} \geq 0 \;and\; integer \tag{20}$$

$$Y^1_{iw}, Y^2_{im}\,, Y^3_{it}, X_i \in \{0,1\} \tag{21}$$

The primary objective of optimization model (1) is to minimize the total cost of agricultural operations. The first term accounts for the costs of hiring and releasing male and female personnel. The second term quantifies overall labor costs on the farm, while the third term covers machinery-related expenses. The fourth term reflects water consumption costs, determined by the chosen irrigation system and cultivation method. The fifth term addresses electricity consumption costs, influenced by the employed cultivation practices. The sixth term includes the combined costs of land acquisition and associated taxes. The seventh term represents expenses for constructing irrigation systems and implementing cultivation technologies, scaled to farm size. Finally, the eighth term encompasses the total fixed costs of establishing farm infrastructure.

Constraint (2) ensures that the water demand for each crop, in each region and time period, based on its cultivation technology, does not exceed the available water supply within the irrigation system. Constraint (3) requires that the total labor hours needed to cultivate each crop during a specific time period, considering the employed cultivation technology, do not surpass the combined available labor hours of the male and female workforce in that period. Constraint (4) specifies that the number of female personnel in each period equals the number of female personnel from the previous period, plus newly hired personnel, minus those no longer employed. Constraint (5) applies the same principle to male personnel within each time frame. Constraints (6) and (7) ensure that the number of employed male and female workers in each region and time period does not exceed the available male and female labor force in that region and period. Constraint (8) limits the difference between the number of employed males and females in each region during each time period to a predetermined percentage of the total workforce, as defined by decision-makers. Constraint (9) ensures that the total operational time required for machinery, given the selected cultivation technology, does not exceed its available working hours. Constraint (10) calculates the tax liability for each geographic area based on production scale, chosen cultivation method, and water supply system. Finally, Constraint (11) stipulates that the farm size in each region cannot exceed the available land area in that region.

Constraints (12) and (13) regulate the selection of cultivation methods and water supply systems in each region based on farm activation within that area. Constraint (14) permits agricultural activities only in regions where farms equipped with the specified technology have been established. Constraint (15) requires the total production in each time period to meet or exceed the corresponding demand. Constraint (16) allows the establishment of urban farms only in regions where the sustainability score, as determined by the ANP-TOPSIS model, meets or exceeds the minimum threshold set by decision-makers. Constraint (17) ensures that total energy consumption for agricultural activities in each region and time period does not exceed the available energy supply. Constraint (18) limits the maximum cultivated area in each region during different time periods to the size of the farms in that region. Finally, Constraints (19-21) define the types and categories of variables included in the model.

3.3. Model linearization

The presented model exhibits non-linearity due to the multiplication of the continuous variables Q_{pimt} and MQ_i by the binary variables Y^1_{iw} and Y^2_{im} in the objective function (1), as well as the presence of the absolute value expression in constraint (8). To linearize the objective function (1) and constraint (10), five new continuous variables are introduced: L^1_{pimwt} and' L^3_{iw}, which represent the size of the farm equipped with irrigation system W and the cultivated area of each crop using irrigation system W, respectively. Additionally, variables L^2_{pimt} and L^4_{im} are introduced to represent the size of the farm equipped with cultivation technology M and the cultivated area of each crop using cultivation technology M. Finally, equations (22–33) are added to the model.

$$L^1_{pimwt} \le Q_{pimt} \tag{22}$$
$$L^1_{pimwt} \le mo * Y^1_{iw} \tag{23}$$
$$L^1_{pimwt} \ge Q_{pimt} - mo * (1 - Y^1_{iw}) \tag{24}$$
$$L^2_{pimt} \le Q_{pimt} \tag{25}$$
$$L^2_{pimt} \le mo * Y^2_{im} \tag{26}$$
$$L^2_{pimt} \ge Q_{pimt} - mo * (1 - Y^2_{im}) \tag{27}$$
$$L^3_{iw} \le MQ_i \tag{28}$$
$$L^3_{iw} \le mo \times Y^1_{iw} \tag{29}$$
$$L^3_{iw} \ge MQ_i - mo \times (1 - Y^1_{iw}) \tag{30}$$
$$L^4_{im} \le MQ_i \tag{31}$$
$$L^4_{im} \le mo \times Y^2_{im} \tag{32}$$
$$L^4_{im} \ge MQ_i - mo \times (1 - Y^2_{im}) \tag{33}$$

As a result, the objective function (1) is reformulated as equation (34), and constraint (10) is transformed into equation (35).

$$\begin{aligned}
\min z = & \sum_i \sum_t \mathrm{wr_i} \times (\mathrm{NWWh_{it}} + \mathrm{NWMH_{it}}) + \mathrm{wk_i} \times (\mathrm{NWWk_{it}} + \mathrm{NWMK_{it}}) \\
& + \sum_p \sum_i \sum_m \sum_t \mathrm{ch_{im}} \times \alpha_{pm} \times \mathrm{Q_{pimt}} \\
& + \sum_P \sum_i \sum_m \sum_t \mathrm{mr_{im}} \times \theta_{pm} \times \mathrm{Q_{pimt}} \\
& + \sum_P \sum_i \sum_m \sum_t \sum_w \mathrm{cw_w} \times \Delta_{pm} \times \mathrm{L^1_{pimwt}} \\
& + \sum_P \sum_i \sum_m \sum_t \mathrm{ce} \times \mathrm{es_{pm}} \times \mathrm{Q_{pimt}} \\
& + \sum_i \mathrm{cog_i} \times \mathrm{MQ_i} + \sum_i \mathrm{VTAX_i} \\
& + \sum_i \sum_w \mathrm{o^1_w} \times \mathrm{L^3_{iw}} + \sum_i \sum_m \mathrm{o^2_m} \times \mathrm{L^4_{im}} \\
& + \sum_i \mathrm{fixcost} \times \mathrm{X_i}
\end{aligned} \tag{34}$$

$$\begin{aligned}
\mathrm{VTAX_i} = & \sum_p \sum_m \mathrm{TAX_i} \times \mathrm{Q_{pimt}} \times \mathrm{TE_{Pm}} + \sum_p \sum_w \sum_m \mathrm{TAXW_{iw}} \times \mathrm{L^1_{pimwt}} \\
& + \sum_p \sum_m \mathrm{TAXM_{im}} \times \mathrm{L^2_{pimt}} \quad \forall\, \mathrm{i, t}
\end{aligned} \tag{35}$$

The linearization of the absolute value expression in constraint (8) is achieved through the substitutions in equations (36–37). Since the difference between the number of employed men and women cannot be negative, these equations ensure that this value remains non-negative.

$$NWM_{it} - NWW_{it} \le rt \times (NWM_{it} + NWM_{it}) \tag{36}$$

$$NWM_{it} - NWW_{it} \geq -rt \times (NWM_{it} + NWM_{it}) \quad (37)$$

Equations (38–40) are introduced to linearize constraint (18).

$$MQ_i \geq \sum_p \sum_m Q_{pimt} \quad \forall\, i\,, t \quad (38)$$

$$MQ_i \leq \sum_p \sum_m Q_{pimt} + mo \times (1 - Y_{it}^3) \quad \forall\, i\,, t \quad (39)$$

$$\sum_i \sum_t Y_{it}^3 = 1 \quad (40)$$

4. Case Study: Kermanshah City, Iran

Located in western Iran, Kermanshah, with a population of approximately 1.1 million, has traditionally relied on agriculture to sustain its food supply. However, the region faces growing challenges, including water scarcity, dust storms, and land subsidence, largely due to the overexploitation of groundwater resources. Additionally, the surrounding pastures and oak forests are at risk of conversion as a result of limited land availability and the low productivity of conventional farming practices. To address these issues, urban agriculture utilizing modern technologies offers a promising solution to increase crop yields and reduce reliance on scarce water and land resources. Figure 3 depicts the map of Kermanshah, highlighting eight key urban areas that are fundamental to the scope of this research.

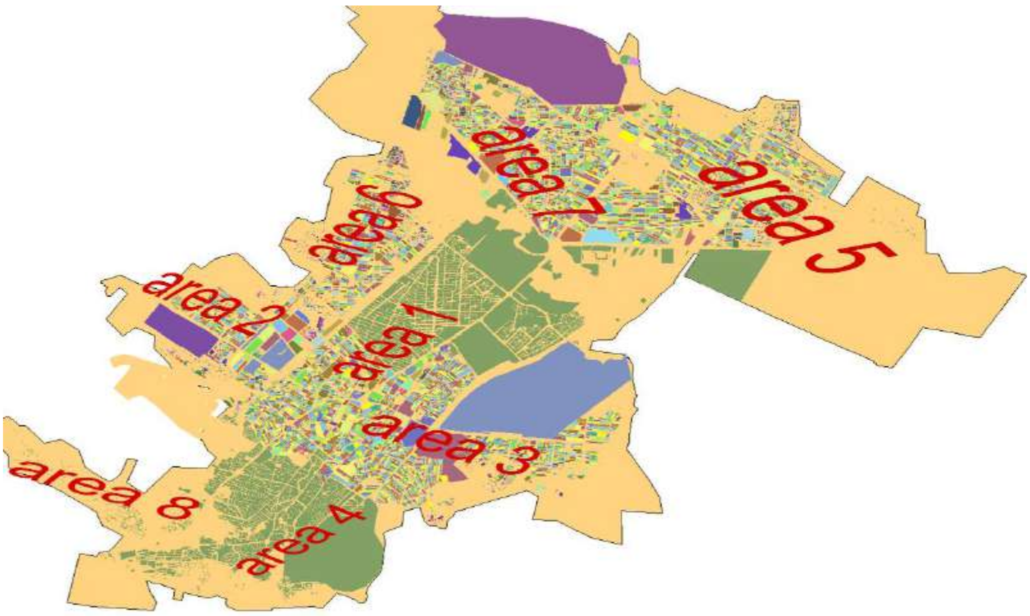

Figure 3. Map of Kermanshah City

This research investigates the efficient supply of two key products, tomatoes and cauliflower, in Kermanshah city. Data from the Kermanshah Agricultural Organization reveals that the demand for tomatoes spans three distinct time periods, each lasting 120 days, with requirements of 3,000 tons, 2,500 tons, and 3,500 tons, respectively. Similarly, cauliflower demand fluctuates over the same time periods, requiring 400 tons, 200 tons, and 350 tons, respectively.

Both tomatoes and cauliflower are particularly susceptible to damage during storage, harvesting, and transportation. Their high-water requirements, coupled with their relatively higher market prices compared to grains, make them ideal candidates for cultivation in greenhouses or urban farms. To support this research, the Kermanshah ABFA organization has provided data on the availability of fresh water and wastewater for non-domestic use during the summer and winter seasons, broken down by day and night, as presented in Table 3.

Table 3. Water and Wastewater of different urban areas in Kermanshah

			winter				summer			
Area	Population	Purification power	Wastewater per person (liters)	Total wastewater volume (10^6 liters)	Effluent usable in cultivation (10^5 W2)	Fresh water available (10^5 W1)	Wastewater per person (liters)	Total wastewater volume (10^6 liters)	Effluent usable in cultivation (10^5 W2)	Fresh water available (10^5 W1)
1	136522	0.2	180	24	49	90	200	27	54	90
2	98747	0.05	150	14.8	7.4	47	170	16	8	47
3	189610	0.1	140	26.5	26	60	160	30	30	60
4	89533	0.2	180	16.1	32	30	200	17	35	30
5	218317	0.1	140	30.5	30	75	160	34	34	75
6	124300	0.2	190	23.6	47	60	220	27	54	60
7	109843	0.1	175	19.2	19	75	190	20	20	75
8	96000	0.15	180	17.2	25	110	200	19	28	110
sum	**1062872**			**172.7**	**235**	**547**		**190**	**263**	**547**

The pricing and allocation of non-residential land in each area are regulated by municipal authorities, as shown in Table 4. These parcels are designated for non-commercial and non-residential purposes, typically intended for the development of cultural, sports, and health facilities, as well as urban gardens and green spaces. Information on farm construction expenses, along with applicable taxes and governmental subsidies, is provided in Table 5.

Table 4. Land prices in Kermanshah

Area	Land available(hectare)	Price per hectare
1	8.75	$3,750,000
2	8	$1,500,000
3	17.5	$750,000
4	8.5	$3,750,000
5	11.25	$1,500,000
6	17.5	$2,500,000
7	17.5	$750,000
8	16.25	$2,500,000

Table 5. Equipment Setup Cost- government Financial Support, Taxes

level of technology	Fixed cost of construction	Government financial support(GFS)$ / taxes $
M^1	1000 $	0
M^2	100000 $	100 (GFS)
M^3	1300000 $	1000 (GFS)
W^1	5000 $	1000 (taxes)
W^2	20000 $	1000(GFS)

The price of each liter of water and each kilowatt-hour of electricity in Kermanshah is $0.01 and $0.002, respectively. Additionally, the wages for each working hour vary by cultivation method: $0.75 for the traditional method, $1.25 for the greenhouse method, and $1.75 for the advanced method. The pairwise comparison matrices for the criteria, as presented in Tables 2 and Figure 2, were analyzed using the Super Decision software to determine the weights of the criteria through the ANP method. These matrices were normalized, and the resulting criteria weights are shown in Tables 6, 7, and 8. The weighted normalized decision matrix is presented in Table 9.

The results indicate that the investor's preference for a specific area is the most significant criterion in the ANP-TOPSIS model. Environmental factors, such as the presence of a wastewater system and access to water resources, rank as the second and third most important criteria. Job satisfaction, a social factor, ranks fourth, while the average regional income, reflecting purchasing power, ranks fifth.

Table 6. Matrix of Paired Comparisons

	e1	e2	e3	e4	e5	s1	s2	s3	s4	s5	s6	en1	en2	en3	en4	en5
Area1	750	25	9	9	9	9	9	5	7	9	9	1	1	3	5	3
Area2	250	30	3	9	9	5	5	3	3	3	3	1	3	3	5	3
Area3	150	70	1	9	9	9	3	1	1	1	1	5	3	3	5	3
Area4	750	28	9	1	5	5	9	9	9	9	9	5	7	5	5	9
Area5	250	45	3	9	5	9	5	5	3	3	3	3	5	9	5	3
Area6	300	70	5	5	7	5	7	5	5	5	5	7	3	7	5	3
Area7	150	70	1	5	1	5	3	3	1	1	1	9	5	9	5	3
Area8	300	65	5	1	3	7	7	5	5	5	5	9	7	7	5	9

Table 7. Normalized Matrix

Alternatives	e1	e2	e3	e4	e5	s1	s2	s3	s4	s5	s6	en1	en2	en3	en4	en5
Area1	0.259	0.062	0.250	0.188	0.188	0.167	0.188	0.139	0.206	0.250	0.250	0.025	0.029	0.065	0.125	0.083
Area2	0.086	0.074	0.083	0.188	0.188	0.093	0.104	0.083	0.088	0.083	0.083	0.025	0.088	0.065	0.125	0.083
Area3	0.052	0.174	0.028	0.188	0.188	0.167	0.063	0.028	0.029	0.028	0.028	0.125	0.088	0.065	0.125	0.083
Area4	0.259	0.069	0.250	0.021	0.104	0.093	0.188	0.250	0.265	0.250	0.250	0.125	0.206	0.109	0.125	0.250
Area5	0.086	0.112	0.083	0.188	0.104	0.167	0.104	0.139	0.088	0.083	0.083	0.075	0.147	0.196	0.125	0.083
Area6	0.103	0.174	0.139	0.104	0.146	0.093	0.146	0.139	0.147	0.139	0.139	0.175	0.088	0.152	0.125	0.083
Area7	0.052	0.174	0.028	0.104	0.021	0.093	0.063	0.083	0.029	0.028	0.028	0.225	0.147	0.196	0.125	0.083
Area8	0.103	0.161	0.139	0.021	0.063	0.130	0.146	0.139	0.147	0.139	0.139	0.225	0.206	0.152	0.125	0.250

Table 8. Weight of Criteria

criteria	e1	e2	e3	e4	e5	s1	s2	s3	s4	s5	s6	en1	en2	en3	en4	en5
Weight	0.178	0.171	0.268	0.188	0.194	0.167	0.172	0.178	0.189	0.163	0.131	0.235	0.206	0.162	0.172	0.225

Table 9. *Weighted Matrix*

Alternatives	e1	e2	e3	e5	e4	s1	s2	s3	s4	s5	s6	en1	en2	en3	en4	en5
Area1	0.046	0.011	0.067	0.035	0.036	0.028	0.032	0.025	0.039	0.041	0.033	0.006	0.006	0.011	0.022	0.019
Area2	0.015	0.013	0.022	0.035	0.036	0.015	0.018	0.015	0.017	0.014	0.011	0.006	0.018	0.011	0.022	0.019
Area3	0.009	0.030	0.007	0.035	0.036	0.028	0.011	0.005	0.006	0.005	0.004	0.029	0.018	0.011	0.022	0.019
Area4	0.046	0.012	0.067	0.004	0.020	0.015	0.032	0.045	0.050	0.041	0.033	0.029	0.042	0.018	0.022	0.056
Area5	0.015	0.019	0.022	0.035	0.020	0.028	0.018	0.025	0.017	0.014	0.011	0.018	0.030	0.032	0.022	0.019
Area6	0.018	0.030	0.037	0.020	0.028	0.015	0.025	0.025	0.028	0.023	0.018	0.041	0.018	0.025	0.022	0.019
Area7	0.009	0.030	0.007	0.020	0.004	0.015	0.011	0.015	0.006	0.005	0.004	0.053	0.030	0.032	0.022	0.019
Area8	0.018	0.028	0.037	0.004	0.012	0.022	0.025	0.025	0.028	0.023	0.018	0.053	0.042	0.025	0.022	0.056

In the fourth step, the positive and negative ideal solutions are calculated using equations (41–42). Here, n represents the number of criteria, and a_{ij} denotes the element at the intersection of row i and column j in the weighted matrix. The positive ideal solution consists of the best element in each column of the weighted matrix, while the negative ideal solution is derived by selecting the worst element from each column. The values for the positive and negative ideal solutions are provided in Table 10.

$$A^{+} = \{\max a_{i1}\ ,\ max\ a_{i2}\ , \dots , max\ a_{in}\ \} \tag{41}$$
$$A^{-} = \{\min a_{i1}\ ,\ min\ a_{i2}\ , \dots , min\ a_{in}\ \} \tag{42}$$

Table 10. The Ideal Solution and Negative Solution

Criteria	e1	e2	e3	e4	e5	s1	s2	s3
A^{+}	0.0460	0.0297	0.0671	0.0352	0.0364	0.0390	0.0386	0.0404
A^{-}	0.0092	0.0106	0.0074	0.0039	0.0040	0.0217	0.0128	0.0044
Criteria	s4	s5	s6	en1	en2	en3	en4	en5
A^{+}	0.0456	0.0563	0.0417	0.0387	0.0367	0.0368	0.0203	0.0327
A^{-}	0.0050	0.0062	0.0046	0.0043	0.0052	0.0122	0.0203	0.0109

The fifth step involves calculating the distances (ds_i) of various options from both the positive and negative ideal solutions, determining their proximity to the negative ideal (c_i), and ranking them accordingly. These calculations are performed using equations (43–45), where a_{ij} represents the element at the intersection of row i and column j in the weighted matrix. The computed distances of each region from the positive and negative ideals, along with their proximity to the negative ideal (c_i) and the corresponding rankings, are summarized in Table 11.

$$ds_i^+ = \sqrt[2]{\sum_{j=1}^{n} (a_{ij} - \max_i a_{ij})^2} \tag{43}$$

$$ds_i^- = \sqrt[2]{\sum_{j=1}^{n} (a_{ij} - \min_i a_{ij})^2} \tag{44}$$

$$C_i^- = \frac{ds_i^-}{(ds_i^- + ds_i^+)} \tag{45}$$

Table 11. Distance from Positive and Negative Alternative, Ranking of Areas

Alternatives	ds_i^+	ds_i^-	C_i	**Rank**
Area1	0.06362	0.11419	0.64220	2
Area2	0.10183	0.05391	0.34615	6
Area3	0.11921	0.05572	0.31853	7
Area4	0.04929	0.12037	0.70943	1
Area5	0.09109	0.06115	0.40168	5
Area6	0.07143	0.07224	0.50282	4
Area7	0.11837	0.05405	0.31347	8
Area8	0.07176	0.07952	0.52564	3

The c_i values consistently range from zero to one, with higher values indicating greater proximity to the positive ideal. These c_i values serve as critical indicators of each region's stability within the mathematical model. The results of applying the model to the cultivation of two specific products, tomato (p1) and cauliflower (p2), in the city of Kermanshah are thoroughly detailed in Table 12.

Table 12. Results of Model Implementation in Kermanshah

Area	**Product**	t^1	t^2	t^3	**Water system**	**Cultivation technology**	**GFS \$ /tax \$**	**Number of workers** Male			Female		
								t^1	t^2	t^3	t^1	t^2	t^3
3	p^1	1.45	6.57	6.88	w^2	M^3	17092.900 (GFS)	11	11	11	10	10	10
	p^2	5.88	0.75	-									
7	p^1	6.44	-	2.32	w^2	M^3	17208.648 (GFS)	11	11	11	10	10	10
	p^2	-	2.18	4.11									
Objective function = 14785473.9													

Figure 4 illustrates the land allocation for each crop across regions and time periods. The farm size in each period corresponds to the maximum cultivated area, which carries over to subsequent periods. For example, in Area 3, a maximum of 7.33 hectares is allocated for cultivation during the first and second periods. Similarly, Area 7 requires a maximum of 6.44 hectares, cultivated during the second and third periods. Notably, in certain periods, the actual cultivation may fall short of the farm's planned capacity. This discrepancy can be attributed to factors such as resource availability, period-specific demand, and product diversity.

Figure 4. Land Allocation in Different Time Periods for Different Products

4.1. Gender Equality Among Employees

This section evaluates the model's ability to maintain gender equality among employees. Figure 5 analyzes the impact of the RT parameter on gender disparity. As shown, an increase in the RT value leads to a widening gap between male and female workers. For instance, at $RT = 0.05$, the maximum disparity is six individuals, which increases to 12 at $RT = 0.1$, 24 at $RT = 0.2$ RT = 0.1, 24 at RT = 0.2, and peaks at 60 at $RT = 0.5$. Addressing this gender gap requires a multifaceted approach, including consideration of local legislation, cultural factors, collaboration with labor unions, and partnerships with women's rights organizations, alongside the implementation of appropriate RT values.

Our analysis indicates that each RT adjustment (0.05, 0.1, 0.2, 0.5) corresponds to changes in the ratio of women's wages to men's wages (0.5, 1, 1.5, 2). When the women's wage-to-men's wage ratio falls below one, the chart representing female workers exceeds that of male workers. Conversely, when the wage ratio exceeds one, the chart of female workers is relatively lower. This pattern emerges from the model's aim to minimize costs while adhering to the prescribed gender gap.

Furthermore, gender disparities are evident at the regional level. Figure 5 provides a detailed breakdown of male and female workers in Areas 3 and 7. Historically, women in Kermanshah have primarily played a supportive role in agriculture, with their contributions often underappreciated. This study aims to promote equitable distribution of agricultural tasks between men and women, acknowledging women's pivotal role in agriculture. By fostering income and economic equality, this approach empowers rural women, enabling them to enhance their household's well-being through investments in nutrition, education, and living standards.

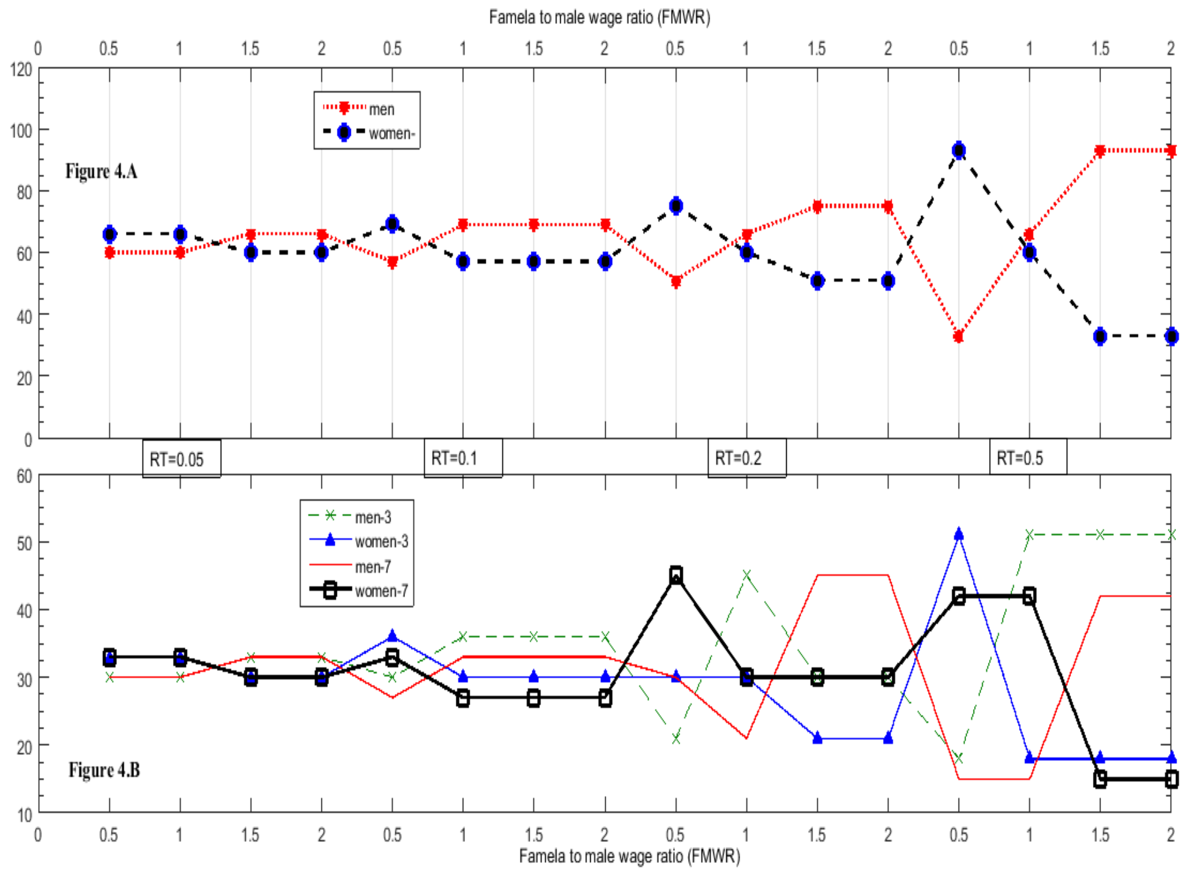

Figure 5. Equality between Men and Women in Obtaining a Job

4.2. The Role of Technology in Resource Consumption

Table 13 presents the impact of cropping technology on resource efficiency, specifically focusing on water, soil, and energy consumption for tomato and cauliflower production in Kermanshah. An educational comparative analysis of the impact of three varying cultivation technologies (M^1, M^2, and M^3, representing open-field, greenhouse, and closed-loop vertical hydroponic farming, respectively) on the utilization of key resources land, water, and energy forms a strong relationship between the level of technological advancement and the trend of resource utilization. Where land and water use are concerned, there is a very high negative correlation: moving in turn from M^1 to M^3, that is, intensification of environmental management and rational spatial use, their utilization drops very significantly. The M^1 (traditional) method, occupying 118.6 hectares of land and 255.6×10^7 liters of water, is the most inefficient since it relies on extensive horizontal cultivation and excessive wastage of water by evaporation, deep percolation, and runoff in open conditions. As opposed to this, M^3 (vertical hydroponics), which utilizes just 15.25 hectares of land and 7.1×10^7 liters of water, records a reduction of about an 87 percent and 97 percent in land and water usage, respectively, when compared to M^1. This dramatic land and water efficiency is attributed largely to the employment of vertical stacking buildings and closed-loop systems that enable recycling and precise delivery of nutrient solutions to plant roots. This natural resource effectiveness, however, is accompanied by a steep, positive slope in the use of energy. Although the M^1 method receives the minimum input of energy 8.5×10^5 kWh), the M^3 method receives the maximum input of 67×10^5 kWh, about 7.9 times the input received from the traditional method. This massive rise in energy demands is directly proportional to the total dependence of vertical systems on artificial sources of energy for providing photosynthetic light (generally through the employment of LED fittings), continuous control of temperature, humidity, and ventilation within, pumping of the nutrient solution through the hydroponic system, etc. Consequently, while more sophisticated technologies like vertical hydroponics have very effective solutions to the land and water shortage problem, particularly in deserts and cities, their primary sustainability challenge is energy and supply management. Becoming overall sustainable for such systems will involve either reducing their energy intensity or converting to renewable supplies.

Table 13. Impact of Cultivation Technology on Used Resources

Cultivation technology	Land(hectare)	Water (Liter)	Energy(kw/h)
M^1	118.6	255.6×10^7	8.5×10^5
M^2	45	23.8×10^7	22×10^5
M^3	15.25	7.1×10^7	67×10^5

4.3. Adapting to Increased Demand

Figure 6 illustrates the model's response to varying levels of demand increase. A systematic sensitivity analysis regarding the fluctuations in the demand for urban agriculture products, which was executed across a range of 10% to 100% increase relative to the baseline scenario, yielded critical insights into demand elasticity and optimal capacity planning. Computational results demonstrated that the model's objective function, which seeks the Total Cost Minimization, exhibited a nearly perfectly linear relationship with the rate of demand growth (the independent variable) as demand increased. The Pearson correlation coefficient between these two variables was calculated to be approximately $r \approx 0.99998$, which confirms a robust linear pattern. Consequently, the value of the objective function increased from $16,264,261 at the 10% demand increase level to $39,059,440 at the 100% level. This approximately 140.15% increase in total costs, in response to a 90% increase in demand, suggests that the model successfully expanded its capacity with nearly Constant Returns to Scale. The average cost growth rate for every 10% increase in demand across the entire range was, on average, approximately 15.57%. an examination of the spatial farm allocation pattern revealed a Sequential Farm Activation decision-making approach, which operates based on prioritizing locations according to their spatial sustainability score (C_i). Areas 3 and 7 were activated from the outset (the 10% demand increase level) and rapidly expanded their capacity to the point of complete Capacity Saturation upon reaching the 20% demand increase level (Area 3 with a size of 8.33 hectares), remaining at this maximum size in all subsequent scenarios. This phenomenon implies that these two areas possessed the lowest unit cost and the highest spatial justification for the project, placing them in absolute priority for resource allocation. At the 20% demand increase critical threshold, with the saturation of initial capacities, the model was compelled to activate Area 5, which commenced operations with an initial size of 0.93 hectares. Capacity allocation in Area 5 continued steadily up to the 60% demand increase level (with a size of 6.79 hectares). However, the most significant critical point occurred at the 70% demand increase level. At this juncture, with the more economically viable capacity of Area 5 being almost fully utilized, Area 2 (which had remained inactive in all previous scenarios) was activated with an area of 3.075 hectares.

- **Marginal Cost Analysis and Capacity Planning Implications**

The analysis of marginal costs validates the linear pattern of total costs, but provides greater detail. Following the initial step (from 10% to 20%), which exhibited a cost increase of $2,176,098, the cost increase for every subsequent 10% demand growth stabilized within a very narrow range, hovering around $2.57 million. For instance, in the transition from 90% to 100% demand, the cost increased by exactly $2,577,561. This stability in the marginal cost, contrary to the typical theoretical expectation under conditions of initial capacity saturation which usually leads to Accelerating costs suggests the potential for planned excess capacity and the availability of suitable land in the new areas (Area 2) that possess a cost structure similar to the preceding areas after initial fixed costs are incurred. This finding holds important implications for long-term capacity planning.

The critical points of 20% (Area 5 activation) and 70% (Area 2 activation) function as Critical Thresholds for urban planners and investors in spatial allocation. Should demand growth be forecasted to exceed 70%, planners must preemptively consider the necessary steps for securing infrastructure and allocating Area 2 (the highest marginal cost location) to manage development delays and sudden cost increases. This sensitivity analysis approach furnishes a powerful Decision Support Tool for the optimal allocation of resources in urban agriculture projects, ensuring that the spatial expansion of capacity occurs not randomly, but in an economic, documented, and resource-optimization based manner.

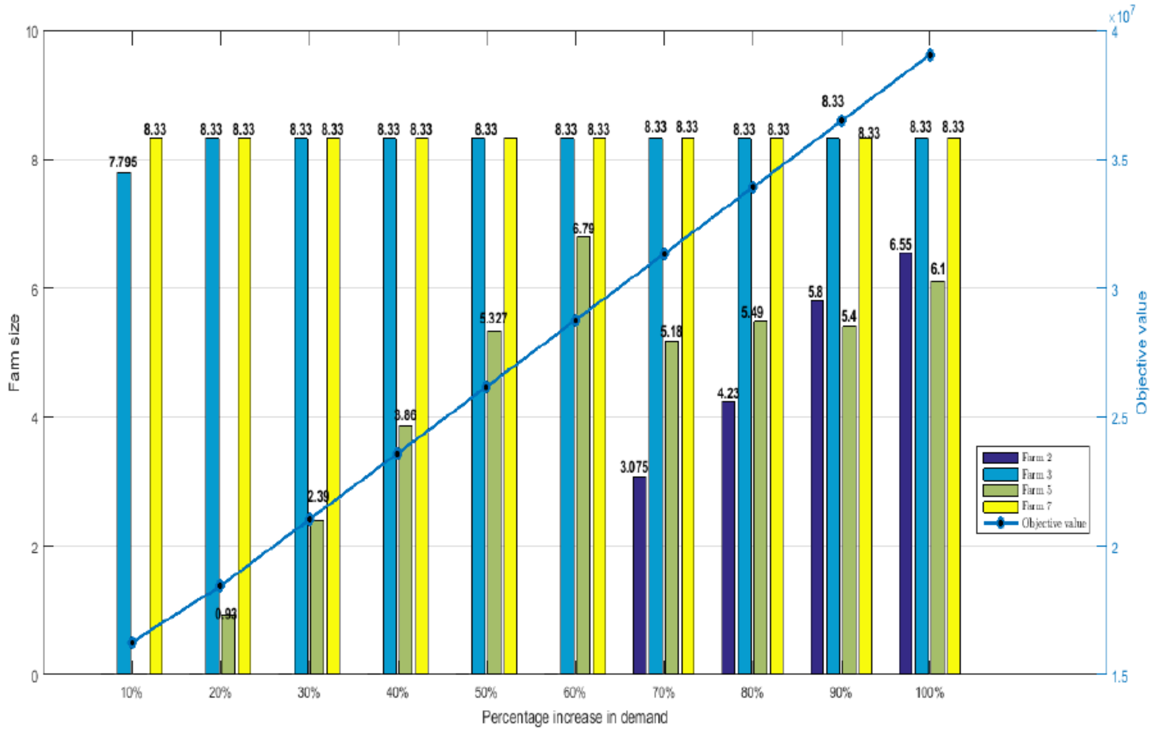

Figure 6. Adapting to Increased Demand

4.4. Return on Investment in Urban Agriculture

Investors naturally prioritize projects that balance low risk with high profitability. In this study, the economic feasibility of the proposed project is evaluated using the net present value (NPV) method, a widely recognized financial valuation technique. The NPV method accounts for the time value of money, emphasizing that future cash flows are worth less than current ones due to factors such as inflation and opportunity cost. By discounting future cash flows to their present value, as expressed in equation (46), the method determines the project's profitability. In this analysis, the investor's minimum expected rate of return (R) is set at 30%, with a time horizon of 15 periods (5 years).

The project's financial data, including costs and revenues for each product over time, are presented in Table 14. The initial investment comprises land acquisition costs of $10,332,817 and agricultural equipment expenses of $2,534,984. While the land, as a non-depreciable capital asset, retains its full value at the end of the five years, the equipment is assumed to have zero residual value. The calculated NPV of £3,522,412 confirms the economic feasibility of establishing the farms.

$$NPV = \sum_{t} \left(\frac{Revenues_t - costs_t}{(1+R)^t} \right) - initial\ investment \quad (46)$$

Table 14. Financial Information of the Urban Farm in Kermanshah

Period time	Revenue from tomatoes	Revenue from cauliflower	Tomato cultivation cost	cauliflower cultivation cost
1	1650000	300000	174008	235644
2	1375000	150000	86479	195495
3	1925000	210000	121071	273693
4	1650000	300000	172958	234594
5	1375000	150000	86479	195495
6	1925000	210000	121071	273693
13	1650000	300000	172958	234594
14	1375000	150000	86479	195495
15	1925000	210000	121071	273693
		NPV $3522412		

In practical scenarios, variations in specific parameters, such as land prices, equipment costs, product values, or changes in an investor's expected return rate, can significantly affect the project's economic feasibility. Table 15 and Figure 7 provide an analysis of the project's economic viability by examining alterations in these parameters.

An increase in cost parameters generally leads to a decrease in the Net Present Value (NPV) of the project. For instance, a rise in land prices results in a lower NPV, and when land prices increase by more than 50%, the project becomes economically unviable. Similarly, a reduction in income parameters leads to a decrease in NPV. If tomato prices fall to less than 0.76% of their current value, the project becomes economically unsustainable. However, fluctuations in cauliflower prices have minimal impact on the project's economic viability, as cauliflower can be substituted with similar products.

Additionally, raising the rate of return to 50% above the current rate $(0.30 \times 1.50 = 0.45)$ pushes the project beyond economic feasibility. This increase in the rate of return reflects higher investor expectations for greater returns and profits, driven by factors such as global price increases, better investment opportunities, and rising bank interest rates.

Ultimately, the sensitivity analysis, as shown in Figure 7, highlights those changes in land prices and the rate of return on investment have the most significant effect on the project's NPV. The steeper slopes in the graphs representing land prices and the rate of return, compared to other parameters, underscore their critical role in determining the project's economic viability.

Table 15. The Effect of Changing Parameters on the Value Of NPV

Percentage of changes	Land cost (NPV)	Facility cost (NPV)	Tomato price (NPV)	Cauliflower price	Variable cost of tomatoes (NPV)	Variable cost of cauliflower (NPV)	Investment return rate (NPV)
0.10	10042173	5803898	-9459689	1762388	5369130	4538061	17459298
0.20	9317755	5550400	-8017233	1957947	5163939	4425211	15023354
0.30	8593337	5296901	-6574777	2153505	4958748	4312361	12896319
0.40	7868919	5043403	-5132322	2349063	4753557	4199512	11030224
0.50	7144501	4789904	-3689866	2544621	4548367	4086662	9385706
0.60	6420083	4536406	-2247410	2740179	4343176	3973812	7930275
0.70	5695666	4282908	-804955	2935738	4137985	3860962	6636971
0.80	4971248	4029409	637501	3131296	3932794	3748112	5483301
0.90	4246830	3775911	2079957	3326854	3727603	3635262	4450409
1.00	**3522412**	**3522412**	**3522412**	**3522412**	**3522412**	**3522412**	**3522412**
1.10	2797994	3268914	4964868	3717970	3317221	3409562	2685872
1.20	2073577	3015415	6407323	3913529	3112030	3296712	1929369
1.30	1349159	2761917	7849779	4109087	2906840	3183862	1243158
1.40	624741	2508418	9292235	4304645	2701649	3071013	618893
1.50	-99677	2254920	10734690	4500203	2496458	2958163	49396
1.60	-824095	2001421	12177146	4695761	2291267	2845313	-471525
1.70	-1548513	1747923	13619602	4891320	2086076	2732463	-949236
1.80	-2272930	1494425	15062057	5086878	1880885	2619613	-1388395
1.90	-2997348	1240926	16504513	5282436	1675694	2506763	-1793065

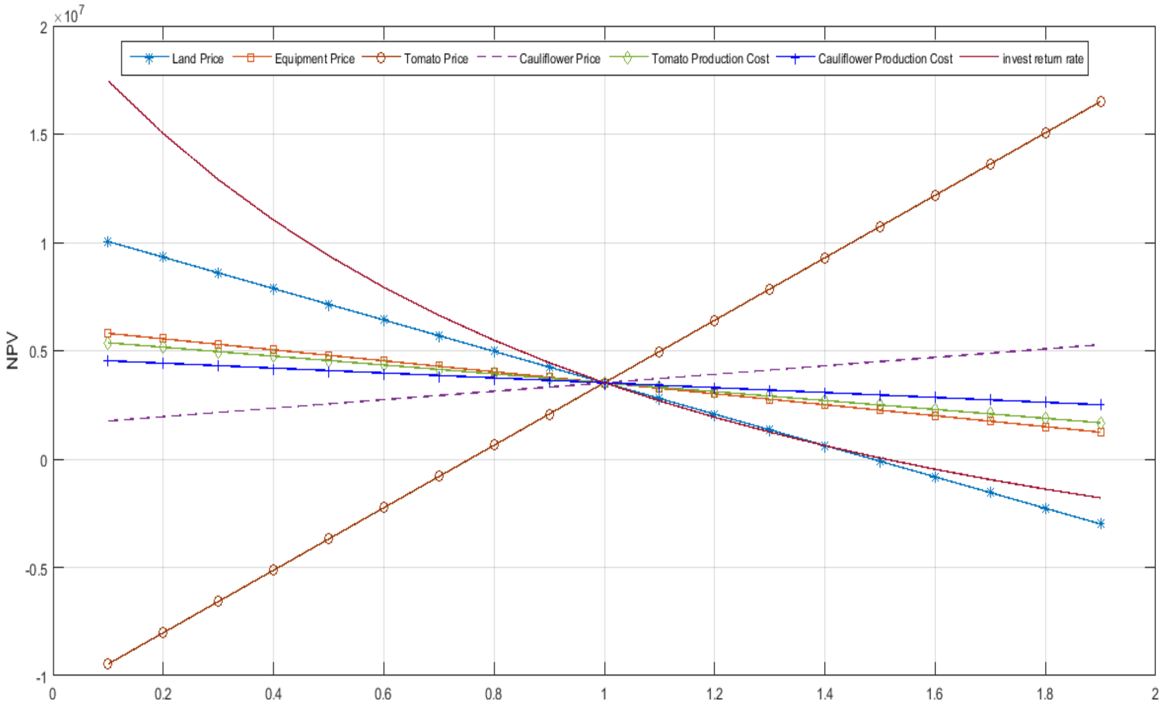

Figure 7. Examining the Change of Economic Parameters on the Economic Viability of the Project

4.5. The Role of ANP-Topsis Decision Making Model in Stability Control

In the proposed model, the parameter 'sus' represents the weight assigned to sustainability by the decision-maker. A higher value for this parameter indicates a greater emphasis on sustainability in the selection of locations for urban farm establishment. Additionally, C_i denotes the sustainability score of region i, which is assessed using the ANP-TOPSIS decision-making model. The results show that increasing the value of 'sus' leads to changes in the chosen locations for establishing urban farms. These shifts directly impact factors such as access to wastewater systems, water resources, and the availability of affordable, suitable land. As a result, key aspects like irrigation systems, farm size, and the economic feasibility of the urban farms are influenced.

Figure 8 illustrates the outcomes when sus = 0.3. In this scenario, regions 7 and 3 emerge as the preferred locations for farm establishment. The farm in region 7 aligns with the positive ideal in three sub-criteria $e_2, en_{1,} en_3$) but corresponds to the negative ideal in 10 sub-criteria. Similarly, the farm in region 3 aligns with the positive ideal in three sub-criteria (e_4, e_5, s_1) but corresponds to the negative ideal in two sub-criteria $(S_3 en_3)$.

As shown in Figure 8B, increasing sus to 0.4 shifts the preferred locations to regions 8 and 5. In this scenario, the farms align with the positive ideal in three and four sub-criteria, respectively, and with the negative ideal in one sub-criterion each. Figure 8C indicates that in this configuration, the farms align with the positive ideal in four sub-criteria and with the negative ideal in three. In Figure 8D, the alignment increases to 11 sub-criteria for the positive ideal and six for the negative ideal. These shifts raise an important question: does increasing the sustainability rate consistently enhance sustainability across all sub-criteria?

It is important to note that merely increasing the number of positive sub-criteria and decreasing the negative ones does not guarantee an overall improvement in sustainability. True sustainable growth depends on progress within the most valuable sub-criteria. As identified in Table 8, the most critical sub-criteria include investor preference, wastewater treatment systems, job satisfaction and quality of life, and average regional income. The relocation of farms from regions 7 and 3 to regions 8 and 5 demonstrates significant improvements in four of the top five criteria. Furthermore, shifting a farm from region 5 to region 6 results in improvements across all five key sustainability sub-criteria.

Therefore, achieving greater sustainability does not require improvements across all sub-criteria but rather prioritizing progress in the most impactful ones. This principle also applies to higher-level dimensions, including economic, social, and environmental aspects. Figure 8 highlights that increasing the decision-maker's sustainability rate does not uniformly enhance all criteria. As a result, incorporating stakeholder perspectives becomes essential in determining the decision-maker's sustainability rate, ensuring a balanced and context-sensitive approach.

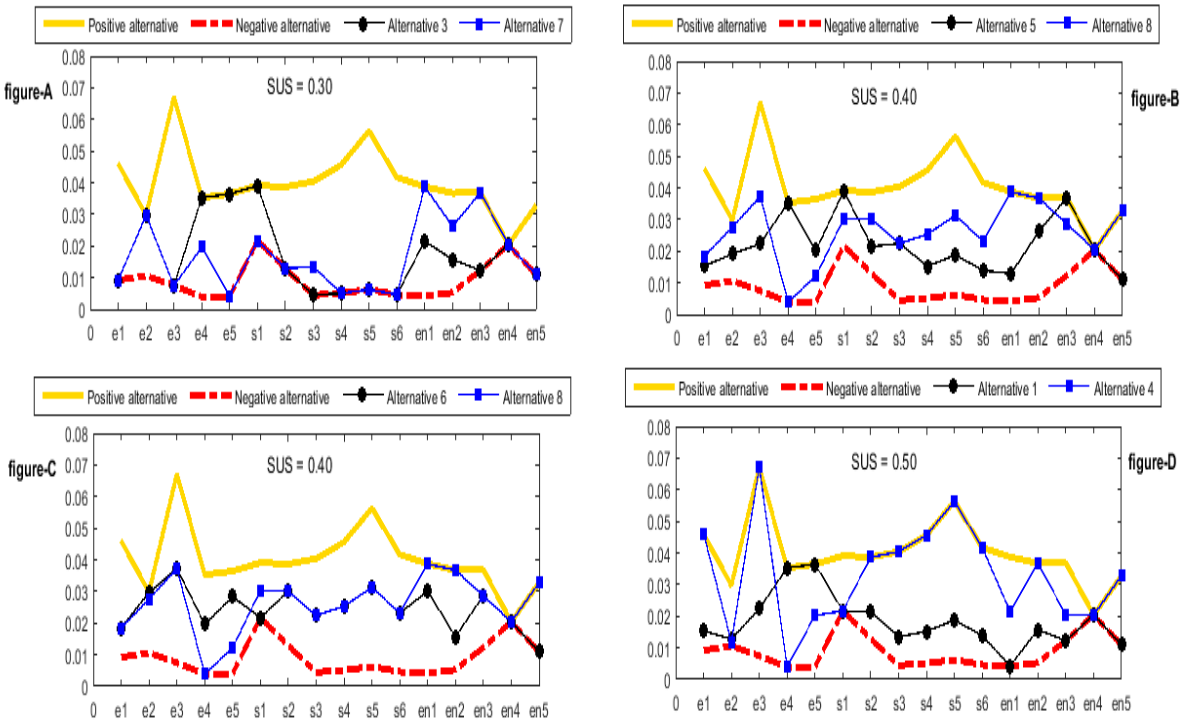

Figure 8. The Effect of Increasing the Degree of Sustainability on the Amount of Sustainability Criteria

The parameter c_i represents the total distance from the negative alternative, a value that increases with the decision-maker's stability rate. It is important to note that this distance can vary across different criteria. For instance, as shown in Figure 9 and Table 16, relocating the farms from options 6 and 8 to options 4 and 1 results in an overall increase in the total, economic, and social distances. However, it simultaneously causes a decrease in the environmental distance. This shift leads to an improved overall rating and higher economic and social rankings but a decline in the environmental ranking of the farms.

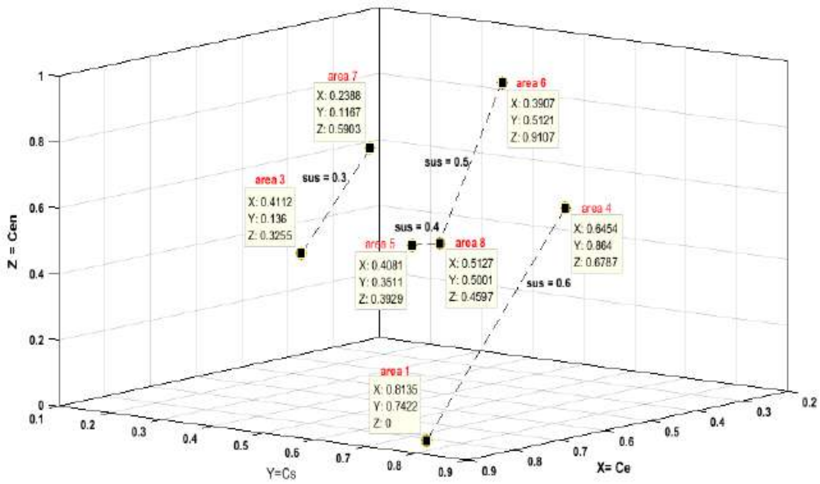

Figure 9. Distance of Area from Negative Economic, Negative Social and Negative Environmental Options

Table 16 presents the rankings of individual areas alongside their respective distances from the negative alternative across economic, social, and environmental dimensions. This table provides decision-makers with a valuable resource to better understand regional conditions and make informed comparisons between different areas.

Table 16. Sustainability Rating and Distances from the Negative Alternative

Alternatives	Economic		Social		Environmental		Total	
	Ce_i	Rank	Cs_i	Rank	Cen_i	Rank	C_i	Rank
area1	0.8135	1	0.742245	2	0	8	0.5724	2
area2	0.45739	4	0.252	6	0.151	7	0.3330	7
area3	0.4112	5	0.136	7	0.32554	6	0.3244	8
area4	0.6453	2	0.863	1	0.67867	2	0.7093	1
area5	0.4081	6	0.351	5	0.39290	5	0.3870	5
area6	0.5127	3	0.500	4	0.45970	4	0.4912	4
area7	0.2387	8	0.116	8	0.590	3	0.3517	6
area8	0.39067	7	0.512125	3	0.9107	1	0.5656	3

5. Management Insights for Sustainable Urban Agriculture Development

The results obtained from the two-stage optimization model (ANP-TOPSIS and Mixed Integer Programming) for the development of Sustainable Urban Agriculture in Kermanshah reveal profound managerial implications for policymakers, urban planners, and private sector investors in regions facing severe water and land crises. These insights center on the pivotal role of technological trade-offs, economic risk management, and the necessity of integrating socio-environmental sustainability considerations into the decision-making process.

- **The Imperative of Proactive Management in Technology-Resource Trade-offs**

The selection of Vertical Hydroponics as the optimal cultivation technology, while offering a massive 97% reduction in water consumption and an added 87% reduction in land, comes with a 7.9-fold rise in energy consumption. This inevitable water-energy trade-off places a priority on the agenda of city management: environmental sustainability of these initiatives will be realized only through mandatory or subsidized integration of renewable energy generation systems (e.g., solar). Therefore, support policies must be targeted towards green energy infrastructure rather than merely subsidizing cultivation technology in order to effectively decrease the carbon footprint and attain true sustainability.

- **Risk Management and Ensuring Economic Viability**

The financial model, which confirms a positive economic return (Net Present Value (NPV) > \$3.5 million), demonstrates the project's high sensitivity to land prices (a 50% increase in price renders the project unfeasible) and the investor's expected rate of return (above 45%). These sensitivities significantly increase the risk for private investment. Consequently, the critical risk mitigation strategy involves:

A) Land Guarantee: The government must utilize legal instruments to identify suitable urban land and make these lands available to investors through long-term, subsidized lease agreements to eliminate the risk arising from land price fluctuations.

B) Demand Guarantee: To manage product price volatility (e.g., tomatoes), the formulation of Off-take Agreements with major distribution chains is essential.

- **Prioritizing Social Sustainability and Multi-Criteria Location Selection**

ANP-TOPSIS analysis highlights that location decision cannot be made on the basis of classical economic criteria alone. The Composite Sustainability Score incorporating criteria such as "Investor Willingness," "Wastewater Treatment System," and "Job Satisfaction" must be the initial filter for city planning.

Furthermore, the model, by offering an equal distribution of 126 jobs to both women and men (RT parameter constraint), identifies the central role of urban agriculture in women's economic empowerment and bridging gender gaps. Institutional policy must transcend recommendation to mandating employment of at least 40% to 50% of women in state-supported projects with attendant specialized training and welfare facilities (e.g., childcare).

Successful implementation of sustainable models in conflict-ravaged cities like Kermanshah demands an integrated decision-support system. In this system, the Sustainability Index (C_i) guides location planning, government subsidy overcomes the economic exposure due to technological trade-offs (energy cost), and institutional policy promotes social equity. This multi-faceted approach transforms urban agriculture from a technical solution to a strategic investment in urban resilience, food security, and social equity.

6. Discussion and Conclusion

The study presents sustainable urban agriculture as a practical solution for food provision, highlighting its diverse benefits, including improved access to fresh food, job creation, and the seamless integration of farms into urban landscapes. Addressing the challenges of urban settings, the study employs a two-stage methodology that combines a decision-making framework with a mathematical model to evaluate traditional cultivation, greenhouse farming, and vertical hydroponic systems. A case study in Kermanshah, Iran, focusing on tomato and cauliflower production, identifies the need for two vertical hydroponic farms, spanning 8.3 and 6.3 hectares, respectively, strategically located in different urban areas to meet demand effectively.

A comprehensive analysis of gender equality in Kermanshah's urban farms, conducted through a mathematical model, demonstrates the equitable distribution of 126 jobs between male and female workers. Sensitivity analysis delves into gender disparities and wage ratios, emphasizing the model's effectiveness in maintaining equity within predefined thresholds. Specifically, RT values of 5%, 10%, 20%, and 50% correspond to maximum job disparities of 6, 12, 24, and 60 positions, respectively. The study also assesses the economic viability of urban farming in Kermanshah, revealing a net present value (NPV) of $3,522,412. Key economic factors such as land and tomato prices, alongside the investor's expected return rate, are identified as critical determinants. Notably, a 50% increase in land prices, a 45% rise in the expected return rate, or a 25% drop in tomato prices could render urban farming economically unfeasible. Access to affordable land emerges as a pivotal factor in the development of urban agriculture, as land costs constitute a substantial share of the expenses involved in establishing and maintaining urban farms. Conversely, advancements in agricultural technology can mitigate the reliance on land and water, enhancing the economic and environmental sustainability of urban farms.

Within the sustainability framework, the ANP-TOPSIS model plays a critical role in evaluating urban farming by defining 16 sub-criteria across economic, social, and environmental dimensions. These sub-criteria, derived through expert consensus and data analysis, provide the foundation for comprehensive assessment. Using SUPER DESIGN software, sustainability scores and rankings are calculated for each urban area, with the decision-maker’s sustainability threshold (sus) serving as a pivotal parameter in the mathematical model. Adjustments to the sus value influence farm location decisions, as demonstrated in scenarios with thresholds ranging from 0.3 to 0.6. Raising the minimum sustainability threshold excludes lower-scoring neighborhoods, favoring regions with higher sustainability ratings. While increasing this threshold enhances overall sustainability, it does not guarantee uniform improvement across all criteria, highlighting regional distinctions in economic, social, and environmental performance.

While this study offers valuable insights, several limitations should be noted. The model's dependence on specific datasets, such as those related to water resource availability and constant demand, may restrict its applicability to other geographic regions. Additionally, variations in sustainability metrics and their relative importance across different contexts limit the generalizability of the findings.

Urban agriculture presents a promising solution to address global food security challenges and mitigate potential food deserts in future urban environments. To further advance this field, future research should explore energy consumption in urban farming and the integration of emerging technologies. Specific areas of focus could include developing mathematical models to maximize workforce efficiency and optimize food accessibility, managing resources effectively, allocating markets to urban farms, and examining the dynamics of competition and cooperation in farm decisions. These decisions encompass critical factors such as location, cultivation methods, and crop selection.

Generative Artificial Intelligence (AI):

we disclose that we used ChatGPT, an AI language model developed by OpenAI, to improve the English language and clarity of our manuscript. The tool was used to enhance the readability and grammatical accuracy of the text.

Declaration of Interests

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

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