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Designing a Food Security Supply Chain for Sustainable Oil Production Using a Non-Dominated Sorting Genetic Algorithm (NSGA-II) Approach

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Abstract

Governments' key priorities include increasing food security and quality. Food security is influenced by food availability, financial ability to get food (affordability or accessibility), quality (utility), and sustainability. In light of food security concerns and the contractual approach, the current study presents and resolves a model for establishing supply chain networks for basic food products. The supply chain network investigated in this study includes two types of consumers: sunflower canola oil producers and oilseed suppliers. This study reviewed prior studies to identify food security dimensions and factors that impact the food security chain. Then, for the field study, two questionnaires were constructed. The factors of food security and associated criteria were approved by research specialists who used the original questionnaire. The resulting questionnaire is then used to identify the most critical factors influencing food security in the supply chain being studied. A mathematical model of the supply chain that promotes domestic production and uses a contractual approach was developed. The "comprehensive criterion (LP-metric)" method was utilized to solve the problem in small dimensions. The multi-objective mathematics presented in this study is NP-hard, and the metaheuristic Non-Dominated Sorting Genetic Algorithm (NSGA-II) was used to solve the model in high dimensions. To validate, the results of this algorithm were compared with the exact solution (a comprehensive benchmark method). The results of the studies indicate that the metaheuristic algorithm performs appropriately. Finally, a sensitivity analysis was performed to examine the effect of parameters on the objective functions.

Keywords: Network design, Supply chain, Food security, Sustainability of food security, Factors affecting food security.

1 | Introduction

Food security is a critical global issue defined as the condition in which all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs. It encompasses a

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broad range of factors, including food availability, accessibility, and utilization, all of which are interconnected with social, economic, and environmental systems. Ensuring food security is essential not only for health and well-being but also for sustainable development and economic stability. As various challenges such as climate change, conflict, and economic disparities continue to impact food systems, understanding and addressing food security becomes increasingly vital for global resilience and equity. In the food security supply chain, there are two categories of influencing factors: direct and indirect. These factors can address the dimensions of food security. The Food and Agriculture Organization of the United Nations defines four fundamental dimensions of food security: availability, access from the physical and economic aspects, quality, and stability (sustainability). In the research by Kazemi and Samouei [1], the sustainability dimension is defined by four main criteria: good governance, environmental integrity, economic resilience, and social welfare. To assess sustainability, the criteria of economic resilience and indicators such as per capita income, population, and profit margins have been used.

Food security and the maintenance of a proper and stable supply chain are critical issues that must be addressed. As a result, this study focuses on developing a supply chain network for staple products (cooking oil) that is grounded in key elements of food security.

The model proposed in this research should be similar to the model shown in *Fig. 1*:

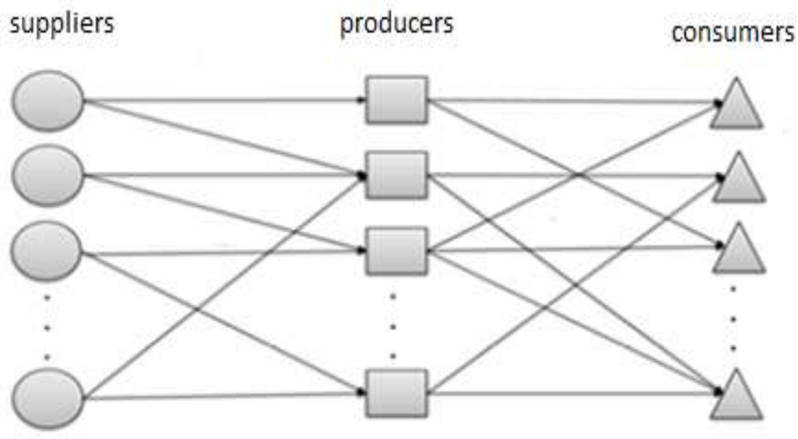

Fig. 1. A three-level model of food security.

In this model, the suppliers refer to the farmers and farms that provide the raw materials for cooking oil (canola and sunflower). The producers refer to the processing factories that produce the oil.

The basic assumptions of the desired model of this research are as follows:

I. The model is considered multi-period and multi-product.

II. All four main aspects of food security, i.e., availability, accessibility, quality, and sustainability, must be met.

III. The demand of all customer areas must be met.

IV. To satisfy the accessibility constraint, the model includes the price component and government tariffs.

V. To assess the sustainability of food security, the model includes parameters related to per capita income and profit margins (economic considerations of sustainability).

The questions that this research seeks to answer are as follows:

I. How is the three-level food security supply chain network of the basic products considered in this research?

II. What are the influencing factors and components in ensuring the food security of the basic products under study?

III. What is the mathematical contractual model of ensuring food security of the basic products studied in the five-year horizon, taking into account the aspects of food security and supporting domestic production?

2 | Literature Review

In this section, the literature on the subject is summarized into two sections: the dimensions of food security and mathematical modeling.

2.1 | Dimensions of Food Security

With the advent of famine in Bangladesh and other countries worldwide in the 1960s and 1970s, a global effort to understand how to combat hunger in vast parts of the developing world emerged [1]. In this part, we review and discuss research on people's access to food. Deng et al. [2] analyzed the hazards in China's rice supply chain. Their findings revealed that the risk to the food supply chain in the western regions is slightly higher than in the eastern regions. Oriekhoe et al. [3] undertook a thorough investigation on the relationship between climate change and food supply chain economics, with a focus on sustainability. Their research revealed that climatic and temperature changes decrease manufacturing efficiency and product quality. Belhadi et al. [4] examined digital drivers in food supply chain management. They examined 14 African farms as case studies. Blockchain and other technologies were used to assist these drivers.

Kozielec et al. [5] explored how the conflict between Russia and Ukraine affects food security in the Middle East and North Africa. Their findings revealed that the Middle Eastern and North African food supply chains rely heavily on food imports. Alam et al. [6] addressed sustainability and food security under risk conditions, as well as the impact of the supply chain. They employed the structural interpretation method to tackle the problem. In their study, 18 drivers were identified, and subsequent analysis revealed that 5 drivers had a stronger influence on minimizing ripple effects in the food supply chain. Amhamed et al. [7] studied food security in critical supply chain situations in Qatar. The findings of their investigation revealed that Qatar is transitioning from a food importer to a producer and even exporter. Barakat et al. [8] investigated and examined the impact of war on food security in Ukraine and the Middle East. Their review clearly shows that humanitarian activities and efforts to develop them have a significant impact on reducing food insecurity.

Sagi and Gokarn [9] developed a multi-stakeholder method to identify the key factors influencing the alleviation of food shortages in the Indian food supply chain. Their research revealed that government support, chain involvement, technical support, customer attitude, and management commitments are the five essential elements in the food supply chain. Tonelli et al. [10] demonstrated that decentralized competitiveness increases food security. Furthermore, their research demonstrated that decentralized manufacturing is dependent on transit costs and supply chain interruptions. Varzakas and Smaoui [11] created a strategy for a sustainable supply chain through 2030. The results of their research demonstrated that, to achieve sustainability, the ecosystem should be protected and climate change reduced. Cunningham et al. [12] investigated food subsidies and dietary consumption in a remote part of India in light of the globalization of food environments. Hashem et al. [13] found that COVID-19 has a detrimental impact on the stability of the food supply chain, based on their investigation. Nhemachena et al. [14] investigated the criteria for food security in Africa, and their findings revealed that the western portion of Africa will face challenging food security conditions in the future.

2.2 | Mathematical Modeling in Food Security

Sundaram and Brennan [15] examined food security in the South Asian region in relation to the coronavirus pandemic. Their methodology accounted for the impact of climate change and investment in rural infrastructure on food security. Lopez et al. [16] developed a mathematical model to improve food security and rural development in Paraguay. They created a mixed-integer model to maximize profits while promoting food security. Over five years, their research yielded the highest profits in the network. Kazemi and Samoui [17] proposed a two-level mathematical model to address food security and reduce the environmental impact of pesticides and fertilizers. Their findings revealed that a 50% increase in pesticide prices and a 30% drop in cultivation led to a rise in environmental impact. Khan et al. [18] investigated food security indicators in 379 rural districts of Pakistan. Their findings showed that population growth and climate change negatively affected food security. Hamidoğlu [19] developed a food supply chain using game theory with government funding. In their model, a game-theoretic framework was developed between farmers and agricultural enterprises, revealing that the government supported increased food production.

Esteso et al. [20] studied the design of a multi-objective optimization model for the planning of fresh produce production, harvesting, storage, packing, transportation, and sales. They pursued five objectives to ensure supply chain sustainability. Their objectives are to maximize supply chain profitability (economic), reduce waste (environmental), reduce unmet demand (social), maximize the freshness of items sold (environmental and social), and minimize economic injustice to farmers (justice). Their case study focused on Argentina's tomato supply chain. Abbas et al. [21] developed a multi-objective conceptual simulation to maximize costs, environmental impacts, quality, safety, and appropriate transportation infrastructure for the perishable food supply chain. Their findings revealed a 108% increase in both cost and environmental consequences.

Furthermore, their findings demonstrated that a 23% increase in economic awareness improves supply chain sustainability by 137%. Daneshvar et al. [22] investigated the distribution of perishable agricultural items under uncertain conditions. Their approach includes three levels: suppliers, distribution centers, and retailers, allowing suppliers to meet retailers' needs directly. The findings indicated that uncertainty boosts demand, supply, distribution, and ordering.

Gholian Jouybari et al. [23] developed a food supply chain network to ensure the sustainability of saffron. They analyzed their intended model using multi-criteria decision-making methodologies and modeling to minimize supply chain costs. Patidar and Agrawal [21] developed a food supply system for perishable goods in India. In their problem, they demonstrated that promoting domestic production boosts profitability throughout the chain. In addition, Azab et al. [24] developed a mixed-integer linear programming model for the sustainable food supply chain. Their model incorporates transportation, inventory, demand, and disposal operations. They incorporated perishability and sustainability into their model. Their concept was applied to the sugar supply chain, increasing food security and sustainability. Rahbari et al. [25] examined the sugarcane supply chain in the context of uncertainty and sustainability. Fasihi et al. [26] investigated a closed-loop supply chain model for fish. They used a new mathematical model to minimize the entire cost of this supply chain. To solve this problem, they employed a linear technique with an epsilon constraint. Esteso et al. [27] explored what a multi-objective optimization model should be for planning, planting, harvesting, storage, packaging, transportation, and sales of fresh fruit.

Yang et al. [28] investigated the profit-sharing contract in the agricultural product supply chain using mathematical modeling. Their findings revealed that this contract promotes profit and involvement among chain members. Hou et al. [29] investigated contract coordination and involvement, as well as the enhancement of food security governance in the agricultural product supply chain. The findings revealed that contract terms and member participation had a substantial impact on supply chain coordination. *Table 1* lists relevant research.

Table 2. Features of relevant studies.

The Author	Research Focus		Dimensions of Food Security				Supply Chain Design									Solution Approach				
								Product		Period		Purpose		Type of Participation						
	Criterion Review	Math Model	Availability	Accessibility	Quality	Sustainability	Number of Levels	Single	Multi	Single	Multi	Single	Multi	Contractual	Non-Contractual	Statistical Methods	Exact Solution	Meta- Heuristic	Dynamic Systems	Game Theory
Jouybari et al		✓	✓			✓	4	✓			✓		✓		✓		✓			
Patidar and Agrawal [30]		✓	✓				5		✓		✓				✓		✓			
Esteso et al		✓	✓			✓	3		✓		✓		✓		✓		✓			
Abbas et al		✓			✓	✓	2		✓		✓		✓		✓		✓			
Daneshvar et al		✓	✓				3		✓				✓		✓			✓		
Azab et al		✓				✓	3		✓		✓		✓		✓			✓		
Rahbari et al		✓	✓			✓	5		✓		✓		✓		✓		✓			
Fasihi et al		✓	✓				3	✓		✓			✓		✓		✓			
Esteso et al		✓	✓			✓	5		✓		✓	✓			✓		✓			
Cunningham et al	✓		✓	✓			2	✓		✓					✓	✓				
Yang et al		✓	✓	✓			3	✓		✓			✓	✓						✓
Hashem et al	✓		✓				1	✓		✓					✓	✓				
Hou et al[29]		✓	✓	✓			2		✓		✓	✓		✓			✓			
Nemachna et al	✓		✓	✓			2	✓		✓					✓	✓				
This research	✓	✓	✓	✓	✓	✓	3		✓		✓		✓	✓		✓	✓	✓		

3 | Research Method

In this research, a questionnaire on influential factors in the food security supply chain was compiled using a field survey and prior research. This questionnaire includes influencing factors in food security, validity and reliability checks, and the identification of the most important factors for each dimension of food security to be applied in the mathematical model of the problem. To address these factors, after interviewing experts and reviewing past research, criteria corresponding to each of the four dimensions of food security were extracted. Then, these dimensions were discussed, and we finally identified the effective factors in food security using the (two-step) interview method. So, after receiving the expert opinions based on the Lawshe formula in *Relation (1)*, the validity of each question is assessed by the number of positive responses and a cutoff point of 0.6, and ultimately, each is either confirmed or discarded.

$$\mathrm{VR} = \frac{\mathrm{N_e} - \frac{\mathrm{N}}{2}}{\frac{\mathrm{N}}{2}} \geq 0/6, \quad (1)$$

CVR: The validity coefficient of the questionnaire items (this value is acceptable if it's above 0.6).

$\mathrm{N_e}$: The number of people who answered positively to the questionnaire.

N: The total number of questionnaires received.

Furthermore, this study establishes the reliability or stability of the information using Cronbach's alpha coefficient (internal consistency of the measurements), thus supporting the results. To determine Cronbach's alpha, compute the variance of the scores for each subset of the questionnaire items as well as the overall variance of all questions, and then use *relation (2)* to obtain the alpha coefficient.

$$\alpha = \frac{\mathrm{n}}{\mathrm{n} - 1}\left(1 - \frac{\sum \mathrm{s_i^2}}{\mathrm{S_i^2}}\right), \quad (2)$$

N: Number of test questions (the number of parts in the exam).

$\mathrm{s_i^2}$: Variance of the question (variance of the data in a column of the data matrix).

$\mathrm{S_i^2}$: Total variance of the test, or in other words, the variance of the total column in the data matrix.

The higher the correlation between the questions and the more dependable the questionnaire, the closer the resultant number is to 1. Notably, an alpha of less than 0.6 is weak, 0.7 to 0.8 is acceptable, and greater than 0.8 is regarded as good. The validity of direct and indirect factors is demonstrated in *Tables 2* and *3*.

Table 2. Calculation of the validity of direct factors based on the Lawshe formula.

Factors	The Number of Answers is Yes	The Number of Answers is No	Lawshe Coefficient
Changes in food import tariffs	30	0	1/00
Agricultural product prices and their fluctuations	30	0	1/00
Subsidies in agriculture	29	1	0.93
Research and development of the agricultural sector	28	2	0.87
Insurance of agricultural products	29	1	0.93
Extra-territorial cultivation	27	3	0.80

Table 3. Calculation of the validity of indirect factors based on the Lawshe formula.

Factors	The Number of Answers is Yes	The Number of Answers is No	Lawshe Coefficient
Climate change	27	3	0.80
Macroeconomic policies	30	0	1/00
Monetary policies	30	0	1/00
Financial policies	28	2	0.87
Price changes of energy carriers	29	1	0.93
National security	30	0	1/00
Water security	30	0	1/00
Education and level of education	28	2	0.87
Nutritional literacy	30	0	1/00
Economic growth	30	0	1/00
Urbanization	27	3	0.80

Cronbach's alpha was also used to assess the reliability of the mentioned criteria. The Cronbach's alpha coefficients for direct and indirect factors were 0.882 and 0.856, respectively, indicating that both sets of factors are statistically reliable.

After identifying the factors influencing food security, several critical factors were selected for inclusion in the mathematical model of the problem, with assistance from specialists. The mathematical model accounts for changes in food import tariffs, product pricing and fluctuations, urbanization and population growth, nutritional literacy, and macroeconomic policies such as per capita income and profit margins. These parameters were utilized to apply consumer regulations in the issue's mathematical model. According to the constraints section, these factors influence the dimensions of food security.

Next, we'll talk about the mathematical model. This study's supply chain consists of multiple levels, products, periods, and objectives. Food products under consideration include canola oil and sunflower oil. Thus, the first level of this chain comprises several suppliers who may provide oilseeds, mainly canola and sunflower. On the second level, edible oil producers (canola oil and sunflower oil) obtain canola and sunflower seeds from supply centers and process them into canola and sunflower oil. In this regard, oil manufacturers can enter into contracts with canola and sunflower supply centers, ensuring that the supply centers purchase the seeds (canola and sunflower). Under the revenue-sharing agreements, the supplier agrees to sell oilseeds to the oil producer at a lower price than before. In exchange, they expect the oil production centers to share a portion of their sales with the supply centers. Consumers are on the third level. This contractual approach will enable the end product (canola and sunflower oil) to reach consumers at a lower cost.

At the second level, production centers (processing plants) and warehouses bear the cost of maintaining these products (canola oil and sunflower oil) to address rapid demand fluctuations and market shocks. When demand is high, and output and inventory levels are insufficient, production centers might increase their capacity. The third level of this chain consists of end consumers whose demand for each type of goods is known in each period. Transportation costs are also factored into the supply chain.

The indices and sets are as follows:

i	Type of oilseeds (canola and sunflower).
i'	Product type (canola oil and sunflower oil).
j	Type of nutrient (vitamin, protein, mineral).
s	oilseed supply centers (can be internal or external).
k	Production centers.
l	Demand areas.
c	Different capacity levels for production center development.
t	Time period.

The necessary parameters for modeling the food security supply chain of the products considered in this research are:

p_{is}^{t}	The price of buying oilseed i from the supply centers in the period t.
$p_{i'k}^{t}$	The purchase price of oil i^'from the producer k in the period t by the consumer.
Cap_{is}	The capacity of the supply centers of oilseed is.
$Cap_{i'k}$	The capacity of the production center k of the product i^'.
$Cap_{i'ck}$	Expandable capacity with level c in the production center k of the product i^'.
$ICR_{i'k}^{t}$	Holding cost per product i^'in the production center k in the period t.
TRC_{isk}^{t}	The cost of transporting a unit of product i from the supply center s to the production center k in the period t.
$TRC_{i'kl}^{t}$	The cost of transporting a product unit i^'from the production center k to the customer area l during the period t.
TT_{s}^{t}	The total percentage of import tariff, customs duties, and transport insurance from the supply centers in the period t.
$DC_{i'ck}$	The cost of developing the production center k for the product i^ for the capacity level c.
e_{s}^{t}	The conversion rate of the currency center s to the base currency unit in the period t.
$D_{i'l}^{t}$	Per capita demand in the region l of the product i^'in the period t.
$NV_{i'j}$	The amount of nutritional value j in one unit of the product i'.
N_{J}	Average nutrient requirement j per person.
H_{l}^{t}	Population in the area l at the period t.
I_{l}^{t}	Average per capita income of people in the customer area l during the period t.
ρ_{l}	The average share of the food basket in the household income in the customer area l.
$Q_{i'l}$	Average acceptable quality index for product i^' in consumer area l.
γ	The supplier's discount percentage for the producer.
$\emptyset$	The percentage of the supplier's profit from the producer's profit in the contract model.
$\alpha_{i'l}$	Average profit margin of the supply chain for the product i^'in the customer area l.

C_i	Cost of oilseed i For the supplier per hectare (buying seeds, planting, keeping, and harvesting).
M	Big number.

The decision variables required for modeling are given below:

G_{isk}^t	The amount of oilseed flow i from the supply centers to the production center k in the period t.
$F_{i'kl}^t$	Product flow rate type i^'From the production center k to the customer area l in the period t.
$IV_{i'k}^t$	Product inventory level i^'in the production center k in the period t.
$IC_{i'k}^t$	The total cost of keeping the product i^'in the production center k in the period t.
$ID_{i'ck}$	Variable zero and one expand the capacity of the production center k aproduct 〖 i〗 ^' with capacitive level c.
LY_{isk}^t	Variable zero and one allocation of production center k to supply center s, period t, for product i.
$RY_{i'kl}^t$	A zero and one variable assigns the customer area lto the production center k for the product i^'in the period t.
$QM_{i'k}^t$	quality index of the product i^'stored in the production center k in the period t.
Basketprice_l^t	The price of the food basket in each region.
Nutrition_{jl}^t	The amount of nutrients in each area.
$\text{Qualitylevel}_{i'l}^t$	The quality level of each product in each region.

3.1| Nonlinear Mathematical Model

3.1.1| Objective functions

For this study, three objective functions have been considered. The first objective function (Z1) is to maximize the supplier's profit (the supply center), the second objective function (Z2) is to maximize the profit of the production centers, and the third objective function (Z3) is to maximize customer satisfaction.

$$\max Z_1 = \sum_i \sum_s \sum_k \sum_t G_{isk}^t * \gamma P_{is}^t (1 + TT_s^t) - \sum_i \sum_s \sum_k \sum_t G_{isk}^t * TRC_{isk}^t - \sum_i C_i + \emptyset(\Delta Z_2), \quad (3)$$

$$\max Z_2 = [\sum_{i'} \sum_k \sum_l \sum_t p_{i'k}^t * F_{i'kl}^t - \sum_{i'} \sum_k \sum_l \sum_t F_{i'kl}^t * TRC_{i'kl}^t - \sum_{i'} \sum_k ID_{i'ck} * DC_{i'ck} - \sum_{i'} \sum_k \sum_t IC_{ik}^t], \quad (4)$$

$$\max Z_3 = \sum_{i'} \sum_l \sum_t \min \left\{ \frac{\sum_k F_{i'kl}^t}{D_{i'l}^t} \right\}, \quad (5)$$

3.1.2 | Limitations

The limitations of the model are as follows:

$$IV_{i'k}^{t} \leq Cap_{i'k} + \sum_{c} Cap_{i'ck} * ID_{i'ck} \text{ for all } i', k, t, \tag{6}$$

$$\sum_{c} ID_{i'ck} \leq 1, \qquad \text{for all } i', k, \tag{7}$$

$$IV_{i'k}^{t} = IV_{i'k}^{t-1} + \sum_{s} G_{isk}^{t} - \sum_{l} F_{i'kl}^{t}, \qquad \text{for all } i', k, t, \tag{8}$$

$$IC_{i'k}^{t} = \frac{IV_{i'k}^{t} + IV_{i'k}^{t-1}}{2} * ICR_{i'k}^{t}, \qquad \text{for all } i', k, t, \tag{9}$$

$$\sum_{i'} \sum_{k} NV_{i'j} * F_{i'kl}^{t} \geq H_{l}^{t} * N_{J}, \qquad \text{for all } j, l, t, \tag{10}$$

$$P_{i'}^{t} = \sum_{s} (((p_{is}^{t} * e_{s}^{t} * (1 + TT_{s}^{t})) + TRC_{isk}^{t}) * G_{isk}^{t}), \qquad \text{for all } i', k, t, \tag{11}$$

$$(\sum_{i'} \sum_{k} (P_{i}^{t} * F_{i'kl}^{t} + TRC_{i'kl}^{t} * F_{i'kl}^{t})) \leq H_{l}^{t} * I_{l}^{t} * \rho_{l}, \qquad \text{for all } l, t, \tag{12}$$

$$QM_{i'k}^{t} = \sum_{s} Q_{is} * LY_{isk}^{t}, \qquad \text{for all} i', k, t, \tag{13}$$

$$QM_{i'k}^{t} * RY_{i'kl}^{t} \geq Q_{i'l} * RY_{i'kl}^{t}, \qquad \text{for all } i', k, l, t, \tag{14}$$

$$\sum_{k} G_{isk}^{t} \leq Cap_{is}, \qquad \text{for all } i, s, t, \tag{15}$$

$$\sum_{k} F_{i'kl}^{t} \geq D_{i'l}^{t} * H_{l}^{t}, \qquad \text{for all } i', l, t, \tag{16}$$

$$Basketprice_{l}^{t} = \left(\sum_{i'} \sum_{k} [P_{i'}^{t} * F_{i'kl}^{t} + TRC_{i'kl}^{t} * F_{i'kl}^{t}] * (1 + \alpha_{i'l})\right) \Big/ H_{l}^{t}, \qquad \text{for all } l, t, \tag{17}$$

$$Nutrition_{jl}^{t} = \sum_{i'} \sum_{k} NV_{ij} * F_{i'kl}^{t} \Big/ H_{l}^{t}, \qquad \text{for all } l, j, t, \tag{18}$$

$$Qualitylevel_{i'l}^{t} = \sum_{k} F_{i'kl}^{t} * QM_{i'k}^{t} \Big/ D_{i'l}^{t} * H_{l}^{t}, \qquad \text{for all } i', l, t, \tag{19}$$

$$LY_{isk}^{t} \leq G_{isk}^{t} \leq M * LY_{isk}^{t}, \qquad \text{for all } i, s, k, t, \tag{20}$$

$$\sum_{s} LY_{isk}^{t} \leq 1, \qquad \text{for all } i, k, t, \tag{21}$$

$$RY_{i'kl}^{t} \leq F_{i'kl}^{t} \leq M * RY_{i'kl}^{t}, \qquad \text{for all } i, k, l, t, \tag{22}$$

$$F_{i'kl}^{t}\ G_{isk}^{t}, IV_{i'k}^{t} IC_{i'k}^{t}\ QM_{i'k}^{t} \geq 0, \qquad LY_{isk}^{t}, RY_{i'kl}^{t} = \{0,1\}. \tag{23}$$

The *relationship (3)* maximizes the profit of suppliers (supply centers), and the *relationship (4)* maximizes the profit of production centers in the supply chain of canola oil and sunflower oil. *Relationship (5)* shows the maximization of consumer satisfaction. *Relationships (6)* and *(7)* are constraints on production center capacity, ensuring that the inventory at each center does not exceed its capacity. Additionally, only one capacity level should be selected for the center's development. *Relationship (8)* relates to the inventory of products in production centers at the end of each period and establishes flow equilibrium. *Relationship (9)* calculates inventory holding costs. *Relationship (10)* defines the first dimension of food security: availability. *Relationships (11)* and *(12)* define the second dimension of food security: the financial capability to procure food. *Relationships (13)* and *(14)* define the third dimension of food security: usefulness (quality). This constraint states that the average quality level of each product type in each region must be at least equal to the acceptable quality level for that product in that region. *Relationship (15)* relates to the capacity of suppliers (supply centers). *Relationship (16)* ensures the satisfaction of demand for population areas. *Relationships (17)*, *(18)*, and *(19)* estimate the price of the product basket, the nutritional value, and the average product quality level for products sent to population areas, respectively. *Relationships (20)* and *(22)* are constraints related to the binary variable flows of the chain members. *Relationship (21)* guarantees the single-sourcing of production centers. *Relationship (23)* specifies the model's positive and binary variables.

Constraints (12) and *(14)* make the model nonlinear. To linearize the model, two continuous variables $x^t_{ii'skl} = LY^t_{isk} * F^t_{i'kl}$ and $x'^t_{ii'skl} = LY^t_{isk} * RY^t_{i'kl}$ are added to the model along with the following restrictions:

$$x^t_{ii'skl} \leq M * LY^t_{isk}, \quad \text{for all } i, i', s, k, l, t, \tag{24}$$

$$x^t_{ii'skl} \geq F^t_{i'kl} - M * (1 - LY^t_{isk}), \quad \text{for all } i, i', s, k, l, t, \tag{25}$$

$$x^t_{ii'skl} \leq F^t_{i'kl}, \quad \text{for all } i, i', s, k, l, t, \tag{26}$$

$$x'^t_{ii'skl} \leq M * LY^t_{isk}, \quad \text{for all } i, i', s, k, l, t, \tag{27}$$

$$x'^t_{ii'skl} \geq RY^t_{i'kl} - M * (1 - LY^t_{isk}), \quad \text{for all } i, i', s, k, l, t, \tag{28}$$

$$x'^t_{ii'skl} \leq RY^t_{i'kl}, \quad \text{for all } i, i', s, k, l, t. \tag{29}$$

4 | Case Study and Findings

4.1 | Exact Solution

Since the suggested model is a Nonlinear Programming (NLP) model, it must first be reformulated as a Mixed-Integer Linear Programming (MILP) model and then precisely adjusted to solve the problem using an exact method. A small-scale random problem is solved using the comprehensive criterion method in GAMS on a system with a 2.7 GHz Intel Core i7 processor to validate the improved model. The objective functions are then analyzed according to different norms. There are two customer regions, two production centers, and two supply centers in this problem. This section examines the results of solving the challenge. The values for the problem's parameters are obtained from *Table 4*.

Table 4. Values of problem parameters.

$\mathbf{Cap_{is} = U\{0, 2000\}}$	$\mathbf{Cap_{i'k} = U\{0, 2000\}}$	$\mathbf{Cap_{i'ck} = U\{1, 4\}}$	$\mathbf{ICR^t_{i'k} = U\{1, 5\}}$	$\mathbf{TRC^t_{isk} = U\{1, 5\}}$
$TRC^t_{i'kl} = U\{1,5\}$	$TT^t_s = U\{0,1\}$	$DC_{i'ck} = U\{0,10\}$	$e^t_s = U\{0,1\}$	$\rho_l = 0.4$
$NV_{i'j} = U\{0,1\}$	$N_J = U\{0,1\}$	$\emptyset = 0.2$	$I^t_l = \{10,100\}$	$Q_{is} = \{0,1\}$
$Q_{i'l} = \{0,1\}$	$\alpha_{i'l} = U\{20,100\}$	$H^t_l = U\{0,1000\}$		$\gamma = 0.15$
$D^t_{i'l} = U\{0,1000\}$		$RE_k = \{1.4\}$	$C_i = 500,700$	

In this problem, there are two customer regions whose populations are randomly distributed according to *Table 4*. Also, based on the amount of oil extracted from oilseeds, the flow of products from production centers to customers accounts for 45% of the flow from supply centers to production centers.

Table (5). separates the pricing of oilseeds (canola and sunflower) from that of final products (canola oil and sunflower oil) due to real-world price disparities.

Table 5. The parameter related to the price of oilseeds and oil.

Oil Price	The Price of Oilseeds	Material/Product
$U\{60, 100\}$	$U\{20, 50\}$	canola
$U\{40, 70\}$	$U\{10, 40\}$	sunflower

To solve small-scale problems, an LP-metric method has been used. Before the solution, it's important to explain this method. In this approach, the total relative deviations of the objectives from their optimal values are minimized. Specifically, for a problem with n objective functions, the optimal value of each objective function (from the first to the nth) must be calculated independently of the other n-1 objective functions, taking into account all the problem's constraints. Because the closer the objective functions are to their optimal values, the better, we are looking for an objective function that aids in the convergence of all functions. To achieve this goal, the total relative deviation of the objectives from their optimal values must be minimized. Thus, the objective function and the model are defined as follows:

$$\min z = \sum_{i=1}^{k} w_i \left(\frac{z_i^* - z_i}{z_i^*}\right)^p,$$

$$g_i(X_1, X_2 \ldots\ldots X_n) \le b_i,$$

So that we have:

$$z_i = f_i(X_1, X_2 \ldots\ldots X_n), \qquad X_i \ge 0,$$

$$z_i: \quad \text{free.} \tag{30}$$

Given the mathematical model's three objectives, this study employs the "comprehensive criterion (LP-metric)" solution approach. First, the optimal values for each objective function are computed independently (using GAMS software), and then combined into a new objective function, as shown below. As previously stated, Z1, Z2, and Z3 denote the objective function values for the supplier, producer, and customer. Thus, the function Z4 is defined as follows:

$$\min Z4 = \left(\frac{Z1^* - Z1}{Z1^*} + \frac{Z2^* - Z2}{Z2^*} + \frac{Z3 - Z3^*}{Z3^*}\right)^p. \tag{31}$$

The above relationship should be minimized to ensure that the standard deviation from the optimal value of each objective function is minimized. The above relationship is solved for different values of p, and the results are examined. Typically, in past research, the best answers have been obtained at $p = 1$, $p = 2$, and $p = \infty$. In this study, the LP metric method has been employed with all three values of $p = 1$, $p = 2$, and $p = \infty$ to solve the multi-objective problem of this research [31].

To solve the problem, the objective functions were first solved separately, considering the constraints, and the following values were obtained in Table 6.

Table 6. Optimal values of the objective functions individually.

The Optimal Value of the Customer Objective Function ($Z3^*$)	The Optimal Value of the Producer Objective Function ($Z2^*$)	The Optimal Value of the Supplier's Objective Function ($Z1^*$)
90/69%	95000	79200

Initially, for the norm $p = 1$, 10 Pareto solutions (non-dominated solutions) are presented in *Table 7*. Since minimizing total deviations is prioritized, Pareto Solution 7 is considered the efficient solution by this method.

Table 7. Efficient solution obtained by LP metric method with $p = 1$.

Pareto Answer Number	Supplier Objective Functionthedoerz1)	Producer Objective Function (Z2)	Customers' Objective Function (Z3)	The Sum of the Relative Deviations From the Optimum
1	68050	82140	%79.8	0.074
2	68700	85300	%82.1	0.069
3	69,000	87500	%83.2	0.064
4	71300	88950	%84.6	0.051
5	74000	92500	%86	0.049
6	76900	93200	%88.2	0.038
7	79050	94800	%90.6	0.004
8	79200	91562	%89.02	0.017
9	78150	89625	%87.2	0.041
10	76253	89521	%86.9	0.077

Based on the results in *Table 7*, in the LP method using the $p = 1$ norm, select the Pareto *Solution 7* from the set of Pareto solutions. This argument is because this solution has the lowest total relative deviation from optimality.

Similar to what was done for $p = 1$, the best efficient solution for the problem for $p = 2\ \infty$ is presented below.

Table 8. Efficient solution obtained by LP metric method with $p = 2$

The Sum of the Relative Deviations	Customers' Objective Function(Z3)	Producer Objective Function (Z2)	Supplier Objective Function (Z1)
0.0001	90.2%	95400	79390

In the Pareto answer obtained in *Table 9*, the maximum deviation from the optimum has its lowest value.

Next, the optimal flows of oilseed (sunflower) and oil products (sunflower oil) over 5 years are presented.

Table 10. The amount of sunflower seed flows from supply centers to production centers in different periods.

G^t_{isk}	First	Second	Third	Fourth	The Fifth
Supply center 1 to production center 1	61.2	52.3	109.1	320	142.9
Supply center 1 to production center 2	21.2	75.1	189	232	222
Supply center 2 to production center 1	31.1	53.2	145	330	165.4
Supply center 2 to production center 2	83.1	70.6	253.5	120	181.1

It can be seen that the amount of sunflowers sent has significantly increased during the fourth and fifth periods.

Table 11. The amount of sunflower oil from production centers to customer centers in different periods.

$F^t_{i'kl}$	First	Second	Third	Fourth	Fifth
Production center 1 to customers in region 1	18	0	38	78	121.5
Production center 1 to customers in region 2	0	81	53	101	59
Production center 2 to customers in region 1	91	119	58	118.5	102
Production center 2 to customers in region 2	125	0	91	99	80

4.2.2 | The solution using a metaheuristic algorithm

The multi-objective mathematical model presented in this study is NP-hard; hence, the non-dominated genetic algorithm NSGA-II is utilized to solve it in high dimensions. Furthermore, to validate the algorithm, their outcomes will be compared to exact solutions. All programming for this large-scale task was done in MATLAB.

4.2.3 | Determining the control parameters of algorithms

To determine the control parameters for the metaheuristic algorithm, the Taguchi method has been used. The control parameters of the genetic algorithm include the population size (nPop), a termination criterion based on a specified number of generations, the crossover probability (pc), and the mutation probability (pm). To set the control parameters for this algorithm, different levels for the NSGA-II parameters were determined based on previous research [32].

After running the NSGA-II algorithm 27 times, the results were entered into Minitab 22 and evaluated using Taguchi. *Fig. 2* shows the results of tests designed with Minitab software.

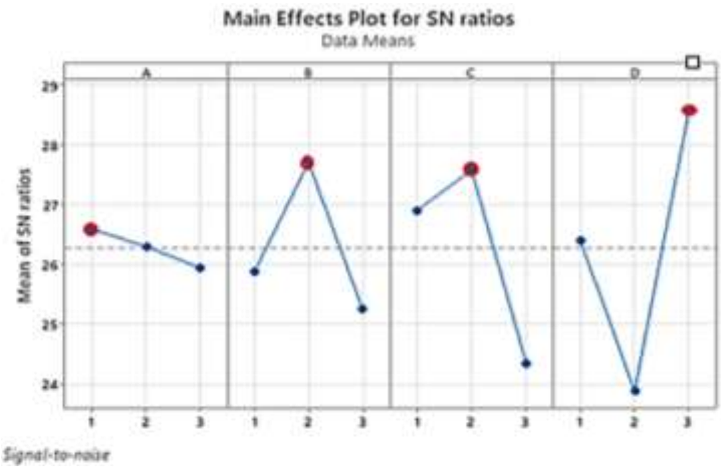

Fig. 2. The average ratio of disturbances resulting from the Minitab software for setting NSGA-II parameters.

The greater the stability of the solutions, the more desirable the outcome. Therefore, the control parameters of the NSGA algorithm for the first objective function are determined using the Taguchi test, as shown in *Table 12*.

Table 12. Control parameters of the NSGA-II algorithm for the first objective function.

NSGA-II			
Mutation probability	Probability of crossover	Termination criteria	Population size
0.20	0.50	200	100

In Table 13, the NSGA-II results are compared with the exact solution for different-dimensional problems.

Table 13. Comparison with the exact solution.

				Exact Solution (Lp-Metric)				**Nsga-Ii**			
Problem No	**Number Of Customer Areas**	**Number Of Production Centers**	**Number Of Supply Centers**	**The First Goal**	**The Second Goal**	**The Third Goal (Percentage)**	**Solving Time (Seconds)**	**The First Goal**	**The Second Goal**	**The Third Goal (Percentage)**	**Solving Time (Seconds)**
1	2	2	2	79145	94900	90.61	72.7	75621	90400	89.00	107.1
2	4	3	3	121254	143211	90.05	295.2	127300	143211	90.1	119
3	5	4	4	162541	183254	92.00	1050.1	155321	174542	89.50	136.2
4	6	5	5	201542	218654	91.65	2662.2	192000	202541	91.65	150.4
5	6	6	6	245124	273210	89.	3985	253,000	279,000	91.00	167.7
6	10	8	8	-	-	-	-	39700	79145	90.02	185.2
7	10	9	9	-	-	-	-	49051	90,000	91.50	199.1
Average (except problems 6 and 7)				161921	182582	91.54	1613	161900	179,000	90.84	160644

The table above shows that the NSGA-II algorithm provides solutions close to the exact solution, as evidenced by the best solutions obtained for each objective function.

4.2.4 | Sensitivity analysis

In this section, the profit levels of suppliers and producers relative to the prices of final products (in this example, sunflower oil) are examined. In this part, "supply centers" are replaced with "supplier," and "production centers" are replaced with "producer."*Fig. 3)* shows the amount of profit for different prices of sunflower oil.

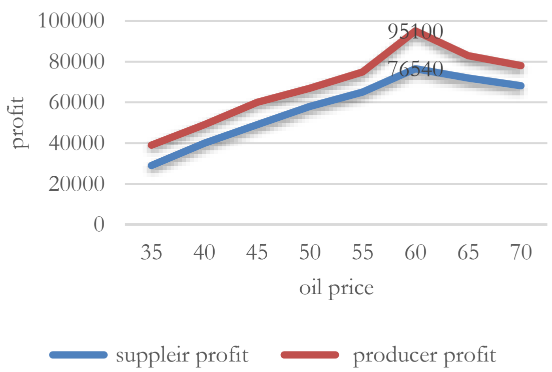

Fig. 3. Supplier and producer profit compared to the price of sunflower oil.

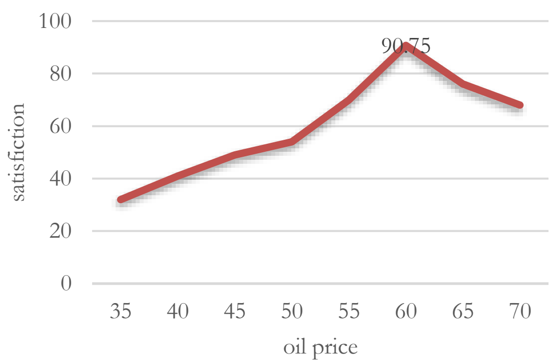

Fig. 4. Customer satisfaction with the price of sunflower oil.

In *Fig. 3*, the optimal profit for both the supplier and the producer is achieved for 60 units of sunflower oil; outside that range, it's not suitable for the supply chain. Also, at this point, customer satisfaction is at its maximum. Additionally, the Pareto solutions in *Tables 7-9 indicate the maximization of supplier profit (z1), producer profit (z2), and* customer satisfaction (z3).

5 | Conclusions

In this research, the validity and reliability of the factors affecting food security were first assessed. After confirming the relevant factors, a few key elements were selected for implementation in the mathematical model based on expert opinions. The factors used in this mathematical model include "changes in import tariffs on food products, product prices and their fluctuations, urbanization and population, nutritional literacy, and macroeconomic policies such as per capita income and profit margins." The problem was then addressed on a smaller scale using a comprehensive criteria approach. Also, due to the NP-Hard nature of the problem under study, the metaheuristic algorithm NSGA-II was used to solve it. To examine the performance of the presented algorithm, the results obtained by it in solving problems of different dimensions were compared with the exact solution, indicating the algorithm's appropriate performance in solving the problem of this research. Finally, a sensitivity analysis was performed to examine the effects of the parameters on the objective functions.

In future research, this problem can be addressed by establishing contracts between lower levels of the supply chain to improve coordination. Another strategy that could prioritize purchasing from domestic suppliers (over foreign ones) is the use of penalty coefficients in the mathematical model, which could also facilitate the implementation of resistant economic policies. By adding a quality decision variable to the customers' objective function, the issue can also be analyzed from the customers' perspective, allowing for a more precise examination of the impacts of consumer-related policies and factors.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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