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Biofuel Supply Chain Network Design based on Microalgae With a Cost-Carbon-Employability Balance Approach

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Abstract

This study focuses on the design of a multi-objective mathematical model for optimizing the biofuel supply chain network based on microalgae. The proposed model considers all stages of the supply chain, from microalgae cultivation to the production of biodiesel, glycerol, and organic fertilizers. The primary goal of this research is to simultaneously optimize three dimensions: economic, social, and environmental. These include cost reduction, job creation, and reducing environmental impacts (specifically, greenhouse gas emissions reduction). The model is solved using the augmented epsilon-constraint method, which leads to a set of Pareto optimal solutions. The numerical results indicate that the simultaneous optimization of these objectives leads to improvements in cost reduction and job creation, along with a significant reduction in environmental impacts. The main innovation of this research lies in providing a comprehensive overview of the third-generation biofuel supply chain and using multi-objective optimization methods to achieve a balance among various objectives. This study addresses the sustainability challenges in the biofuel supply chain and provides optimal solutions for achieving a sustainable and efficient model.

Keywords: Biofuel supply chain, Microalgae, Multi-objective mathematical model, Augmented epsilon-constraint method, Sustainability.

1 | Introduction

The rapid increase in global energy consumption has become an international crisis. Two main groups of fuel sources, namely non-renewable fossil fuels such as oil, natural gas, and petroleum derivatives, and renewable biofuels, are primarily responsible for this rise in consumption. Although fossil fuels still account for a

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significant portion of global energy consumption, the use of biofuels is continuously expanding [1]. Crude oil and biofuels each have their own advantages and disadvantages, which influence their future consumption outlook. While crude oil remains popular due to its high energy production and consumption, this trend is associated with pollution and negative environmental impacts. Additionally, a large portion of oil and its derivatives is produced in developing countries, raising concerns about energy security in developed nations. On the other hand, biofuels face numerous challenges, including high costs, the need for advanced technology, competition with the agricultural sector, and water resource limitations [2].

Biofuels are divided into four generations, with third-generation biofuels being produced from sources such as algae and microbes. Due to their lower requirements for water and land resources, they have been proposed as a viable option for the production of green energy [3].

Among these, microalgae, as a third-generation biofuel, are recognized as a promising option for clean energy production due to their high photosynthetic ability, rapid growth, and non-competition with agricultural land. These microscopic organisms can absorb carbon dioxide and grow in various environmental conditions, such as freshwater, saline water, and wastewater. In addition to producing bioethanol and biodiesel, microalgae can generate diverse products, including hydrogen, chemicals, pharmaceuticals, dietary supplements, animal and aquaculture feed, and biofertilizers, all of which help reduce environmental impacts [4]. Given the selective biomass characteristics, water is a key resource for the production and processing of microalgae. This study emphasizes optimizing water usage and reducing its waste in the biofuel supply chain. Furthermore, the reuse of wastewater and the transfer of carbon dioxide emissions from other industries to algae cultivation ponds help reduce environmental impacts and improve sustainable technologies. From an economic perspective, process optimization and cost reduction across the supply chain are essential, while reducing greenhouse gas emissions is also considered a critical issue.

In this study, Section 2 is dedicated to the literature review. Section 3 describes the development of the mathematical model. Section 4 introduces the solution method for the model and analyzes the results. Finally, Section 5 will provide a conclusion of the study.

2 | Literature Review

Biofuels have attracted considerable attention in recent decades as renewable and sustainable energy resources. Biofuels and biodiesel, due to their environmental benefits and renewability, are among the most prominent types of bioenergy and have gained a distinctive position in scientific research. In this context, researchers have investigated various solutions to optimize the processes associated with the biofuel supply chain. Accordingly, Savoji et al. [5] developed a mathematical model aimed at reducing carbon emissions and costs in the biofuel supply chain by employing a robust stochastic programming approach and the epsilon-constraint method. This model contributed to enhancing the sustainability of the biofuel supply chain. Furthermore, Kalhor et al. [6] proposed a model for the design and management of a biofuel supply chain network with the objective of minimizing costs and environmental impacts. By leveraging robust optimization and a fuzzy approach to address uncertainties, this model improved the supply chain's overall performance.

Mohammadi et al. [7] examined the impact of the water–energy nexus on policymaking in Iran and developed a multi-objective model for energy production from sewage sludge. This model can contribute to improving the management of primary resources. Finally, Yıldız et al. [8] proposed a model for optimizing the design of a sustainable renewable energy supply chain network based on biomass, incorporating strategic decisions regarding processing facilities and warehouses.

On the other hand, numerous studies have been published on biodiesel production from microalgae, addressing various aspects of this field. Initially, Ahn et al. [9] investigated several mathematical programming models for optimizing bioethanol supply chains based on cellulosic biomass. Given the challenges related to food supply and the low processing efficiency of lignocellulosic biomass, microalgal biomass was proposed as an alternative feedstock for biodiesel production. In this study, a deterministic mathematical model was developed to design a microalgal biomass-to-biodiesel supply chain network, accounting for resource, demand, and technology constraints. The model assisted in determining facility locations, feedstock quantities, and the number of refineries in order to minimize total costs. Subsequently, Mohseni and Pishvaee [10] proposed a sustainable supply chain model aimed at achieving commercial viability. This model, based on batch and continuous production modes, examined the future of the microalgal biofuel supply chain and proposed strategies to reduce costs.

Moreover, Mohseni et al. [11] stated that microalgae have emerged as a promising source for biodiesel due to their substantial oil productivity. To accelerate the commercialization of microalgal biodiesel, a two-stage supply chain design and planning model was proposed. In this study, an Relax Mixed-Integer Linear Programming (RMILP) optimization model was developed to optimize strategic and tactical supply chain decisions under uncertainty.

Arabi et al. [12] proposed a mixed-integer linear programming model for the design of a microalgae-based biobutanol supply chain network. The objective of this study was to minimize fixed facility construction costs, transportation costs, and operational costs, including harvesting, pretreatment, purification, and energy conversion. Uncertainties associated with the volume of harvested and dried algae were addressed using a fuzzy programming approach.

Kang et al. [13] proposed a three-stage model for the design of a microalgal biofuel supply chain aimed at commercialization. In the first stage, the layout and economic assessment of biorefineries were conducted. In the second stage, suitable locations were selected using a Geographic Information System (GIS). In the third stage, a mathematical optimization model was formulated to minimize total costs and was analyzed using a two-stage decomposition solution strategy. This framework was applied to a ten-year case study in Texas.

Given the critical importance of water and energy for sustainable development and the growing global concerns arising from increasing demand, Mahjoub and Sahebi [14] developed a model for the design of a bioenergy supply chain network based on second-generation biomass (Jatropha, agricultural residues, and animal manure) and third-generation biomass (microalgae). A hybrid multi-objective mathematical model was formulated with four objectives: minimizing total costs, reducing environmental impacts, maximizing energy production, and minimizing water consumption.

To investigate uncertainty in biodiesel production from microalgae, Yu et al. [15] developed a new model that encompasses the supply chain from cultivation to biodiesel distribution. Owing to demand uncertainty, a stochastic approach was proposed for different scenarios and compared with deterministic models. The number and locations of carbon capture systems and refineries were determined within this framework.

Mahjoub et al. [16] developed a multi-objective Mixed-Integer Linear Program (MILP) model for the design of a second-generation and third-generation biofuel supply chain using agricultural residues and animal manure, microalgae, and Jatropha[1]. The model makes key decisions, including selecting feedstock sources, locating production facilities, determining warehouse placement, and optimizing material flows, with the objectives of minimizing total costs and maximizing energy production. The results indicated that, when the amount of bioenergy produced is taken into account, energy generation from microalgae and Jatropha is more sustainable than that from bio-waste.

Ahn and Kim [17] developed a two-stage stochastic model to determine the optimal configuration of a microalgae-based biodiesel supply chain network. The model accounted for uncertainties in carbon dioxide supply and biodiesel demand, which influence the locations of carbon capture and storage systems and biorefineries. Using a mixed-integer linear programming framework, the proposed model identified an optimal configuration that minimizes the overall cost of biodiesel production.

Subsequently, Zerafati et al. [18] developed a two-stage model for the design of a microalgae-based biofuel supply chain network. The model considered the production of biodiesel, bioethanol, biomethane, and

[1] Jatropha Curcas L

biobutanol. Suitable cultivation locations were identified using the Analytic Hierarchy Process (AHP). A mixed-integer linear programming mathematical model was formulated by considering economic and environmental impacts over a five-year planning horizon. The optimization objective was to minimize fossil fuel consumption, and the epsilon-constraint method was employed to solve the multi-objective problem. The model was evaluated through a case study in Iran, in which optimal locations, feedstock quantities, microalgae species, technologies, and transportation methods were identified.

To improve greenhouse gas emissions from biofuels, Mobarezkhoo et al. [19] proposed a sustainable MILP model for the design of a microalgae-based biofuel production and distribution network. The model aimed to minimize the total network cost while maximizing greenhouse gas emission savings. To achieve this, Data Envelopment Analysis (DEA) and a composite distance-based evaluation approach were employed. Additionally, the environmental impacts of the microalgal biofuel supply chain were assessed using Life Cycle Assessment (LCA) methodology and the OpenLCA software.

Rasekh et al. [20] developed a multi-period, multi-objective model for the design of a sustainable supply chain network using hybrid second-generation and third-generation biomass. The model included five objectives: maximizing energy production and job creation, and minimizing water consumption, carbon emissions, and costs. The results indicated that energy production from Jatropha was more advantageous compared to other feedstocks, and the proposed model, integrated with the Water-Energy-Carbon (WEC) nexus linkage, outperformed the classical model.

Gilani et al. [21] proposed a wastewater-based biofuel supply chain utilizing second- and third-generation feedstocks to ensure food security and comply with freshwater constraints. This study addressed potential operational risks in the supply chain using a flexible and robust optimization model. The results indicated that greater reliance on energy production from microalgae reduced the conservatism of the proposed approach while maintaining robustness compared to classical models.

Recently, Shirazaki et al. [22] proposed a two-stage model for the design of a microalgae-based biofuel supply chain network and the optimization of the refinery infrastructure. In the first stage, the design of carbon capture, utilization, and storage networks was performed using mixed-integer linear programming. This model optimized strategic decisions, including the selection of emission sources, capture facilities, pipelines, and transportation locations. The second stage focused on optimizing the biorefinery infrastructure. The results indicated that, under current diesel prices, biodiesel production is not yet cost-competitive; however, improvements in biomass productivity could enable significant cost reductions.

2.1 | Research Gaps

Despite extensive research on biofuel supply chains, several critical gaps remain:

I. Sustainability: Most studies on biofuel supply chains have focused on economic and technical aspects, with comparatively less attention to sustainability concepts. Sustainability involves the efficient use of natural resources and the reduction of environmental impacts. Investigating strategies to enhance the sustainability of biofuel supply chains, particularly in the face of environmental, economic, and social challenges, is essential. According to the literature, 48% of studies address economic dimensions, 43% address both economic and environmental dimensions, and only 9% consider economic, environmental, and social dimensions, indicating a predominant focus on economic and environmental aspects.

II. Diversity of Feedstocks: The majority of research has concentrated on agricultural products, which may raise concerns regarding food security and land-use changes. In contrast, studies on using microalgae as a sustainable feedstock for biofuel production are limited and scarce.

III. Supply Chain Levels: Most existing studies on microalgae-based biofuel supply chains analyze three- or four-tier levels. This approach may not provide a comprehensive analysis of all stages and details of the supply chain. In this study, a holistic approach is considered for the levels of the microalgae-based biodiesel supply chain, encompassing all stages from primary production to the sale of biodiesel, glycerol, and biofertilizer. This comprehensive perspective can facilitate better understanding and optimization of each level within the supply chain.

Other significant issues in this field include accounting for uncertainties and selecting appropriate solution methods. Some problems require exact solutions, and approximate methods are only used when exact solutions are unavailable, particularly in large-scale problems. This study addresses these gaps by proposing a multi-objective mathematical model for the design of a microalgae-based biofuel supply chain, providing a holistic framework for the structure of a third-generation biofuel supply network.

3 | Methodology

The primary objective of this study is the production of biodiesel and the fulfillment of market demand using Chlorella microalgae. In addition to biodiesel, the supply chain generates valuable by-products, including biofertilizer, glycerol, and organic fertilizers, which can be used in agriculture and various industries. The components of the supply chain considered in this study include: microalgae cultivation farms, harvesting sites, drying facilities, lipid extraction plants, biorefineries, anaerobic digestion units, and end-users of biodiesel and glycerol. *Fig. 1* presents a schematic overview of the studied supply chain network (BSCNM):

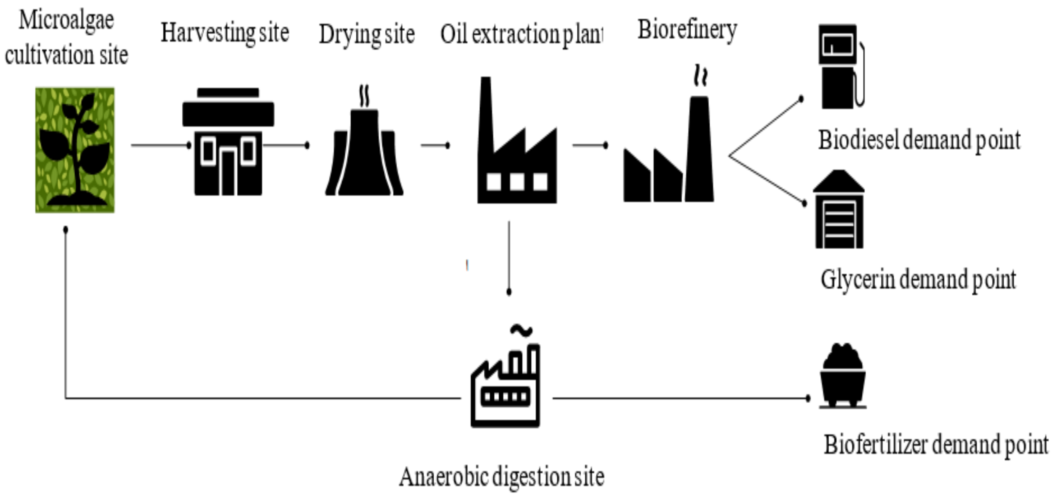

Fig. 1. Schematic overview of BSCNM.

In the production of biofuels from microalgae, several stages are involved, including cultivation, harvesting, drying, lipid extraction, refining, and by-product processing.

Cultivation Stage: Microalgae are grown under controlled conditions in suitable cultivation environments, such as open ponds or photobioreactors. Saline, freshwater, or wastewater can be used as culture media. The use of wastewater not only benefits the environment but also supplies nutrients such as phosphorus and potassium, reducing competition with agricultural industries. Additionally, carbon dioxide from the atmosphere or nearby industrial sources is injected into the cultivation system, promoting microalgal growth and mitigating greenhouse gas emissions.

Harvesting Stage: Upon reaching maturity, microalgae are harvested from the culture medium using methods such as filtration, centrifugation, or sedimentation. The choice of harvesting method depends on the microalgal species and cultivation conditions [23].

Drying Stage: After harvesting, microalgae must be dried. Various methods are used for this purpose, including hot-air drying, freeze-drying, and microwave drying. The final moisture content must be appropriate for subsequent processing stages [24].

Lipid Extraction Stage: Lipids are extracted from microalgal biomass using hydrolysis technology, which employs acids or bases to break cell walls and release lipids. Other extraction methods include solvent-based and mechanical techniques.

Biorefinery Stage: In this stage, the extracted lipids are purified and refined. Fatty acids react with methanol to produce biodiesel. The biodiesel is then refined for use in diesel engines, while glycerol is obtained as a valuable by-product.

Waste Processing Stage: The residual microalgal biomass can be directed to anaerobic digestion, where microorganisms decompose the organic matter. The resulting solid residues can be used as biofertilizer or recycled for further microalgae cultivation.

These stages comprehensively represent the microalgae-based biofuel production process, emphasizing resource optimization, cost reduction, and environmental sustainability. In this study, three objective functions are considered for optimizing the microalgae-based biodiesel supply chain. First of all, minimization of Supply Chain Costs: This objective encompasses all costs associated with production, transportation, and other related activities. Second of all, maximization of Social Impact: This objective focuses on increasing employment opportunities, thereby enhancing socio-economic conditions related to biodiesel production.

And the third one, Reduction of Greenhouse Gas Emissions: This objective aims to minimize the environmental impact throughout the supply chain.

3.1 | Assumptions

The assumptions of the proposed mathematical model are as follows:

I. Among the suitable locations for establishing microalgae cultivation farms, options such as harvesting centers, drying facilities, lipid extraction plants, biorefineries, and anaerobic digestion units are selected for implementation.

II. Microalgae can utilize various water sources, including freshwater, saline water, and wastewater, for growth.

III. The required carbon dioxide is supplied from nearby industrial facilities and plants.

IV. Feedstock and raw materials are supplied at different levels of the supply chain; for example, hexane is needed in the lipid extraction stage, and methanol is required in the biorefinery stage.

V. Material storage is possible in the drying and anaerobic digestion units.

VI. The biofertilizer produced within the supply chain can be reused as a nutrient source in the cultivation stage.

3.2 | Mathematical Model

Initially, the indices are defined as follows: $R1$ for freshwater sources, $R2$ for wastewater sources, $R3$ for saline water sources, and $R4$ for carbon dioxide sources. Candidate cities for establishing facilities are indexed as A, B, d, z, e, and h, corresponding to cultivation centers, harvesting sites, drying facilities, anaerobic digestion units, lipid extraction plants, and biorefineries, respectively. Demand cities for biodiesel, glycerol, and biofertilizer are indexed as L, u, q, and the planning horizon is indexed by t. *Tables 1-4* present the parameters and decision variables used in the model, respectively.

Table 1. Cost function parameters.

Parameter	Definition
$Fr_{R1,t}, Wa_{R2,t}, Sa_{R3,t}, Ca_{R4,t}$	Available freshwater at location R1, wastewater at R2, saline water at R3, and carbon dioxide at R4 during period t (m^3).
$Mq_{A,t}$	Harvestable microalgae biomass per unit area at cultivation site A during period t (ton biomass).
$Zar^1_B, Zar^2_d, Zar^3_e, Zar^4_h, Zar^5_z$	Capacity of the harvesting facility B, drying unit d, lipid extraction plant e, biorefinery h, and anaerobic digestion unit z (ton).
$cec_A, ceh_B, ced_d, cee_e, ceb_h, cea_z$	Construction cost of the cultivation unit A, harvesting facility B, drying unit d, lipid extraction plant e, biorefinery h, and anaerobic digestion unit z ($).
$oec_A, oeh_B, oed_d, oee_e, oeb_h, oea_z$	Operating cost of the cultivation unit A, harvesting facility B, drying unit d, lipid extraction plant e, biorefinery h, and anaerobic digestion unit z ($).
$COF_{R1,A,t}, COW_{R2,A,t}, COS_{R3,A,t}, COC_{R4,A,t}$	Transportation cost per unit of resources R1, R2, R3, R4 to the cultivation site A during period t ($/m^3).
$CTH_{A,B,t}, CTD_{B,d,t}$	Transportation costs per unit of microalgae from the cultivation site A to the harvesting facility B, and from the harvesting facility B to the drying unit d during period t ($/ton).
$CTE_{d,e,t}, CTB_{e,h,t}$	Transportation costs per unit of dried microalgae from the drying facility d to the lipid extraction plant e, and from the lipid extraction plant e to the biorefinery h during period t ($/ton).
$CTA_{e,z,t}, CTO_{h,L,t}$	Transportation costs per unit of residual biomass from the lipid extraction plant e to the anaerobic digestion unit z, and per unit of biodiesel from the biorefinery h to the demand point L during period t ($/ton).
$CTP_{h,u,t}, CTQ^1_{z,q,t}, CTQ^2_{z,A,t}$	Transportation costs per unit of glycerol from the biorefinery h to the demand point u, and per unit of biofertilizer from the anaerobic digestion unit z to the demand point q and to the cultivation site A during period t ($/ton).
hn^1_t, hn^2_t	Storage cost at the drying facilities and anaerobic digestion units during period t ($).
$region_A$	Area of the open pond for biomass cultivation at site A (m^2).
Omega	Maximum allowable proportion of wastewater used in microalgae cultivation.
$Demand_{L,t}$	Biodiesel demand in city L during period t (ton).
$\varepsilon_1, \varepsilon_2$	Respectively, the nitrogen content and phosphorus content per unit of digested biomass (ton/ton biomass).
τ_1, τ_2	Available nitrogen and available phosphorus per unit of wastewater (ton/m^3).
$\Upsilon_1, \Upsilon_2, \Upsilon_3, \Upsilon_4$	Respectively, the conversion rates of dried microalgae to lipids, lipids to biodiesel, lipids to glycerol, and residual biomass to biofertilizer.
$\eta_1, \eta_2, \eta_3, \eta_6$	Required amounts of nitrogen, phosphorus, and carbon dioxide for producing one unit of biomass, and the required amount of methanol for lipid processing (ton/ton biomass).
η_4, η_5	Required amount of water to produce one unit of biomass, and the required amount of hexane in the extraction plant to process one unit of biomass (m^3/ton biomass).
$pric^n_{A,t}, pric^p_{A,t}$	Price of nitrogen and phosphorus fertilizers at the cultivation site A during period t ($).
$pric^h_{e,t}, pric^m_{h,t}$	Price of hexane at the lipid extraction plant e and price of methanol at the biorefinery h during period t ($).
$pric^b_{L,t}, pric^g_{u,t}, pric^Q_{q,t}$	Selling price of biodiesel at the demand point L, selling price of glycerol at the demand point p, and selling price of biofertilizer at the demand point q during period t ($).

Table 2. Greenhouse Gas Emission Function Parameters

Parameter	Definition
En^1, En^2	Carbon emissions per transport unit for solid materials (microalgae, dried microalgae, biofertilizer, glycerol) and for liquid materials (biodiesel, lipids) (ton/km).
$fas^1_{A,B}$	Distance between the cultivation site A and the harvesting facility B (km).
$fas^2_{B,d}$	Distance between the harvesting facility B and the drying unit d (km).
$fas^3_{d,e}$	Distance between the drying unit d and the lipid extraction plant e (km).
$fas^4_{e,h}$	Distance between the lipid extraction plant e and the biorefinery h (km).
$fas^5_{e,z}$	Distance between the lipid extraction plant e and the anaerobic digestion unit z (km).
$fas^6_{h,L}$	Distance between the biorefinery h and the biodiesel demand point L (km).
$fas^7_{h,u}$	Distance between the biorefinery h and the glycerol demand point u (km).
$fas^8_{z,q}$	Distance between the anaerobic digestion unit z and the biofertilizer demand point q (km).
$fas^9_{z,A}$	Distance between the anaerobic digestion unit z and the cultivation site A (km).
C2e, C2r, C2d	CO2 emissions from the lipid extraction plant during extraction, CO2 emissions from the biorefinery during refining, and CO2 emissions from the anaerobic digestion unit during digestion (ton).

Table 3. Social function parameters.

Parameter	Definition
$ner^1_A, ner^2_B, ner^3_d, ner^4_e, ner^5_h, ner^6_z$	Respectively, Unemployment rates at the cultivation sites A, harvesting facilities B, drying units d, lipid extraction plants e, biorefineries h, and anaerobic digestion units z.
pv_1, pv_2, pv_3	Respectively, the number of variable jobs created by transporting cultivated microalgae, harvested microalgae, and dried microalgae.
pv_4, pv_5, pv_6	Respectively, the number of variable jobs created by transporting produced lipids, transporting biodiesel and glycerol from the biorefinery, and transporting biofertilizer produced from the anaerobic digestion unit.
$pf^1_A, pf^2_B, pf^3_d, pf^4_e, pf^5_h$, pf^6_z	Respectively, the number of permanent jobs created by establishing cultivation sites A, harvesting facilities B, drying units d, lipid extraction plants e, biorefineries h, and anaerobic digestion units z.

Table 4. Decision Variables

Decision Variables	Definitions
$flo^1_{R1,A,t}$	Freshwater flow from source R1 to cultivation site A during period t (m^3).
$flo^2_{R2,A,t}$	Wastewater flow from source R2 to cultivation site A during period t (m^3).
$flo^3_{R3,A,t}$	Saline water flows from source R3 to cultivation site A during period t (m^3).
$flo^4_{R4,A,t}$	Carbon dioxide flow from source R4 to cultivation site A during period t (ton).
$fn_{A,t}$	Amount of nitrogen fertilizer for cultivation site A during period t (ton).
$fp_{A,t}$	Amount of phosphorus fertilizer for cultivation site A during period t (ton).
$Y^1_{A,B,t}$	Amount of microalgae transferred from cultivation site A to harvesting unit B during period t (ton).
$Y^2_{B,d,t}$	Amount of microalgae transferred from harvesting unit B to drying unit d during period t (ton).
$Y^3_{d,e,t}$	Amount of dried microalgae transferred from drying unit d to lipid extraction plant e during period t (ton).

Table 4. continued.

Decision Variables	Definitions
$Y^4_{e,h,t}$	Amount of lipid transferred from the lipid extraction plant e to the bio-refinery h during period t (ton).
$Y^5_{e,z,t}$	Amount of residue transferred from the lipid extraction plant e to the anaerobic digestion unit z during period t (ton).
$Y^6_{h,L,t}$	Amount of biodiesel transferred from the bio-refinery h to the consumer L during period t (ton).
$Y^7_{h,u,t}$	Amount of glycerin transferred from the bio-refinery h to the consumer u during period t (ton).
$Y^8_{z,q,t}$	Amount of biofertilizer transferred from the anaerobic digestion unit z to the consumer q during period t (ton).
$Y^9_{z,A,t}$	Amount of biofertilizer transferred from the anaerobic digestion unit z to the cultivation site A during period t (ton).
ϑ^1_A	If freshwater is used for cultivation at site A, 1; otherwise, 0.
ϑ^2_A	If saline water is used for cultivation at site A, 1; otherwise, 0.
G^1_A	If the cultivation site A is established, 1; otherwise, 0.
G^2_B	If the harvesting facility B is established, 1; otherwise, 0.
G^3_d	If the drying unit d is established, 1; otherwise, 0.
G^4_e	If the lipid extraction plant e is established, 1; otherwise, 0.
G^5_h	If the bio-refinery h is established, 1; otherwise, 0.
G^6_z	If the anaerobic digestion unit z is established, 1; otherwise, 0.
$An^1_{d,t}$	Inventory level in the dryer d during period t (ton).
$An^2_{z,t}$	Inventory level in the anaerobic digestion unit z during period t (ton).
BuildCost	Total investment costs ($).
OPCost	Total operational costs ($).
WNCost	Total water and nutrient consumption costs ($).
StorCost	Total maintenance costs ($).
LogiCost	Total transportation costs ($).
Bypro	Total revenue from by-product sales ($).
Vjobs	Total variable jobs created.
Fjobs	Total fixed jobs created.
GreenT	Total greenhouse gas emissions from transportation (ton).
GreenE	Total greenhouse gas emissions from the lipid extraction plant process (ton).
GreenR	Total greenhouse gas emissions from the bio-refinery process (ton).
GreenD	Total greenhouse gas emissions from the anaerobic digestion process (ton).

3.2.1. Mathematical model formulation

s.t.

$$\text{Min (Economic)} = \text{BuildCost} + \text{OPCost} + \text{WNCost} + \text{StorCost} + \text{LogiCost} - \text{Bypro}\,, \quad (1)$$

$$\text{Max (Social impact)} = \text{Fjobs} + \text{Vjobs}, \quad (2)$$

$$\text{Min (Environmental impact)} = \text{GreenT} + \text{GreenE} + \text{GreenR} + \text{GreenD}\,, \quad (3)$$

$$\text{BuildCost} = \sum_{A}(G^1_A \times cec_A) + \sum_{B}(G^2_B \times ceh_B) + \sum_{d}(G^3_d \times ced_d) + \sum_{e}(G^4_e \times cee_e) + \sum_{h}(G^5_h \times ceb_h) + \sum_{z}(G^6_z \times cea_z), \quad (4)$$

$$\text{OPCost} = \sum_{A,B,t}(Y^1_{A,B,t} \times oec_A) + \sum_{A,B,t}(Y^1_{A,B,t} \times oeh_B) + \sum_{B,d,t}(Y^2_{B,d,t} \times oed_d) + \sum_{d,e,t}(Y^3_{d,e,t} \times oee_e) + \sum_{e,h,t}(Y^4_{e,h,t} \times oeb_h) + \sum_{e,z,t}(Y^5_{e,z,t} \times oea_z), \quad (5)$$

$$\begin{aligned} \text{WNCost} = & \sum_{R1,A,t} (flo^{1}_{R1,A,t} \times COF_{R1,A,t}) + \sum_{R2,A,t} (flo^{2}_{R2,A,t} \times COW_{R2,A,t}) \\ & + \sum_{R3,A,t} (flo^{3}_{R3,A,t} \times COS_{R3,A,t}) + \sum_{R4,A,t} (flo^{4}_{R4,A,t} \times COC_{R4,A,t}) \\ & + \sum_{A,t} (fn_{A,t} \times pric^{n}_{A,t}) + \sum_{A,t} (fp_{A,t} \times pric^{p}_{A,t}) \\ & + \sum_{d,e,t} \left(Y^{3}_{d,e,t} \times pric^{h}_{e,t} \times \eta_5\right) + \sum_{e,h,t} (Y^{4}_{e,h,t} \times pric^{m}_{h,t} \times \eta_6), \end{aligned} \quad (6)$$

$$\text{StorCost} = \sum_{d,t} (An^{1}_{d,t} \times hn^{1}_{t}) + \sum_{z,t} (An^{2}_{z,t} \times hn^{2}_{t}), \quad (7)$$

$$\begin{aligned} \text{LogiCost} = & \sum_{A,B,t} (Y^{1}_{A,B,t} \times CTH_{A,B,t}) + \sum_{B,d,t} (Y^{2}_{B,d,t} \times CTD_{B,d,t}) + \sum_{d,e,t} (Y^{3}_{d,e,t} \times CTE_{d,e,t}) \\ & + \sum_{e,h,t} (Y^{4}_{e,h,t} \times CTB_{e,h,t}) + \sum_{e,z,t} (Y^{5}_{e,z,t} \times CTA_{e,z,t}) + \sum_{h,L,t} (Y^{6}_{h,L,t} \times CTO_{h,L,t}) \\ & + \sum_{h,u,t} (Y^{7}_{h,u,t} \times CTP_{h,u,t}) + \sum_{z,q,t} (Y^{8}_{z,q,t} \times CTQ^{1}_{z,q,t}) \\ & + \sum_{z,A,t} (Y^{9}_{z,A,t} \times CTQ^{2}_{z,A,t}), \end{aligned} \quad (8)$$

$$\text{Bypro} = \sum_{h,u,t} (Y^{7}_{h,u,t} \times pric^{g}_{u,t}) + \sum_{z,q,t} (Y^{8}_{z,q,t} \times pric^{Q}_{q,t}), \quad (9)$$

$$\begin{aligned} \text{Vjobs} = & \sum_{A,B,t} (Y^{1}_{A,B,t} \times pv_1) + \sum_{B,d,t} (Y^{2}_{B,d,t} \times pv_2) + \sum_{d,e,t} (Y^{3}_{d,e,t} \times pv_3) + \sum_{e,h,t} (Y^{4}_{e,h,t} \times pv_4) \\ & + \sum_{e,z,t} (Y^{5}_{e,z,t} \times pv_4) + \sum_{h,L,t} (Y^{6}_{h,L,t} \times pv_5) + \sum_{h,u,t} (Y^{7}_{h,u,t} \times pv_5) \\ & + \sum_{z,q,t} (Y^{8}_{z,q,t} \times pv_6) + \sum_{z,A,t} (Y^{9}_{z,A,t} \times pv_6), \end{aligned} \quad (10)$$

$$\begin{aligned} \text{Fjobs} = & \sum_{A} (G^{1}_{A} \times pf^{1}_{A} \times ner^{1}_{A}) + \sum_{B} (G^{2}_{B} \times pf^{2}_{B} \times ner^{2}_{B}) + \sum_{d} (G^{3}_{d} \times pf^{3}_{d} \times ner^{3}_{d}) \\ & + \sum_{e} (G^{4}_{e} \times pf^{4}_{e} \times ner^{4}_{e}) + \sum_{h} (G^{5}_{h} \times pf^{5}_{h} \times ner^{5}_{h}) + \sum_{z} (G^{6}_{z} \times pf^{6}_{z} \times ner^{6}_{z}), \end{aligned} \quad (11)$$

$$\begin{aligned} \text{GreenT} = & \sum_{A,B,t} (Y^{1}_{A,B,t} \times fas^{1}_{A,B} \times En^{1}) + \sum_{B,d,t} (Y^{2}_{B,d,t} \times fas^{2}_{B,d} \times En^{1}) \\ & + \sum_{d,e,t} (Y^{3}_{d,e,t} \times fas^{3}_{d,e} \times En^{1}) + \sum_{e,h,t} (Y^{4}_{e,h,t} \times fas^{4}_{e,h} \times En^{2}) \\ & + \sum_{e,z,t} (Y^{5}_{e,z,t} \times fas^{5}_{e,z} \times En^{1}) + \sum_{h,L,t} (Y^{6}_{h,L,t} \times fas^{6}_{h,L} \times En^{2}) \\ & + \sum_{h,u,t} (Y^{7}_{h,u,t} \times fas^{7}_{h,u} \times En^{1}) + \sum_{z,q,t} (Y^{8}_{z,q,t} \times fas^{8}_{z,q} \times En^{1}) \\ & + \sum_{z,A,t} (Y^{9}_{z,A,t} \times fas^{9}_{z,A} \times En^{1}), \end{aligned} \quad (12)$$

$$\text{GreenE} = \sum_{d,e,t} (Y^{3}_{d,e,t} \times C2e), \quad (13)$$

$$\text{GreenR} = \sum_{e,h,t} (Y^{4}_{e,h,t} \times C2r), \quad (14)$$

$$\text{GreenD} = \sum_{e,z,t}(Y^{5}_{e,z,t} \times C2d), \tag{15}$$

$$\sum_{A} flo^{1}_{R1,A,t} \leq Fr_{R1,t}, \quad \forall\, R1, t, \tag{16}$$

$$\sum_{A} flo^{2}_{R2,A,t} \leq Wa_{R2,t}, \quad \forall\, R2, t, \tag{17}$$

$$\sum_{A} flo^{3}_{R3,A,t} \leq Sa_{R3,t}, \quad \forall\, R3, t, \tag{18}$$

$$\sum_{A} flo^{4}_{R4,A,t} \leq Ca_{R4,t}, \quad \forall\, R4, t, \tag{19}$$

$$\eta_4 \times region_A \times Mq_{A,t} \times G^{1}_{A} \leq \sum_{R1} flo^{1}_{R1,A,t} + \sum_{R2} flo^{2}_{R2,A,t} + \sum_{R3} flo^{3}_{R3,A,t}, \quad \forall\, A, t, \tag{20}$$

$$\eta_3 \times region_A \times Mq_{A,t} \times G^{1}_{A} \leq \sum_{R4} flo^{4}_{R4,A,t}, \quad \forall\, A, t, \tag{21}$$

$$\eta_1 \times region_A \times Mq_{A,t} \times G^{1}_{A} \leq \tau_1 \times \sum_{R2} flo^{2}_{R2,A,t} + fn_{A,t} + \varepsilon_1 \times \sum_{z,A,t} Y^{9}_{z,A,t-1}, \quad \forall\, A, t, \tag{22}$$

$$\eta_2 \times region_A \times Mq_{A,t} \times G^{1}_{A} \leq \tau_2 \times \sum_{R2} flo^{2}_{R2,A,t} + fp_{A,t} + \varepsilon_2 \times \sum_{z,A,t} Y^{9}_{z,A,t-1}, \quad \forall\, A, t, \tag{23}$$

$$\sum_{R1,t} flo^{1}_{R1,A,t} \leq \vartheta^{1}_{A} \times \text{big } M, \quad \forall\, A, t, \tag{24}$$

$$\sum_{R3,t} flo^{3}_{R3,A,t} \leq \vartheta^{2}_{A} \times \text{big } M, \quad \forall\, A, t, \tag{25}$$

$$\vartheta^{1}_{A} + \vartheta^{2}_{A} \leq 1, \quad \forall\, A, \tag{26}$$

$$region_A \times Mq_{A,t} \times G^{1}_{A} \leq \sum_{B} Y^{1}_{A,B,t}, \quad \forall\, A, t, \tag{27}$$

$$\sum_{d} Y^{2}_{B,d,t} = \sum_{A} Y^{1}_{A,B,t}, \quad \forall\, B, t, \tag{28}$$

$$An^{1}_{d,t-1} + \sum_{B} Y^{2}_{B,d,t} = \sum_{e} Y^{3}_{d,e,t} + An^{1}_{d,t}, \quad \forall\, d, t, \tag{29}$$

$$\sum_{h} Y^{4}_{e,h,t} = \Upsilon_1 \times \sum_{d} Y^{3}_{d,e,t}, \quad \forall\, e, t, \tag{30}$$

$$\sum_{d} Y^{3}_{d,e,t} = \sum_{h} Y^{4}_{e,h,t} + \sum_{z} Y^{5}_{e,z,t}, \quad \forall\, e, t, \tag{31}$$

$$\sum_{e} Y^{4}_{e,h,t} = \sum_{L} Y^{6}_{h,L,t} + \sum_{u} Y^{7}_{h,u,t}, \quad \forall\, h, t, \tag{32}$$

$$\sum_{L} Y^{6}_{h,L,t} = \Upsilon_2 \times \sum_{e} Y^{4}_{e,h,t}, \quad \forall\, h, t, \tag{33}$$

$$An^{2}_{z,t-1} + \Upsilon_4 \times \sum_{e} Y^{5}_{e,z,t} = \sum_{q} Y^{8}_{z,q,t} + \sum_{A} Y^{9}_{z,A,t} + An^{2}_{z,t}, \quad \forall\, z, t, \tag{34}$$

$$\sum_{A,t} Y^{1}_{A,B,t} \leq Zar^{1}_{B} \times G^{2}_{B}, \quad \forall\, B, \tag{35}$$

$$\sum_{B,t} Y^{2}_{B,d,t} \leq Zar^{2}_{d} \times G^{3}_{d}, \quad \forall d, \tag{36}$$

$$\sum_{d,t} Y^{3}_{d,e,t} \leq Zar^{3}_{e} \times G^{4}_{e}, \quad \forall e, \tag{37}$$

$$\sum_{e,t} Y^4_{e,h,t} \leq Zar^4_h \times G^5_h, \qquad \forall h, \tag{38}$$

$$\sum_{e,t} Y^5_{e,z,t} \leq Zar^5_z \times G^6_z, \qquad \forall z, \tag{39}$$

$$\sum_{h} Y^6_{h,L,t} \geq Demand_{L,t}, \qquad \forall L, t, \tag{40}$$

$$\sum_{R2} flo^2_{R2,A,t} \leq Omega \times \left(\sum_{R1} flo^1_{R1,A,t} + \sum_{R3} flo^3_{R3,A,t} \right), \qquad \forall A, t. \tag{41}$$

Eq. (1) represents the total costs of the BSCNM. These costs include investment, operational, water and nutrient costs, storage, transportation, and the revenue from the sale of by-products. The objective of this equation is to minimize the total costs through optimal resource management. *Eq. (2)* represents the total social impacts resulting from job creation. These impacts include both permanent and variable employment arising from the establishment and the production and delivery levels of each facility. The goal of this equation is to maximize positive social impacts by increasing employment opportunities. *Eq. (3)* represents the total environmental impacts. This equation includes greenhouse gas emissions resulting from transportation, lipid extraction processes, bio-refineries, and anaerobic digestion. The objective of this equation is to minimize environmental impacts through optimal process management. *Eqs. (4)* and *(5)* represent the investment costs for establishing infrastructure and the operational costs. These costs include the cultivation site, harvesting, drying units, lipid extraction plant, bio-refinery, and anaerobic digestion unit. *Eq. (6)* represents the costs associated with water consumption and nutrients. These costs include freshwater, saline water, and wastewater, as well as the costs of providing carbon dioxide and nutrients such as nitrogen and phosphorus. *Eq. (7)* represents the maintenance costs in the drying unit and anaerobic digestion unit. *Eq. (8)* represents the transportation costs along the supply chain. *Eq. (9)* represents the revenue generated from the sale of by-products, glycerin, and biofertilizer. *Eq. (10)* represents the variable jobs created based on the production and output levels of each unit. This equation focuses on evaluating and analyzing employment opportunities related to the production process. *Eq. (11)* represents the fixed jobs created with the establishment of each unit, considering the unemployment rate in each city. *Eq. (12)* represents the total greenhouse gas emissions from transportation between each unit.

Eqs. (13)-(15) represent the total greenhouse gas emissions from the processes of the lipid extraction plant, bio-refinery, and anaerobic digestion. *Eq. (16)* states that the total amount of freshwater transferred from each source R1 to the cultivation site A must not exceed the available maximum amount. This concept also applies to saline water, wastewater, and carbon dioxide in *Eqs. (17)-(19)*. *Eq. (20)* ensures that, if the cultivation site A is established, sufficient water is supplied to that unit. *Eq. (21)* guarantees that the required carbon dioxide is sourced from external suppliers.

Eq. (22) states that, if site A is established, nitrogen will be supplied from three sources: wastewater, external fertilizer, and fertilizer produced by the anaerobic digestion unit. This condition also applies to phosphorus in *Eq. (23)*. Since the cultivation unit A can only grow in either saline or freshwater, both types of water should not be used simultaneously for microalgae cultivation. Therefore, *Eqs. (24)-(26)* address this issue. *Eq. (27)* ensures that the microalgae transferred from cultivation site A to the harvesting unit do not exceed the biomass amount. *Eq. (28)* indicates that the output from the cultivation site is equal to the amount harvested. *Eqs. (29)-(34)* explain the flow balance at each unit. *Eqs. (35)-(39)* ensure that for each facility constructed, the total input does not exceed the facility's capacity. *Eq. (40)* shows that the volume of biodiesel produced must meet the total demand. *Eq. (41)* determines the percentage of wastewater that must be mixed with freshwater and saline water.

3.3 | Augmented Epsilon Constraint (AEC) Method

In this method, one objective function is first optimized, while the other functions are treated as constraints and controlled parametrically, as formulated in Eq. (42). By varying the value of the epsilon parameter, a set of Pareto solutions is obtained, which is highly useful in multi-objective optimization [25].

$$\begin{cases} \text{Min } f_1(x) - \sum_{g=2}^{G} \phi_g s_g \\ f_g(x) + s_g = e_g \quad g = 2,3,\dots,G \\ x \in X \\ s_g \geq 0 \end{cases} \tag{42}$$

4 | Numerical Results

4.1 | Parameter Values

In this section, following the approach of Mohseni and Pishvaee [11], a supply chain is considered, including one microalgae cultivation site, one harvesting unit, two drying units, one oil extraction plant, two bio-refineries, one anaerobic digestion unit, one demand point for biofertilizer and glycerin, and finally, ten centers designated as biodiesel consumers. *Table 5* presents the values of various model parameters. It is worth noting that the values of other parameters were generated randomly.

Table 5. Scalar values.

Parameter	Values	Parameter	Values
ε_1	0.1 (ton/ton biomass)	η_2	0.011 (ton/ton biomass)
ε_2	0.01(ton/ton biomass)	η_3	2 (ton/ton biomass)
τ_1	0.000042(ton/m^3)	η_4	150 (m^3/ton biomass)
τ_2	0.0000069(ton/m^3)	η_5	0.1(ton/ton biomass)
Υ_1	0.25	η_6	0.002(ton/ton biomass)
Υ_2	0.95	$region_A$	60000 (m^2)
Υ_3	0.05	hn_t^1	10($)
Υ_4	0.75	hn_t^2	9($)
Υ_5	0.1	Omega	0.5
η_1	0.08 (ton/ton biomass)	Big M	1000000

4.2 | Mathematical Model Validation

In this phase, the parameters provided in Section 3 were entered as inputs into the GAMS software version 25.1. The model was then solved on a laptop with a Core i7 processor and 16 GB of RAM using the CPLEX solver, and the results obtained were evaluated.

4.3 | Analysis of Goal Conflicts

In this section, the conflict between objective functions is examined by solving the mathematical model as a single-objective optimization and comparing the values of the objectives. The results of this analysis are presented in *Table 6*.

Table 6. Goal conflict.

	Value of Objective Function 1	Value of Objective Function 2	Value of Objective Function 3
Minimization of Objective Function 1	4634868.385	180811.383	163. 409
Maximization of Objective Function 2	3.191638E+7	691341.570	626.387
Minimization of Objective Function 3	1.553886+E7	160220.330	110.568

According to *Table 6*, optimizing the first objective function cannot lead to finding the optimal value for the second and third objective functions. In other words, when the first objective function is at its minimum value, the second objective function takes a value different from its ideal. This argument holds true for other conditions and objective functions as well. As a result, the objectives of the proposed mathematical model are in conflict. Therefore, AEC is used to find the set of Pareto-optimal solutions. Using the data presented in *Tables 1-5*, the AEC method was implemented, and its results are shown in *Table 7* and *Fig. 2*.

Table 7. Pareto solutions.

Pareto Solution	Objective Function 1	Objective Function 2	Objective Function 3
1	3107373.899	180835.255	162.969
2	3627104.837	213348.952	190.794
3	4476791.261	266459.243	235.862
4	5327453.180	319569.534	281.313
5	6178346.321	372679.825	326.538
6	7037010.156	425790.116	370.805
7	7899908.019	478900.407	415.174
8	8786990.802	532010.698	460.384
9	9691265.163	585120.989	505.583
10	1.074364E+7	638231.280	526.653
11	1.320602E+7	691341.570	526.653

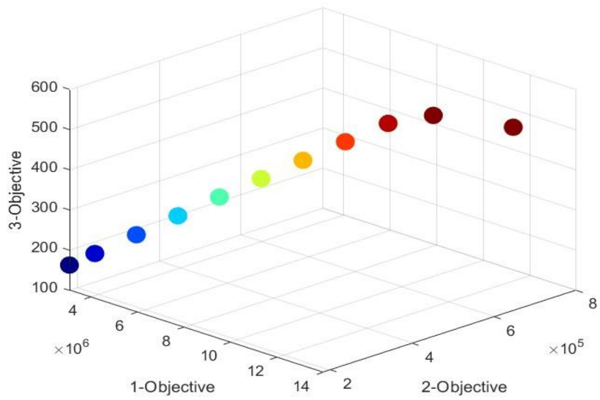

Fig. 2. AEC solution results.

Based on the results obtained from solving the model as both single-objective and multi-objective, the following conclusions can be drawn:

In the single-objective scenario, the mathematical model focuses solely on one objective function. For example, in the case of minimizing the first objective function, costs are reduced to their minimum value. However, in this scenario, the second (social) and third (environmental) objective functions significantly deviate from their ideal values. In other words, optimizing costs in the single-objective model leads to reduced performance in the social and environmental aspects, as these dimensions are not involved in the optimization process.

However, in the multi-objective model solution using the AEC method, an attempt is made to balance all the different objectives. In this case, by considering all three objective functions simultaneously (cost reduction, improvement of social aspects, and reduction of environmental impacts), although costs may slightly increase, an optimal trade-off between the three objectives is achieved. Specifically, energy production and job creation are improved while environmental impacts are reduced. As a result, using the multi-objective approach not only creates an optimal balance among costs, social factors, and environmental impacts but also helps resolve conflicts among these objectives, ultimately leading to a set of comprehensive and sustainable solutions. The argument highlights the importance of using multi-objective models in problems involving conflicts between economic, social, and environmental goals.

5 | Conclusion

In recent years, biofuels have garnered significant attention as renewable and sustainable energy sources. Biodiesel and biofuels, due to their renewability and greenhouse gas reduction potential, are considered suitable alternatives to fossil fuels. In this regard, microalgae, as one of the prominent biofuel sources, have attracted considerable interest due to their rapid growth and low consumption of natural resources, particularly their ability to absorb CO2.

This study focuses on the design of a multi-objective mathematical model for optimizing the biofuel supply chain network based on microalgae. The main innovation of this research lies in providing a comprehensive overview of the third-generation biofuel supply chain, where all stages from microalgae cultivation to the production of biodiesel, glycerin, and biofertilizer are examined. In this model, in addition to addressing economic, social, and environmental objectives, special attention is given to the triad of water, cost, and carbon.

The use of wastewater as a sustainable source for providing nutrients for microalgae cultivation is a key feature of this study. It not only helps meet the required resources but also reduces environmental impacts and improves the sustainability of the process. The proposed model uses the AEC method to simultaneously optimize three main objectives: cost reduction, job creation, and environmental impact reduction. It is worth noting that, due to the suitability of the AEC outputs and the creation of an appropriate efficient frontier, the implementation of other multi-objective methods was excluded. The results show that this approach has successfully established an optimal balance among the various objectives. Although costs may increase under certain conditions, energy production and job creation have improved, while environmental impacts have decreased. This study emphasizes that by comprehensively optimizing the biofuel supply chain, a sustainable and effective model can be achieved.

From a managerial perspective, this study demonstrates that the use of multi-objective models can assist in decision-making within the biofuel supply chain, contributing to enhanced economic efficiency and reduced environmental impacts. For future research, it is recommended that optimization models be developed considering uncertainty conditions, particularly in the context of supply and demand fluctuations. Additionally, further investigations can be conducted on the use of other sustainable resources for microalgae cultivation to improve the sustainability of the biofuel production process.

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Data Availability

The data used in this study were generated and processed by the authors for numerical analyses and model validation. The datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Wang, Q., Dong, Z., Li, R., & Wang, L. (2022). Renewable energy and economic growth: New insight from country risks. *Energy*, *238*, 122018. https://doi.org/10.1016/j.energy.2021.122018

[2] Ghobadian, B., & Rahimi, H. (2004). Biofuels-past, present and future perspective. In *international Iran and russian congress of agricultural and natural science. Shahre Kord, Iran: Shahre-Kord University*. 781-788. https://iirc.narod.ru/4conference/Fullpaper/30127.pdf

[3] Fenton, O., & others. (2012). Agricultural nutrient surpluses as potential input sources to grow third generation biomass (microalgae): A review. *Algal research*, *1*(1), 49–56. https://doi.org/10.1016/j.algal.2012.03.003

[4] Anyaoha, K. E., Krujatz, F., Hodgkinson, I., Maletz, R., & Dornack, C. (2024). Microalgae contribution in enhancing the circular economy drive of biochemical conversion systems-a review. *Carbon resources conversion*, *7*(2), 100203. https://doi.org/10.1016/j.crcon.2023.10.003

[5] Savoji, H., Mousavi, S. M., Antucheviciene, J., & Pavlovskis, M. (2022). A robust possibilistic bi-objective mixed integer model for green biofuel supply chain design under uncertain conditions. *Sustainability*, *14*(20), 13675. https://doi.org/10.3390/su142013675

[6] Kalhor, T., Sharifi, M., & Mobli, H. (2023). A robust optimization approach for an integrated hybrid biodiesel and biomethane supply chain network design under uncertainty: case study. *International journal of energy and environmental engineering*, *14*(2), 189–210. https://doi.org/10.1007/s40095-022-00513-5

[7] Mohammadi, F., Sahebi, H., & Abdali, H. (2023). Biofuel production from sewage sludge network under disruption condition: studying energy-water nexus. *Biomass conversion and biorefinery*, *13*(4), 2921–2931. https://doi.org/10.1007/s13399-021-01566-y

[8] Yıldız, H. G., Ayvaz, B., Kuşakcı, A. O., Deveci, M., & Garg, H. (2024). Sustainability assessment of biomass-based energy supply chain using multi-objective optimization model. *Environment, development and sustainability*, *26*(6), 15451–15493. https://doi.org/10.1007/s10668-023-03258-1

[9] Ahn, Y. C., Lee, I. B., Lee, K. H., & Han, J. H. (2015). Strategic planning design of microalgae biomass-to-biodiesel supply chain network: Multi-period deterministic model. *Applied energy*, *154*, 528–542. https://doi.org/10.1016/j.apenergy.2015.05.047

[10] Mohseni, S., & Pishvaee, M. S. (2016). A robust programming approach towards design and optimization of microalgae-based biofuel supply chain. *Computers & industrial engineering*, *100*, 58–71. https://doi.org/10.1016/j.cie.2016.08.003

[11] Mohseni, S., Pishvaee, M. S., & Sahebi, H. (2016). Robust design and planning of microalgae biomass-to-biodiesel supply chain: A case study in Iran. *Energy*, *111*, 736–755. https://doi.org/10.1016/j.energy.2016.06.025

[12] Arabi, M., Yaghoubi, S., & Tajik, J. (2019). A mathematical model for microalgae-based biobutanol supply chain network design under harvesting and drying uncertainties. *Energy*, *179*, 1004–1016. https://doi.org/10.1016/j.energy.2019.04.219

[13] Kang, S., Heo, S., Realff, M. J., & Lee, J. H. (2020). Three-stage design of high-resolution microalgae-based biofuel supply chain using geographic information system. *Applied energy*, *265*, 114773. https://doi.org/10.1016/j.apenergy.2020.114773

[14] Mahjoub, N., & Sahebi, H. (2020). The water-energy nexus at the hybrid bioenergy supply chain: A sustainable network design model. *Ecological indicators*, *119*, 106799. https://doi.org/10.1016/j.ecolind.2020.106799

[15] Yu, J., Lee, I.-B., Han, J., & Ahn, Y. (2020). Stochastic approach to optimize the supply chain network of microalga-derived biodiesel under uncertain diesel demand. *Journal of chemical engineering of japan*, *53*(1), 24–35. https://doi.org/10.1252/jcej.19we110

[16] Mahjoub, N., Sahebi, H., Mazdeh, M., & Teymouri, A. (2020). Optimal design of the second and third generation biofuel supply network by a multi-objective model. *Journal of cleaner production*, *256*, 120355. https://doi.org/10.1016/j.jclepro.2020.120355

[17] Ahn, Y., & Kim, J. (2021). Economic design framework of microalga-based biodiesel supply chains under uncertainties in CO2 emission and diesel demand. *Computers & chemical engineering*, *155*, 107538. https://doi.org/10.1016/j.compchemeng.2021.107538

[18] Zerafati, M. E., Bozorgi-Amiri, A., Golmohammadi, A.-M., & Jolai, F. (2024). RETRACTED ARTICLE: A multi-objective mixed integer linear programming model proposed to optimize a supply chain network for microalgae-based biofuels and co-products: a case study in Iran. *Environmental science and pollution research*, *31*(34), 47421. https://doi.org/10.1007/s11356-022-19465-8

[19] Mobarezkhoo, H., Saidi-Mehrabad, M., & Sahebi, H. (2022). Life cycle evaluation of microalgae based biorefinery supply network: A sustainable multi-criteria approach. *Algal research*, *66*, 102816. https://doi.org/10.1016/j.algal.2022.102816

[20] Rasekh, A., Hamidzadeh, F., Sahebi, H., & Pishvaee, M. S. (2023). A sustainable network design of a hybrid biomass supply chain by considering the water-energy-carbon nexus. *Energy science & engineering*, *11*(3), 1107–1132. https://doi.org/10.1002/ese3.1374

[21] Gilani, H., Sahebi, H., Jabalameli, M. S., & Hosseininezhad, S. J. (2023). Flexible robust optimization planning of wastewater-energy nexus-based biofuel network design under cultivation rate and climate change uncertainty. *Industrial & engineering chemistry research*, *62*(47), 20300–20325. https://pubs.acs.org/doi/pdf/10.1021/acs.iecr.3c02545

[22] Shirazaki, S., Pishvaee, M. S., & Sobati, M. A. (2024). Integrated supply chain network design and superstructure optimization problem: A case study of microalgae biofuel supply chain. *Computers & chemical engineering*, *180*, 108468. https://doi.org/10.1016/j.compchemeng.2023.108468

[23] Singh, G., & Patidar, S. K. (2018). Microalgae harvesting techniques: A review. *Journal of environmental management*, *217*, 499–508. https://doi.org/10.1016/j.jenvman.2018.04.010

[24] Kim, G. M., & Kim, Y. K. (2022). Drying techniques of microalgal biomass: A review. *Applied chemistry for engineering*, *33*(2), 145–150. https://doi.org/1010.14478/ace.2022.1007

[25] Mavrotas, G. (2007). Generation of efficient solutions in multiobjective mathematical programming problems using GAMS. *Effective implementation of the ε-constraint method*. https://www.academia.edu/download/75710754/epscm.pdf