A Multi-objective MILP Model Proposed to Optimize a Supply Chain Network for Microalgae-based Biofuels and Co-products: A Case Study in Iran

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A multi-objective MILP model proposed to optimize a supply chain network for microalgae-based biofuels and co-products: A case study in Iran

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Abstract

Recently, due to the efficiency of cultivating microalgae, researchers and investors have paid considerable attention to the production of different biofuel products that are environmentally friendly. In this study, a two-stage deterministic model is proposed to design a microalgae-based biofuels and co-products supply chain network (MBCSCN). In the first stage, the appropriate locations for the cultivation of microalgae are identified through the analytical hierarchy process (AHP). In the second stage, a deterministic mathematical mixed integer linear programming (MILP) model is developed for a period of five years based on the criteria of economic and environmental impacts. The economic objective function maximizes the overall profit, while the environmental impacts objective function seeks to minimize the consumed fossil fuel throughout the supply chain. Then, a multi-objective MILP optimization problem is solved using the ϵ -constraint method. The proposed model is evaluated through a case study in Iran. It has helped to identify appropriate locations for the cultivation of microalgae and to specify the required quantity of feedstock, the species of microalgae, the required technology, and the transportation modes in each step of the supply chain.

Keywords: Biofuel and co-product supply chain, Microalgae, Mathematical mixed integer linear programming, Multi-objective optimization, Analytical hierarchy process (AHP) method

1. Introduction

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In recent years, the growth of population and economy has led to the increase of demand for energy. Furthermore, environmental concerns about massive greenhouse gas (GHG) emissions from fossil fuels have made renewable energy resources a key and desired solution to bring security to the supply of sustainable and environmentally-friendly energy (Coleman et al., 2014; Mohtashami, Aghsami, & Jolai, 2020). Among different renewable energy resources, biofuels have attracted great attention (Fallahpour et al., 2021; Mohtashami, Bozorgi-Amiri, & Tavakkoli-Moghaddam, 2021). However, their production, which is based on agricultural biomass, faces major sustainability challenges. Cultivating biomass like corn and soybeans on a large scale requires huge amount of fresh water. Since fresh water resources are limited, supplying water for farmers is costly. In addition, biomass cultivation competes with agricultural food production for fresh water, and it requires large areas of fertile land (Adeniyi, Azimov, & Burluka, 2018; Coleman et al., 2014; Nasr, Niaki, Kashan, & Seifbarghy, 2021; Rahemi, Torabi, Avami, & Jolai, 2020).

Some studies have shown microalgae as a beneficial type of biomass owing to several properties. It needs less land for cultivation, can be cultivated in various types of water and is used in industrial and municipal wastewater. Microalgae can also be used to mitigate atmospheric carbon dioxide, which is due to their ability to absorb CO₂ emitted from power plants, and transform it into products (Andrade, Telles, & Castro, 2020). Microalgae are feedstock with a rapid growth rate and have high oil yields for the production of various biofuels. They can be used to produce large amounts of fat that are convertible into biodiesel. There are other biofuels such as bio-ethanol and bio-methane to derive from microalgae. Microalgae form a great source of valuable co-products (Arabi, Yaghoubi, & Tajik, 2019b). They are mainly used to produce human food supplements, animal feed and natural food colorants. Since they are anti-oxidants, they are also of pharmaceutical applications (Coleman et al., 2014; Efroymson, Jager, Mandal, Parish, & Mathews, 2020; Ismail, Ismail, & El-Sheekh, 2020).

In recent years, there has been considerable research about the processes of producing microalgae and their commercial applications. The first step in this regard is to specify the species of microalgae and to determine the location of microalgae cultivation based on multiple criteria (Branyikova, Prochazkova, Potocar, Jezkova, & Branyik, 2018; Sharma et al., 2015). Generally, microalgae cultivation systems can be classified into two categories including open pond and photo-bioreactor (PBR). Microalgae cultivation in an open pond system is widely practiced due to its relatively cheaper construction, maintenance and operation on a large scale (Bahadar & Khan, 2013; Chen, Zhao, & Qi, 2015; Slade & Bauen, 2013). The technical and economic evaluation of microalgae cultivation and preprocessing as well as the production of biofuels and their co-products is another common issue to consider in the production of biofuel and commercial products derived from microalgae (Kim et al., 2013; Parsaeifar, Bozorgi-Amiri, Naimi-Sadigh, & Sangari, 2019). Beside the economic issues, some researchers have focused on the network of processing pathways to specify the optimal pathway for the production of biofuels. For example (Rizwan, Lee, & Gani, 2013) proposed a processing network model to determine the optimal pathway to produce biodiesel based on microalgae. They also analyzed five steps of the process and then solved the problem with the mixed integer linear programming (MILP) model. (Van Boxtel, Perez-Lopez, Breitmayer, & Slegers, 2015) discussed a process design for algae production and evaluated the result through the Life Cycle Assessment (LCA) approach. Several studies have also been conducted on environmental considerations, especially the mitigation of GHG emission using microalgae (Ghosh & Bakshi, 2019; Idrees, 2014). In this case, (Gutiérrez-Arriaga, Serna-González, Ponce-Ortega, & El-Halwagi, 2014) developed a multi-period multi-objective optimization model to maximize the profit and minimize the environmental impacts in a bio-refinery supply chain. For this purpose, they used the Eco-indicator99 LCA technique. Also, (Shi, Handler,

& Shonnard, 2019) conducted seven gate-to-gate LCAs of novel unit technologies and evaluated 14 scenarios of incorporating different harvesting and extraction technology combinations into a full algae RD life cycle. Similarly, [21] performed a cradle-to-gate LCA for the industrial production of micro-algal biodiesel. They used an autochthonous Chilean *Phaeodactylum tricornutum* strain, considering 1 MJ of biodiesel as the functional unit.

Strategic planning for a supply chain involves specifying the location of facilities, the number of facilities in each location, the capacity of each facility and the amount of production so as to minimize the total cost of the chain (Akbarian-Saravi, Mobini, & Rabbani, 2020; Hadian, Chahardoli, Golmohammadi, & Mostafaeipour, 2020; Li, Xie, Peng, Gao, & Wan, 2021). The first step in many research projects is to specify the type of biomass (Babazadeh, Razmi, Rabbani, & Pishvae, 2015; Shabbir et al., 2021). Other important strategic decisions concerning a biofuel supply chain include determining the location of feedstock (Balaman & Selim, 2014), determining the location of the preprocessing site and specifying its capacity (Gong & You, 2015), locating the processing site and specifying its capacity, and determining the warehouse location for the end-products and its capacity (An, Wilhelm, & Searcy, 2011; L. Zhang, 2013). The other strategic decisions that have been reviewed in the literature include designing biofuel supply chain networks based on the life cycle assessment approach and environmental issues (Akgul, Shah, & Papageorgiou, 2012; Bai, Ouyang, & Pang, 2012; Pahlevan, Hosseini, & Goli, 2021) and specifying transportation modes throughout the networks (Mojtahedi, Fathollahi-Fard, Tavakkoli-Moghaddam, & Newton, 2021).

Deterministic and stochastic models are the most frequently used ones to solve supply chain problems. Deterministic models are divided into two categories, namely those with single-objective functions and those with multi-objective functions (Hosseinalizadeh, Khamseh, & Akhlaghi, 2019). The mathematical mixed integer linear programming (MILP) is the most widely used solution to biofuel supply chain management problems with a single-objective function (Ahn, Lee, Lee, & Han, 2015; Babazadeh, Ghaderi, & Pishvae, 2019). Multi-objective optimization models bring together contradictory objectives to optimize them simultaneously, so an optimal decision has to be made between two or more contradictory objectives. Various types of multi-objective optimization problems are associated with the use of many settlement methods such as the global criterion method, the weighted-sum method and the ε -constraint method. The ε -constraint and the weighted sum methods have been commonly used in the literature to solve multi-objective optimization problems (Abraham & Jain, 2005; Beiki, Seyedhosseini, Mihardjo, & Seyedaliakbar, 2021; Branke, Deb, Miettinen, & Slowiński, 2008; Ghaderi, Moini, & Pishvae, 2018; Golmohammadi, Honarvar, Hosseini-Nasab, & Tavakkoli-Moghaddam, 2020). In many similar studies, analytical hierarchy process (AHP) and data envelopment analysis (DEA) have been used in decision-making processes with several competing options and criteria (Salomon, 2018).

This study seeks to study the development of microalgae and the corresponding industries in Iran. High levels of demand for energy and fuel products, environmental concerns, great diversity of microalgae species, abundant sunlight, favorable temperature as well as vast barren areas and inexpensive land for microalgae cultivation are the features which can provide desirable conditions for a lucrative algal industry in Iran (Arabi, Yaghoubi, & Tajik, 2019a; Mohseni, Pishvae, & Sahebi, 2016; Najafi, Ghobadian, & Yusaf, 2011). Recently, some studies have been conducted on microalgae-based supply chains in the country. For example, (Asadi, Habibi, Nickel, & Sahebi, 2018) introduces a viable two-objective model to design an algae biofuel production and distribution network with the integrated formulation of location, inventory

and routing decisions. Also, (Arabi et al., 2019b) has proposed a MILP model to plan and design a microalgae-based bio-butanol supply chain network. The goal of that study is to minimize the fixed cost of constructing the required facilities, transportation costs, and operational costs. A DEA method is used to reduce the complexity of solving the proposed model. In this line, [46] has proposed a multi-period multi-objective MILP model to design a supply chain of bioenergy production from three different types of biomass including microalgae, Jatropha, and agricultural and livestock wastes.

As summarized in Table 1, in this study, in order to have the comprehensive assessment of the production cost, we have developed a microalgae-based biofuel and co-products supply chain network with six steps which includes cultivation, harvesting, preprocessing, biofuel and co-products production, storage and transporting end products to the customer. Although some research has been done on the applications of the species of microalgae in industry, to the best of our knowledge, there is no study which has focused on biofuels and co-products supply chain with respect to the various species of microalgae. As mentioned in table 1, this research has used 3 species of microalgae for the production of biofuel and co-products. Despite the fact that microalgae can be converted into several types of biofuels and co-products, as far as we know, all of the papers have only studied the production of biofuel in the supply chain, but in this paper, we have studied the production of 3 types of biofuels and 5 types of co-products at the same time in the microalgae-base supply chain network. Moreover, in this research we have applied the corresponding technology according to the microalgae type in all 6 steps of the supply chain. Therefore, the possibilities of finding a better solution have prompted us to develop a new and efficient mathematical model.

To fill the research gaps, the present study proposes a two-stage model for the strategic designing of a microalgae-based biofuel and co-product supply chain network (MBCSCN) in Iran. In the first stage, the AHP method is used to identify appropriate locations for the cultivation of microalgae. In the second stage, a multi-stage and multi-objective MILP model is developed for MBCSCN. The model aims to evaluate the breakeven points of the two objective functions, namely a) maximizing the profit and b) minimizing the environmental impacts of fossil fuel consumption. Therefore, the main contributions of this work are as follows:

- Developing a mathematical model with five steps in the microalgae supply chain, including feedstock supply, cultivation, preprocessing, production of the biofuel and its co-products, and storage and delivery of the end-products to the customer
- Designing a model with two objective functions including the maximization of the profit and the minimization of the environmental impacts of fossil fuel consumption
- Considering three species of microalgae
- Considering three types of biofuels and five types of co-products
- Adopting the corresponding technology and procedure according to microalgae type

Table 1. Summary of the literature review

Articles	Supply chain steps							Objective functions				Algae types included	Final biofuel products				Final co-product				
	Cultivation	Harvesting	Preprocessing	Biofuel production	Co-product production	Storage of end products	End products to the customer	Economic	Social	Energy consumption	Environmental		Biodiesel	Bioethanol	Bio-methane	Bio-butanol	Astaxanthin	Health products	Aquaculture	Beta-carotene	Human and animal foodstuffs
(Ahn et al., 2015)	*			*				*					*								
(Andrade et al., 2020)	*			*				*					*			*					
(Arabi et al., 2019b)		*	*	*			*	*								*					
(Arabi et al., 2019a)	*	*	*	*			*	*			*		*	*		*					
(Asadi et al., 2018)	*	*	*	*		*		*			*										
(Babazadeh et al., 2019)	*		*	*				*					*								
(Mohseni et al., 2016)		*	*	*				*					*								
(Mahjoub, Sahebi, Mazdeh, & Teymouri, 2020)	*		*	*		*		*					*	*							*
This paper	*	*	*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*

The rest of this paper is organized in several sections. Section 2 is given to the statement of the problem and the formulation of a mathematical model. Section 3 presents a real case study in Iran, sensitivity analyses and the results. Finally, the paper ends up with the conclusion of the study in section 4.

2. Problem statement

2.1. Species of microalgae

This study partly seeks to produce several biofuels and their co-products using different species of microalgae. Microalgae are in various types and can save significant amounts of lipid. The species of microalgae appropriate for this study are those that give higher yields of oil and provide the possibility of producing the intended biofuels and co-products. They should be native to the location of the case study and be compatible with its climatic conditions. Therefore, three species of microalgae including *Chlorella vulgaris*, *Spirulina platensis* and *Dunaliella salina* have been chosen to cultivate (Ismail et al., 2020; Mata, Martins, & Caetano, 2010).

2.2. Biofuels

With regard to the species of microalgae and the employed technology, various biofuels can be produced. Based on the demand in Iran, this study has taken into account three types of biofuels, including biodiesel, bioethanol, and biomethane.

2.3. Co-products

Products of different types can be obtained from microalgae (Barry, Wolfe, English, Ruddick, & Lambert, 2016; K. Zhang, Zhang, & Wu, 2021). Each one is produced according to the microalgae species and the production technology involved. Therefore, this study focuses on Astaxanthin, health products, aquaculture, and beta-carotene as well as human and animal foodstuffs as co-products.

2.4. Primary feedstock for microalgae cultivation

2.4.1. Water and wastewater treatment system (WWT)

One of the primary feedstocks required for microalgae cultivation is water, which can be obtained from seas, saline water sources, lakes, or wastewater (WWT) systems (Chu et al., 2021). This research makes use of saline water and WWT to provide the water needed for microalgae cultivation (Fathollahi-Fard, Ahmadi, & Al-e-Hashem, 2020; Mohseni et al., 2016). The cost of investment in WWT systems is neglected because it is supposed that such systems in Iran have already been constructed.

2.4.2. CO₂ and Carbon Capture System (CCS)

CO₂ is another resource required for microalgae cultivation. It can be obtained from power plants, factories and petrochemical refineries (Aliyu, Lee, & Harvey, 2021). However, power plants and other industries should be equipped with a Carbon Capture System (CCS) to absorb the outgoing CO₂ (Ahn et al., 2015; Pokoo-Aikins, Nadim, El-Halwagi, & Mahalec, 2010). The cost of investment in CCSs is ignored because they have already been constructed.

2.4.3 Nutrients

The nutrients needed for the cultivation of microalgae include nitrogen, phosphorus, flocculent, hydrogen and butanol solvent. These can be obtained from the markets near the microalgae cultivation sites (Ahn et al., 2015; Mahjoub et al., 2020; Mohseni et al., 2016).

2.5. A brief overview of technology

In each step of the supply chain, namely cultivation, preprocessing, biofuel production, or co-products production, different technologies can be adopted based on the microalgae species and costs. Table 2 presents these points in brief (Barros, Gonçalves, Simões, & Pires, 2015; Quinn & Davis, 2015).

Table 2. Production technologies in all the steps of the supply chain according to the microalgae species

Supply chain steps	Procedures	Microalgae types		
		Chlorella vulgaris	Spirulina platensis	Dunaliella salina
Cultivation	Open pond	*	*	*
	Photo bioreactor			*
Preprocessing	Flocculation and drying	*	*	*
	Sedimentation and drying	*	*	*
	Filtration and drying			*
Biofuel production	Transesterification	*	*	*
	Fermentation	*	*	*
	Anaerobic digestion	*	*	*
Production of the co-products	Thermal treatment	*	*	*
	Anaerobic digestion	*	*	*

2.6. Transportation

In this study, the transportation modes within the supply chain network are considered to be train and truck. The truck transportation is possible among all the 35 cities selected for cultivation, and the train transportation is only possible for 15 cities (Babazadeh et al., 2015). These transportation modes are used to transfer the cultivated and preprocessed microalgae to conversion facilities and then to transport the end-products to the customers.

2.7. Network structure

This paper discusses the proposed MBCSCN in terms its six layers and double objectives already mentioned in the Introduction section. The MBCSCN is shown in Fig.1. In this network, first, the feedstock including water, CO₂ and nutrients is brought to the microalgae cultivation location, and the intended species of microalgae is cultivated. Then, the cultivated microalgae are preprocessed. This second step involves two operations, including a) harvesting and dewatering and b) drying. Each operation needs a different technology with regard to the species used (Gutiérrez-Arriaga et al., 2014).

Fig. 1. Structure of the microalgae-based biofuel and co-product supply chain network

After the microalgae are dried, they are taken to the extraction and separation unit. This process is done to reduce the size and the volume of the obtained biomass. It leads to easier transportation, bigger number of delivered shipments, lower transportation costs and lower energy costs. Afterwards, the extracted products are delivered to the warehouses to be prepared for the production step (Davis, Aden, & Pienkos, 2011).

The next step of the supply chain is the conversion of the preprocessed microalgae to a biofuel and its co-products. The lipid or other products obtained from the microalgae goes to a biofuel refinery. Then, the end-products are taken to the warehouse and subsequently to the customer (Ismail et al., 2020).

This is how the cultivation location, microalgae species, required technology, production capacity and transportation modes are specified in the MBCSCN. This network ultimately helps to reduce the production costs and fossil fuel consumption.

2.8. Formulation of the mathematical model

Briefly speaking, the steps of the microalgae supply chain include microalgae cultivation, preprocessing, production of a biofuel, production of co-products, storage, and delivery to the customer. The sets, indices, parameters and variables are also defined in Tables 3-6 as follows:

Table 3. Sets and indices

Sets and indices	Description
G	Set of microalgae species ($g \in G$)
F	Set of biofuel types ($f \in F$)
P	Set of co-product types ($p \in P$)
M	Set of markets ($m \in M$)
U	Set of microalgae cultivation methods ($u \in U$)
H	Set of microalgae preprocessing methods ($h \in H$)
S	Set of microalgae warehouses ($s \in S$)
A	Set of biofuel conversions ($a \in A$)
B	Set of co-product conversions ($b \in B$)
LU	Set of microalgae cultivation locations ($lu \in LU$)
LH	Set of microalgae preprocess locations ($lh \in LH$)
LS	Set of warehouse locations ($ls \in LS$)
LA	Set of biofuel conversion facility locations ($la \in LA$)
LB	Set of co-product conversion facility locations ($lb \in LB$)
I	Set of feedstock locations ($i \in I$)
L	Set of feedstock types ($l \in L$)
V	Set of vehicle modes ($v \in V$)
T	Set of time periods ($t \in T$)

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233 Table 4. Parameters

Parameters	Description
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$f_{lu,u}^F$	Annualized fixed setup cost of microalgae cultivation facility lu with technology u at time phase t
$f_{lu,u}^V$	Annualized unit capital for the microalgae cultivation facility at location lu with technology u at time phase t
$f_{lu,u}^O$	Annualize fixed operating cost of microalgae cultivation facility lu , with technology u at time phase t .
LPR_{lu}	Land price for microalgae cultivation facility at location lu
Cap_u	Maximum allowable capacity with technology u
$RL_{cultivation}$	Required land size for the microalgae cultivation facility
ALS_{lu}	Available land size for microalgae cultivation facility lu
$f_{lh,h}^F$	Annualized fixed setup cost of microalgae preprocess facility lh with technology h at time phase t
$f_{lh,h}^V$	Annualized unit capital for the microalgae preprocess facility at location lh with technology h at time phase t
$f_{lh,h}^O$	Annualize fixed operating cost of microalgae preprocess facility lh with technology h at time phase t
LPR_{lh}	Land price for the microalgae preprocessing facility at location lh
Cap_h	Maximum allowable capacity with technology h
$RL_{preprocess}$	Required land size for the microalgae preprocess facility
ALS_{lh}	Available land size for microalgae preprocess facility lh
$f_{ls,s}^F$	Annualized fixed setup cost of warehouse ls with technology s at time phase t
$f_{ls,s}^V$	Annualized unit capital for the warehouse at location ls with technology s at time phase t

$fo_{ls,s}$	Annualize fixed operating cost of warehouse ls with technology s at time phase t
LPR_{ls}	Land price for the warehouse at location ls
Cap_s	Maximum allowable capacity with technology s
$RL_{storage}$	Required land size for the warehouse
ALS_{ls}	Available land size for warehouse ls
$f_{la,a}^F$	Annualized fixed setup cost of bio-refinery facility la with technology a at time phase t
$f_{la,a}^V$	Annualized unit capital for the bio-refinery facility at location la with technology a at time phase t
$fo_{la,a}$	Annualize fixed operating cost of bio-refinery facility la with technology a at time phase t
LPR_{la}	Land price for the bio-refinery facility at location la
Cap_a	Maximum allowable capacity with technology a
$RL_{biofuel}$	Required land size for the bio-refinery facility
ALS_{la}	Available land size for bio-refinery facility la
$f_{lb,b}^F$	Annualized fixed setup cost of co-product bio-refinery facility lb with technology b at time phase t
$f_{lb,b}^V$	Annualized unit capital for the co-product bio-refinery facility at location lb with technology b at time phase t
$fo_{lb,b}$	Annualize fixed operating cost of co-product bio-refinery facility lb with technology b at time phase t
LPR_{lb}	Land price for the co-product bio-refinery facility at location lb
Cap_b	Maximum allowable capacity with technology b

$RL_{coproduct}$	Required land size for the co-product bio-refinery facility
ALS_{lb}	Available land size for co-product bio-refinery facility lb
$C_{transport_v}$	Cost of transportation (fix & variable) via mode v
$D_{m,f}^t$	Demand for biofuel type f at market m during time phase t
$D_{m,p}^t$	Demand for co-product type p at market m during time phase t
$DIS_{i,lu}$	Distance between location of feedstock i and microalgae cultivation facility lu
$DIS_{lu,lh}$	Distance between microalgae cultivation facility lu and microalgae preprocessing facility lh
$DIS_{lh,la}$	Distance between microalgae preprocessing facility lh and bio-refinery facility la
$DIS_{lh,lb}$	Distance between microalgae preprocessing facility lh and co-product bio-refinery facility lb
$DIS_{la,ls}$	Distance between bio-refinery facility la and warehouse ls
$DIS_{lb,ls}$	Distance between co-product bio-refinery facility la and warehouse facility ls
$DIS_{ls,m}$	Distance between warehouse ls and market m
$FF_{g,lu,u}$	Fossil fuel (FF) inputs for producing microalgae species g at microalgae cultivation facility lu with technology u (MJ/ton-1)
$FF_{g,lh,h}$	FF inputs for harvesting and drying microalgae species g at microalgae preprocessing facility lh with technology h (MJ/ton ⁻¹)
$FF_{f,la,a}$	FF inputs for producing biofuel type f at bio-refinery facility la with technology a (MJ/ton ⁻¹)
$FF_{p,lb,b}$	FF inputs for producing co-product type p at co-product bio-refinery facility lb with technology b (MJ/ton ⁻¹)

$FFls,s$	FF inputs for storing the final products at warehouse ls with technology s (MJ/ton ⁻¹)
$FFtransport_{total}$	FF inputs of transportation (MJ/ton ⁻¹)
η_{algae}	Rate of conversion from feedstock to microalgae
$\eta_{process}$	Rate of conversion from microalgae to processed microalgae
η_{fuel}	Rate of conversion from microalgae to biofuel
$\eta_{coproduct}$	Rate of conversion from microalgae to co-product
P_f	Price of biofuel type f
P_p	Price of co-product type p
mp_l	Material price of feedstock l
α	Penalty cost of biofuel shortage
$rawlu,u,l$	Amount of feedstock l in cultivation facility lu with technology u
CO_{2pt}	CO2 product flows

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236 Table 5. Decision variables

Decision variables	Description
$x_{l,i,lu,v}^t$	Amount of feedstock type l transported from field i to microalgae cultivation facility lu via mode v at time phase t
$xp_{l,i,lu,u}^t$	Amount of feedstock type l transported from field i to microalgae cultivation facility lu with technology u at time phase t
$F_{g,lu,lh,v}$	Flow of microalgae species g from microalgae cultivation facility lu to microalgae preprocessing facility lh via mode v

$F_{lh,la,v}$	Flow from microalgae preprocessing facility lh to biofuel bio-refinery facility la via mode v
$F_{lh,lb,v}$	Flow from microalgae preprocessing facility lh to co-product bio-refinery facility lb via mode v
$F_{f,la,ls,v}$	Flow of biofuel type f from biofuel bio-refinery facility la to warehouse ls via mode v
$F_{p,lb,ls,v}$	Flow of co-product type p from co-product bio-refinery facility lb to warehouse ls via mode v
$F_{f,ls,m,v}$	Flow of biofuel type f from warehouse ls to market m via mode v
$F_{p,ls,m,v}$	Flow of co-product type p from warehouse ls to market m via mode v
$q_{f,m}^t$	Shortage of biofuel type f demanded from market m at time phase t
$q_{p,m}^t$	Shortage of co-product type p demanded from market m at time phase t
$pr_{g,lu,u}^t$	Amount of microalgae species g produced at microalgae cultivation facility lu with technology u at time phase t
$pr_{lh,h}^t$	Amount of microalgae processed at microalgae preprocess facility lh with technology h at time phase t
$pr_{f,la,a}^t$	Amount of biofuel type f produced at bio-refinery facility la with technology a at time phase t
$pr_{p,lb,b}^t$	Amount of co-product type p produced at co-product bio-refinery facility lb with technology b at time phase t
$C_{lu,u}^t$	Cultivation capacity of microalgae cultivation facility lu with technology u at time phase t
$C_{lh,h}^t$	Preprocessing capacity of microalgae preprocess facility lh with technology h at time phase t

$C_{la,a}^t$	Capacity of bio-refinery facility la with technology a at time phase t
$C_{lb,b}^t$	Capacity of co-product bio-refinery facility lb with technology b at time phase t
$C_{ls,s}^t$	Storage capacity of warehouse ls with technology s at time phase t

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238 Table 6. Binary variables

Binary variables	Description
$X_{lu,u}^t$	1, if microalgae cultivation facility lu with technology u at time phase t is constructed; otherwise, 0.
$X_{lh,h}^t$	1, if microalgae preprocessing facility lh with technology h at time phase t is constructed; otherwise, 0.
$X_{la,a}^t$	1, if biofuel bio refinery facility la with technology a at time phase t is constructed; otherwise, 0.
$X_{lb,b}^t$	1, if co-product bio refinery facility lb with technology b at time phase t is constructed; otherwise, 0.
$X_{ls,s}^t$	1, if warehouse ls with technology s at time phase t is constructed; otherwise, 0.
XCO_2^t	1, if carbon capture system i is working at time phase t ; otherwise, 0.
$ZX_{lu,u}^t$	Value of difference in $X_{lu,u}^t$ between t and $t+1$
$ZX_{lh,h}^t$	Value of difference in $X_{lh,h}^t$ between t and $t+1$
$ZX_{la,a}^t$	Value of difference in $X_{la,a}^t$ between t and $t+1$
$ZX_{lb,b}^t$	Value of difference in $X_{lb,b}^t$ between t and $t+1$
$ZX_{ls,s}^t$	Value of difference in $X_{ls,s}^t$ between t and $t+1$

239

2.8.1. Objective functions

Eq. (1) illustrates the main objective function of the study, and Equations (2) to (4) belong to the proposed framework. The main objective of the study is to maximize the profit. Therefore, the income should be maximized and the costs ought to be minimized.

$$MaxZ = Revenue - Cost \quad (1)$$

$$Revenue = (\sum_{f} \sum_{ls} \sum_{m} F_{f,ls,m,v} P_f + \sum_{p} \sum_{ls} \sum_{m} F_{p,ls,m,v} P_p) + (30000 \times (\frac{CO_2^{pt}}{1000}) X CO_2^t) \quad (2)$$

Eq. (2) specifies the income, which should be maximized. The income is earned from selling the biofuels and their co-products. According to Kyoto Protocol, 30000 IRR² are paid per each reduced ton of CO₂. This has been entailed in this equation as another source of income.

$$\begin{aligned} Cost = & \sum_t \{ (\sum_{lu} (ZX_{lu,u}^t f_{lu,u}^F + C_{lu,u}^t f_{lu,u}^v + ZX_{lu,u}^t LPR_{lu})) \\ & + (\sum_{lu} X_{lu,u}^t f_{lu,u}^{fo}) + (\sum_l \sum_i \sum_{lu} \sum_v x_{l,i,lu,v}^t mp_l) \} \\ & + (\sum_{ls} (\sum_s (ZX_{ls,s}^t f_{ls,s}^F + C_{ls,s}^t f_{ls,s}^v + ZX_{ls,s}^t LPR_{ls})) + (\sum_{ls} \sum_s X_{ls,s}^t f_{ls,s}^{fo})) \\ & + (\sum_{lh} (\sum_h (ZX_{lh,h}^t f_{lh,h}^F + C_{lh,h}^t f_{lh,h}^v + ZX_{lh,h}^t LPR_{lh})) + (\sum_{lh} \sum_h X_{lh,h}^t f_{lh,h}^{fo})) \\ & + (\sum_{la} (\sum_a (ZX_{la,a}^t f_{la,a}^F + C_{la,a}^t f_{la,a}^v + ZX_{la,a}^t LPR_{la})) + (\sum_{la} \sum_a X_{la,a}^t f_{la,a}^{fo})) \\ & + \sum_{f,m} \alpha q_{f,m}^t + (\sum_{lb} (\sum_b (ZX_{lb,b}^t f_{lb,b}^F + C_{lb,b}^t f_{lb,b}^v + ZX_{lb,b}^t LPR_{lb})) \\ & + (\sum_{lb} \sum_b X_{lb,b}^t f_{lb,b}^{fo})) \} + TC \quad (3) \end{aligned}$$

Eq. (3) shows the costs that should be minimized. The expenses include fixed costs, variable costs, land price, operational costs, feedstock price and transportation cost in different steps of the microalgae supply chain. In case there is a shortage in the biofuel production step, the shortage costs are also taken into account. In addition, TC cost has been explained in Equation (4).

² Iranian Rial currency

$$\begin{aligned}
TC = & C_{transport} \left(\sum_l \sum_i \sum_{lu} \sum_v x_{l,i,lu,v}^t DIS_{i,lu} + \sum_g \sum_{lu} \sum_{lh} \sum_v F_{g,lu,lh,v} DIS_{lu,lh} \right. \\
& + \sum_{lh} \sum_{la} \sum_v F_{lh,la,v} DIS_{lh,la} + \sum_{lh} \sum_{lb} \sum_v F_{lh,lb,v} DIS_{lh,lb} \\
& + \sum_f \sum_{la} \sum_{ls} \sum_v F_{f,la,ls,v} DIS_{la,ls} + \sum_p \sum_{lb} \sum_{ls} \sum_v F_{p,lb,ls,v} DIS_{lb,ls} \\
& \left. + \sum_f \sum_{ls} \sum_m \sum_v F_{f,ls,m,v} DIS_{ls,m} + \sum_p \sum_{ls} \sum_m \sum_v F_{p,ls,m,v} DIS_{ls,m} \right)
\end{aligned} \tag{4}$$

253 This equation concerns the transportation cost of the feedstock, cultivated and preprocessed microalgae,
254 and biofuels and co-products.

$$EI_{Total} = FF_{production} + FF_{transportation} \tag{5}$$

255 Eq. (5) refers to the second objective function of the study which seeks to minimize the environmental
256 impacts of the supply chain. It includes Equations (6) and (7) below. This objective function is, indeed,
257 postulated to minimize the amount of the fossil fuel input in the production and transportation steps.

$$\begin{aligned}
FF_{production} = & \sum_g \sum_{lu} \sum_u pr_{g,lu,u}^t FF_{g,lu,u} + \sum_g \sum_{lh} \sum_h pr_{g,lh,h}^t FF_{g,lh,h} \\
& + \sum_f \sum_{la} \sum_a pr_{f,la,a}^t FF_{f,la,a} + \sum_p \sum_{lb} \sum_b pr_{p,lb,b}^t FF_{p,lb,b}
\end{aligned} \tag{6}$$

258 Eq. (6) shows the amount of the fossil fuel input in the cultivation, preprocessing as well as biofuel and co-
259 product production steps.

$$\begin{aligned}
FF_{transport} = & FF_{transport_{total}} \left(\sum_l \sum_i \sum_{lu} \sum_v x_{l,i,lu,v}^t DIS_{i,lu} \right. \\
& + \sum_g \sum_{lu} \sum_{lh} \sum_v F_{g,lu,lh,v} DIS_{lu,lh} + \sum_{lh} \sum_{la} \sum_v F_{lh,la,v} DIS_{lh,la} \\
& + \sum_{lh} \sum_{lb} \sum_v F_{lh,lb,v} DIS_{lh,lb} + \sum_f \sum_{la} \sum_{ls} \sum_v F_{f,la,ls,v} DIS_{la,ls} \\
& + \sum_f \sum_{la} \sum_{ls} \sum_v F_{p,lb,ls,v} DIS_{lb,ls} + \sum_f \sum_{ls} \sum_m \sum_v F_{f,ls,m,v} DIS_{ls,m} \\
& \left. + \sum_f \sum_{ls} \sum_m \sum_v F_{p,ls,m,v} DIS_{ls,m} \right)
\end{aligned} \tag{7}$$

260 Eq. (7) formulates the amount of the fossil fuel input in the transportation process at different steps of the
261 supply chain.

262

263 2.8.2. Constraints

Eq. (8) ensures that the sum of the produced microalgae species g in cultivation location lu with technology u at time t will at most be equal to the quantity of the feedstock that is delivered from different locations i to microalgae cultivation location lu and is converted into microalgae at the rate of η_{algae} .

$$pr_{g,lu,u}^t \leq \sum_i x_{l,i,lu,v}^t \times \eta_{algae} \quad \forall g, lu, v, l \quad (8)$$

$$pr_{g,lu,u}^t \leq \sum_i xp_{l,i,lu,u}^t \times \eta_{algae} \quad \forall g, lu, u, l = CO_2 \quad (9)$$

Eq. (9) ensures that the sum of the produced microalgae species g in cultivation location lu with technology u at time t will at most be equal to the quantity of the CO₂ that is delivered from different locations i to microalgae cultivation location lu and is converted into microalgae at the rate of η_{algae} .

$$pr_{g,lh,h}^t \leq \sum_{lu} F_{g,lu,lh,v} \times \eta_{process} \quad \forall g, lh, h, v \quad (10)$$

Eq. (10) ensures that the sum of the preprocessed microalgae species g in preprocessing location lh with technology h at time t will at most be equal to the quantity of the microalgae cultivated at location lu and is transported to processing facility lh and converted into processed microalgae at the rate of $\eta_{process}$.

$$pr_{f,la,a}^t \leq \sum_{lh} F_{lh,la,v} \times \eta_{fuel} \quad \forall f, la, a, v \quad (11)$$

Eq. (11) ensures that the sum of the produced biofuel type f in production location la with technology a at time t will at most be equal to the quantity of the microalgae processed at processing location lh which is transported to biofuel production facility la and converted into a biofuel at the rate of η_{fuel} .

$$pr_{p,lb,b}^t \leq \sum_{lh} F_{lh,lb,v} \times \eta_{coproduct} \quad \forall p, lb, b, v \quad (12)$$

Eq. (12) ensures that the sum of the produced co-product type p in production location lb with technology b at time t will at most be equal to the quantity of the microalgae processed at processing location lh which is transported to biofuel production facility lb and converted into a biofuel at the rate of $\eta_{coproduct}$.

$$\sum_i x_{l,i,lu,v}^t \leq raw_{lu,u,l} X_{lu,u}^t \quad \forall lu, u, l, v \quad (13)$$

Eq. (13) ensures that the sum of the feedstock from all lands i transported to microalgae cultivation location lu is at most equal to the feedstock needed in cultivation location lu .

$$pr_{f,la,a}^t \leq \sum_m F_{f,ls,m,v} \quad \forall f, ls, la, a, v \quad (14)$$

$$pr_{p,lb,b}^t \leq \sum_m F_{p,ls,m,v} \quad \forall p, ls, lb, b, v \quad (15)$$

Constraints (14) and (15) ensure that the amount of the biofuel and co-products delivered from the warehouse to the customer is bigger than or equal to that of the biofuel and co-products produced in the bio-refinery.

$$C_{lu,u}^t \leq Cap_u X_{lu,u}^t \quad \forall lu, u, t \quad (16)$$

$$C_{lh,h}^t \leq Cap_h X_{lh,h}^t \quad \forall lh, h, t \quad (17)$$

$$C_{la,a}^t \leq Cap_a X_{la,a}^t \quad \forall la, a, t \quad (18)$$

$$C_{lb,b}^t \leq Cap_b X_{lb,b}^t \quad \forall lb, b, t \quad (19)$$

$$C_{ls,s}^t \leq Cap_s X_{ls,s}^t \quad \forall ls, s, t \quad (20)$$

Constraints (16) to (20) ensure that the amount of production in different steps of the MBCSCN will not surpass the maximum allowable capacity of the respective steps.

$$C_{lu,u}^{t-1} \leq C_{lu,u}^t \quad \forall lu, u, t = 2, \dots, T \quad (21)$$

$$C_{ls,s}^{t-1} \leq C_{ls,s}^t \quad \forall ls, s, t = 2, \dots, T \quad (22)$$

$$C_{lh,h}^{t-1} \leq C_{lh,h}^t \quad \forall lh, h, t = 2, \dots, T \quad (23)$$

$$C_{la,a}^{t-1} \leq C_{la,a}^t \quad \forall la, a, t = 2, \dots, T \quad (24)$$

$$C_{lb,b}^{t-1} \leq C_{lb,b}^t \quad \forall lb, b, t = 2, \dots, T \quad (25)$$

289 Constraints (21) to (25) ensure that the capacity of each step of the MBCSCN is not less than its capacity
 290 in the previous period.

$$X_{lu,u}^{t-1} \leq X_{lu,u}^t \quad \forall lu,u,t=2,...,T \quad (26)$$

$$X_{lh,h}^{t-1} \leq X_{lh,h}^t \quad \forall lh,h,t=2,...,T \quad (27)$$

$$X_{la,a}^{t-1} \leq X_{la,a}^t \quad \forall la,a,t=2,...,T \quad (28)$$

$$X_{lb,b}^{t-1} \leq X_{lb,b}^t \quad \forall lb,b,t=2,...,T \quad (29)$$

$$X_{ls,s}^{t-1} \leq X_{ls,s}^t \quad \forall ls,s,t=2,...,T \quad (30)$$

291 Constraints (26) to (30) ensure that the facility of each step of the MBCSCN will not be closed after it is
 292 opened.

$$ZX_{lu,u}^t = X_{lu,u}^t - X_{lu,u}^{t-1} \quad \forall lu,u,t=2,...,T \quad (31)$$

$$ZX_{lh,h}^t = X_{lh,h}^t - X_{lh,h}^{t-1} \quad \forall lh,h,t=2,...,T \quad (32)$$

$$ZX_{la,a}^t = X_{la,a}^t - X_{la,a}^{t-1} \quad \forall la,a,t=2,...,T \quad (33)$$

$$ZX_{lb,b}^t = X_{lb,b}^t - X_{lb,b}^{t-1} \quad \forall lb,b,t=2,...,T \quad (34)$$

$$ZX_{ls,s}^t = X_{ls,s}^t - X_{ls,s}^{t-1} \quad \forall ls,s,t=2,...,T \quad (35)$$

293 Constraints (31) to (35) ensure that there will not be two facilities for each step of the MBCSCN in one
 294 location.

$$ZX_{lu,u}^t = X_{lu,u}^t \quad \forall lu,u,t=1 \quad (36)$$

$$ZX_{lh,h}^t = X_{lh,h}^t \quad \forall lh,h,t=1 \quad (37)$$

$$ZX_{la,a}^t = X_{la,a}^t \quad \forall la,a,t=1 \quad (38)$$

$$ZX_{lb,b}^t = X_{lb,b}^t \quad \forall lb,b,t=1 \quad (39)$$

$$ZX_{ls,s}^t = X_{ls,s}^t \quad \forall ls,s,t=1 \quad (40)$$

295 Constraints (36) to (40) show the number of the facilities for each step of the MBCSCN that are established
 296 in the first year.

$$RL_{cultivation} X_{lu,u}^t \leq ALS_{lu} \quad \forall lu, u, t \quad (41)$$

$$RL_{preprocess} X_{lh,h}^t \leq ALS_{lh} \quad \forall lh, h, t \quad (42)$$

$$RL_{fuel} X_{la,a}^t \leq ALS_{la} \quad \forall la, a, t \quad (43)$$

$$RL_{coproduct} X_{lb,b}^t \leq ALS_{lb} \quad \forall lb, b, t \quad (44)$$

$$RL_{storage} X_{ls,s}^t \leq ALS_{ls} \quad \forall ls, s, t \quad (45)$$

297 Constraints (41) to (45) ensure that the land area needed for each step of the MBCSCN should not exceed
 298 the available land area for that step.

$$pr_{g,lu,u}^t \leq C_{lu,u}^t \quad \forall lu, u, g, t \quad (46)$$

$$pr_{lh,h}^t \leq C_{lh,h}^t \quad \forall lh, h, t \quad (47)$$

$$pr_{f,la,a}^t \leq C_{la,a}^t \quad \forall la, a, f, t \quad (48)$$

$$pr_{p,lb,b}^t \leq C_{lb,b}^t \quad \forall lb, b, p, t \quad (49)$$

299 Constraints (46) to (49) ensure that the amount of production in each step of the MBCSCN will not exceed
 300 the capacity designed for that location.

$$\sum_{f} \sum_{ls} F_{f,ls,m,v} + \sum_{f} q_{f,m}^t = \sum_{f} D_{m,f}^t \quad \forall m, v, t \quad (50)$$

Constraints (50) shows the customer demand for biofuel type f from warehouse ls to customer m

$$\sum_{p} \sum_{ls} F_{p,ls,m,v} + \sum_{p} q_{p,m}^t = \sum_{p} D_{m,p}^t \quad \forall m, v, t \quad (51)$$

Constraint (51) regards the customer demand for co-product type p from warehouse ls to customer m .

$$\sum_{lu} X_{lu,u}^t \leq 1 \quad \forall u, t \quad (52)$$

$$\sum_{lh} X_{lh,h}^t \leq 1 \quad \forall h, t \quad (53)$$

$$\sum_{la} X_{la,a}^t \leq 1 \quad \forall a, t \quad (54)$$

$$\sum_{lb} X_{lb,b}^t \leq 1 \quad \forall b, t \quad (55)$$

$$\sum_{ls} X_{ls,s}^t \leq 1 \quad \forall s, t \quad (56)$$

301 Constraints (52) to (56) ensure that, for each step of the MBCSCN with any type of technology, only one
 302 facility will be established.

$$x_{l,i,lu,v}^t \geq 0 \quad \forall l, i, lu, v, t \quad (57)$$

$$xp_{l,i,lu,u}^t \geq 0 \quad \forall l, i, lu, u, t \quad (58)$$

$$F_{g,lu,lv} \geq 0 \quad \forall g, lu, lv \quad (59)$$

$$F_{lh,la,v} \geq 0 \quad \forall lh, la, v \quad (60)$$

$$F_{lh,lb,v} \geq 0 \quad \forall lh, lb, v \quad (61)$$

$$F_{f,la,ls,v} \geq 0 \quad \forall f, la, ls, v \quad (62)$$

$$F_{p,lb,ls,v} \geq 0 \quad \forall p, lb, ls, v \quad (63)$$

$$F_{f,ls,m,v} \geq 0 \quad \forall f, ls, m, v \quad (64)$$

$$F_{p,ls,m,v} \geq 0 \quad \forall p, ls, m, v \quad (65)$$

$$q_{f,m}^t \geq 0 \quad \forall f, m, t \quad (66)$$

$$pr_{g,lu,u}^t \geq 0 \quad \forall g, lu, u, t \quad (67)$$

$$pr_{lh,h}^t \geq 0 \quad \forall lh, h, t \quad (68)$$

$$pr_{f,la,a}^t \geq 0 \quad \forall f, la, a, t \quad (69)$$

$$pr_{p,lb,b}^t \geq 0 \quad \forall p, lb, b, t \quad (70)$$

$$C_{lu,u}^t \geq 0 \quad \forall lu, u, t \quad (71)$$

$$C_{ls,s}^t \geq 0 \quad \forall ls, s, t \quad (72)$$

$$C_{lh,h}^t \geq 0 \quad \forall lh, h, t \quad (73)$$

$$C_{la,a}^t \geq 0 \quad \forall la, a, t \quad (74)$$

$$C_{lb,b}^t \geq 0 \quad \forall lb, b, t \quad (75)$$

$$X_{lu,u}^t = \{0,1\} \quad \forall lu, u, t \quad (76)$$

$$X_{ls,s}^t = \{0,1\} \quad \forall ls, s, t \quad (77)$$

$$X_{lh,h}^t = \{0,1\} \quad \forall lh, h, t \quad (78)$$

$$X_{la,a}^t = \{0,1\} \quad \forall la, a, t \quad (79)$$

$$X_{lb,b}^t = \{0,1\} \quad \forall lb, b, t \quad (80)$$

$$XCO_2^t_i = \{0,1\} \quad \forall i, t \quad (81)$$

$$ZX_{lu,u}^t = \{0,1\} \quad \forall lu, u, t \quad (82)$$

$$ZX_{ls,s}^t = \{0,1\} \quad \forall ls, s, t \quad (83)$$

$$ZX_{lh,h}^t = \{0,1\} \quad \forall lh, h, t \quad (84)$$

$$ZX^t_{la,a} = \{0,1\} \quad \forall la,a,t \quad (85)$$

$$ZX^t_{lb,b} = \{0,1\} \quad \forall lb,b,t \quad (86)$$

303

304 2.9. Solution method

305 In the ε -constraint method, one of the objective functions is chosen and the other ones are used as
 306 constraints. Efficient solutions to the problem are obtained through the parametrical variation in the RHS
 307 of the constrained objective functions. Assume the following multi-objective optimization problem:

$$\begin{aligned} \max \quad & (f_1(x), f_2(x), L, f_p(x)) \\ \text{st} \quad & \\ & x \in S, \end{aligned} \quad (87)$$

308 The general form of the ε -constraint model is as shown below (Mavrotas, 2009):

$$\begin{aligned} \max \quad & f_1(x) \\ \text{st} \quad & \\ & f_2(x) \geq e_2, \\ & f_3(x) \geq e_3, \\ & L \\ & f_p(x) \geq e_p, \\ & x \in S \end{aligned} \quad (88)$$

309 3. Case study and the results

310 The proposed model was implemented through a case study to specify its feasibility in Iran. The case study
 311 was conducted in this country due to a) the increasing demand for energy, b) the high level of demand for
 312 medication, health products and foodstuffs, c) the increased amount of environmental pollutants in large
 313 cities and the motivating policies to decrease them, d) the great diversity of microalgae species on the
 314 southern coasts of Iran, e) enough sunlight, and f) the existence of barren and inexpensive farm lands for
 315 microalgae cultivation (Arabi et al., 2019b; Mohseni et al., 2016).

316

317 3.1. The criteria to select locations for algae cultivation

318 In this study, the AHP method was used to identify the locations for microalgae cultivation. At first, three
 319 main criteria including land, accessibility to resources and climate were taken into consideration. These

criteria were then categorized into 12 sub-criteria. Table 7 presents the corresponding data obtained from an active corporation³ in this field in Iran and some other studies (Mohseni et al., 2016; Najafi et al., 2011). The criteria are evaluated as follows:

- Land price: The money spent on buying or renting a piece of land can positively or negatively affect the final cost of the supply chain and lead to more or less profit.
- Job opportunities: The development of this industry in an area can create jobs for the neighboring residents.
- Distance to the customer: In order to sell the end products, shorter distance to the customer will reduce the transportation cost.
- Land use: The land used for microalgae cultivation should not be a part of grassland, jungle or farmland; it should be located in a sizable area. Therefore, finding cheaper land can be helpful in this regard (Adenle, Haslam, & Lee, 2013; Coleman et al., 2014; Mohseni et al., 2016).
- Distance to water resources: This criterion refers to saline water, fresh water and wastewater. In order to deliver a huge amount of water to microalgae pools or PBR, there is a need for pipelines and a pumping system, but this imposes extra costs. Therefore, locations with easy access to water resources or previously built WWTs should be looked for so as to decrease the water costs (Coleman et al., 2014; Mohseni et al., 2016; Zhou et al., 2014).
- Distance to a power plant: The delivery of CO₂ to microalgae cultivation pools requires pipes and pumps, which entails the same costs as water delivery does. Therefore, it is necessary to build cultivation locations with the least distance to CO₂ production sites (Kim et al., 2013; Mohseni et al., 2016; Pokoo-Aikins et al., 2010; Sharma et al., 2015).
- Distance to nutrient resource markets: In order to buy a feedstock and nutrients for micro-algae cultivation, a short distance to the resource market will be cost-effective.
- Humidity: Sufficient humidity in the location will lead to suitable conditions for microalgae cultivation (Adenle et al., 2013; Chisti, 2013).
- Solar radiation: The more sunlight during the year, the faster the microalgae will grow (Adenle et al., 2013; Chisti, 2013).
- Temperature: Most of the commonly cultured species of microalgae can tolerate temperatures from 16°C to 27°C. Temperatures lower than 16°C slow the growth down, whereas those higher than 35°C are lethal for a number of species.

³ Qeshm Microalgae Biorefinery (QMAB)

Table 7. The weights of the criteria and the sub-criteria to select the candidate cities for microalgae cultivation

Criteria	Weight	Sub-criteria	Weight
Land	0.1845	Land price (IRR)	0.2890
		Job opportunities	0.1800
		Distance to the market (Km)	0.3000
		Land use	0.2310
Accessibility of resources	0.4733	Distance to saline water (sea) (Km)	0.1480
		Distance to fresh water (Km)	0.1701
		Distance to WWT (Km)	0.2132
		Distance to power plant (Km)	0.3207
		Distance to nutrient resource market (Km)	0.1480
Climate	0.3422	Humidity (RH)	0.1376
		Solar radiation (Kwh/m2)	0.4836
		Temperature (°C)	0.3788

3.2. Results of the first stage: Identifying the locations for microalgae cultivation

In order to identify the locations for cultivation, it is necessary to choose areas with higher priority to establish the microalgae cultivation facilities. In this case study, as Table 8 suggests, some Iranian cities were found to have the required capabilities for this purpose (Mohseni et al., 2016; Najafi et al., 2011; Tzeng & Huang, 2011).

Table 8. Candidate cities

No.	City	No.	City	No.	City	No.	City	No.	City
1	Ahvaz	8	Birjand	15	Isfahan	22	Qeshm	29	Shiraz
2	Arak	9	Bojnurd	16	Jask	23	Qom	30	Tabriz

3	Ardabil	10	Bushehr	17	Kerman	24	Rasht	31	Tehran
4	Bandar Abbas	11	Chabahar	18	Kermanshah	25	Sanandij	32	Urmia
5	Bandar Kangan	12	Chalus	19	Khorram abad	26	Sari	33	Yasuj
6	Bandar-e Lengeh	13	Gorgan	20	Mashhad	27	Semnan	34	Yazd
7	Bandar-e Mahshahr	14	Hamedan	21	Qazvin	28	Shahrekord	35	Zanjan

3.3. Solving the multi-objective optimization model using the ε -constraint method

The proposed multi-objective function model was solved with the ε -constraint method, the CPLEX solver and the GAMs software on a computer equipped with the Intel® Core(TM) i7-7700 HQ operating at 2.81 GHz.

The model was first solved with the economic objective function as the main objective function. The lower and upper bounds of the main objective function were 0 and 834484198 in epsilon values respectively. The problem was, indeed, solved according to the main objective function and the determined epsilon values. Table 9 shows the results of solving the model with 10 epsilon values. The first objective function is regarded economic considerations and aimed to maximize the profit. The second objective function was about environmental impacts and sought to minimize the fossil fuel consumption. Basically, economic and environmental features are widely known as sustainability determiners. Although economic considerations make up the top-priority objective function, the importance of environmental sustainability cannot be ignored (Rabbani, Momen, Akbarian-Saravi, Farrokhi-Asl, & Ghelichi, 2020). The former is concerned with the maximization of the economic profit. Since it attracts private-sector investors and expands the industry, it is considered more important than environmental issues. Therefore, it was set as the main objective function in this study.

According to the Pareto optimal solutions for the economic and fossil energy input problems (Figure 2), decision makers can choose a preferred point. For example, at the point with ε of 5.38E+08, the profit value is 538,627,026 million Rials, while the fossil energy input is 8.9 MJ. When more algal products are produced, more fossil energy is needed to produce the end products and transport them to the customer. Contrary to the first objective function, which induces more fossil fuel consumption, the second objective function aims at minimizing the consumption of those fuels throughout the MBCSCN. Indeed, the less fossil fuel is consumed, the less GHG is emitted. Therefore, in the Pareto optimal solutions, the model seeks a breakeven point where the value of each objective function is satisfied while its total value is optimized.

Table 9. Multi-objective model results

Points	E	Economic benefit (MIRR ⁴)	Fossil energy input (MJ)
--------	---	---------------------------------------	--------------------------

⁴ Million Iranian Rials

1	0	0	0
2	9.92E+07	9.92E+07	16.71
3	1.93E+08	1.93E+08	15.18
4	2.87E+08	2.87E+08	13.65
5	3.82E+08	3.82E+08	12.12
6	4.76E+08	4.76E+08	10.59
7	5.38E+08	5.38E+08	8.9
8	6.73E+08	6.73E+08	7.5
9	7.93E+08	7.93E+08	6.2
10	8.34E+08	8.34E+08	4.8

Fig. 2. Pareto optimal solutions

3.4. Results of the second stage

The optimal costs include the fixed, variable and operational costs for each step of the MBCSCN. The transportation costs relate to the transporting of the feedstock from the feedstock market to the microalgae

cultivation sites, then to the preprocessing facilities, then to the biofuel and co-products bio-refinery, then to the end-products warehouse, and finally to the customers in Iran. The amount of fossil fuel affecting the environment is studied in all the steps of the supply chain. It is noteworthy that all of these studies have been done for a 5-year planning horizon.

Table 8 shows 35 candidate cities where investments can be made for microalgae cultivation. With regard to the results obtained from the AHP method, 10 cities are selected for constructing microalgae cultivation facilities (Table 10). In addition, Fig. 3 illustrates the technologies and the types of microalgae to be used in the selected cities. According to the results of this model, most of the cultivation locations use Open Pond technology for microalgae cultivation owing to its lower cost.

Table 10. Cities selected for constructing cultivation facilities with the corresponding technologies and microalgae species

No.	City	Cultivation technology	
		Open pond	Photo bioreactor
4	Bandar Abbas	C,S,D	
5	Bandar Kangan	S	
6	Bandar-e Lengeh	D	
7	Bandar-e Mahshahr	S,D	
10	Bushehr	C,S,D	D
11	Chabahar	C,S,D	D
16	Jask	C,S	
22	Qeshm	C,S	D
26	Sari	D	
32	Urmia	C	

Abbreviations: C: *Chlorella vulgaris* , S: *Spirulina platensis* , D: *Dunaliella salina*

The optimal microalgae preprocessing locations are placed in the cultivation sites, which leads to the reduction of transportation costs (Fig. 4) (Ismail et al., 2020).

Fig. 3. Cities selected for constructing cultivation facilities with the corresponding technologies and microalgae species

Table 11 shows the technologies applied in the preprocess step. In this study, the preprocess step involves two operations, harvesting and dewatering as well as drying. Each of these operations needs a different technology with regard to the species of the microalgae (Gutiérrez-Arriaga et al., 2014; Ismail et al., 2020). In the preprocess step, three technologies are applied (Arabi et al., 2019a).

Fig. 4. Cities selected for constructing preprocessing (harvesting, dewatering and drying) facilities along with the corresponding technologies

Table 11. Cities selected for constructing preprocessing (harvesting, dewatering and drying) facilities with the corresponding technologies

No.	City	Preprocessing technology		
		Flocculation and drying	Sedimentation and drying	Filtration and drying
4	Bandar Abbas	*	*	
5	Bandar Kangan	*		
6	Bandar-e Lengeh	*		

7	Bandar-e Mahshahr	*			
10	Bushehr	*		*	
11	Chabahar	*		*	
16	Jask	*			
22	Qeshm	*		*	*
26	Sari	*			
32	Urmia	*			

421

422 Fig. 5 illustrates 13 cities for biofuel production, and Fig. 6 introduces nine cities to produce co-products.
423 Three technologies have been applied in the biofuel production, and the two technologies of anaerobic
424 digestion and thermal treatment have served to produce co-products. Moreover, biodiesel, bioethanol and
425 biogas (methane) are the products obtained from the selected bio-refineries, and astaxanthin, health
426 products, aquaculture, β -carotene and human and animal foodstuffs are the end products taken from the
427 selected co-product production facilities (Tables 12 and 13).

Fig. 5. Cities selected for constructing bio-refinery facilities to produce biofuels with the corresponding technologies

Table 12. Cities selected for constructing bio-refinery facilities to produce biofuels with the corresponding technologies

No.	City	Bio-refinery technology to produce biofuels		
		Transesterification	Fermentation	Anaerobic digestion
2	Arak	BD		M
4	Bandar Abbas			
6	Bandar-e Lengeh	BD		M

7	Bandar-e Mahshahr	BD		M
10	Bushehr	BD	BE	BD,M
11	Chabahar	BD		
15	Isfahan	BD	BE	BD,M
16	Jask	BD	BE	M
20	Mashhad			BD
22	Qeshm	BD	BE	M
29	Shiraz			BD
31	Tehran	BD	BE	BD,M
32	Urmia			BD

Abbreviations: BD: Biodiesel, BE: Bioethanol, M: Biogas (Methane)

434

435 Table 13. Cities selected for constructing bio-refinery facilities to produce co-products with the
436 corresponding technologies

No.	City	Bio-refinery technology to produce co-products	
		Thermal treatment	Anaerobic digestion
2	Arak		H,B,F
4	Bandar Abbas	A,H,F	
10	Bushehr	A,H,F	C,B
11	Chabahar	A,H,F	
15	Isfahan		H,B,F
16	Jask		A,H,C,B
22	Qeshm		H,C,B
29	Shiraz		H,B
31	Tehran	A,H,F	C,B

Abbreviations: A: Astaxanthin, H: Health products, C: Aquaculture, B: β -carotene, F: human and animal foodstuffs

This research has brought warehouse facilities into account to store the end products. Table 14 refers to 13 cities for biofuel products and eight others for co-products; they have been selected to store the end products (Fig. 7). The end products are sent from their warehouses to the customer. Fig. 8 shows the biofuel and co-products customers. They are chosen based on their demand for the end products in each city.

Fig. 6. Cities selected for constructing bio-refinery facilities to produce co-products with the corresponding technologies

Table 14. Cities selected for constructing warehouses

No.	City	Warehouse	
		Biofuels	Co-products
2	Arak	*	*

4	Bandar Abbas	*	*
6	Bandar-e Lengeh	*	
7	Bandar-e Mahshahr	*	
10	Bushehr	*	*
11	Chabahar	*	*
15	Isfahan	*	*
16	Jask	*	
20	Mashhad	*	
22	Qeshm	*	*
29	Shiraz	*	*
31	Tehran	*	*
32	Urmia	*	

446

447

Fig. 7. Cities selected for constructing warehouses

Table 15. Biofuel customers

No.	City	No.	City	No.	City
1	Ahvaz	17	Kerman	27	Semnan
2	Arak	19	Khorram abad	29	Shiraz
3	Ardabil	20	Mashhad	30	Tabriz
4	Bandar Abbas	21	Qazvin	31	Tehran
10	Bushehr	23	Qom	32	Urmia

14	Hamedan	24	Rasht	34	Yazd
15	Isfahan	26	Sari	35	Zanjan

452

453

454 Table 16. Co-product customers

No.	City	No.	City
1	Ahvaz	24	Rasht
2	Arak	29	Shiraz
3	Ardabil	30	Tabriz
4	Bandar Abbas	31	Tehran
15	Isfahan	21	Qazvin
20	Mashhad		

455

456

Fig. 8. Markets for the end products

The microalgae cultivation step has four types of costs including variable cost, fixed cost, operational cost, and the cost for the delivery of feedstock to the cultivation location. The variable cost depends on the quantity of the materials spent during the construction of the Open Pond and PBR, while the operational cost is incurred only after the cultivation of microalgae is started in the Open Pond and PBR. The costs of microalgae cultivation have an increasing trend in a 5-year planning horizon, while the fixed and transportation costs are the highest expenses due to the far distance of the feedstock resources from the microalgae cultivation facilities. The vast areas in the provinces of Iran are another factor for the high transportation costs. Since the preprocessing of microalgae is carried out in the same location as the microalgae cultivation, there would be no need to transport the cultivated microalgae to a preprocessing facility. The microalgae transportation cost is, thus, ignored in this step (Fig. 9).

Fig. 9. Microalgae cultivation and the preprocessing costs

Fig. 10 shows the costs of producing biofuels and co-products. It is assumed that the refineries converting the microalgae to biofuels and co-products have already been built. Consequently, the fixed and the investment costs sharply decrease. Just like the previous steps of the supply chain, however, the variable and the operational costs have an increasing trend. Since the distance between the preprocessing facilities and the bio-refinery locations is long, the transportation costs increase. It should be noted that all the costs have been calculated according to the average inflation rate of 13% in Iran.

479

480 Fig.10. Costs of producing the biofuel and co-products

481 Fig. 11 reports the warehouse cost for biofuels and co-products. The cost of transportation from the biofuel
 482 and co-product refineries to the warehouses and that of transporting the end-products to the customer are
 483 also given. Here, the costs of the two transportation modes (i.e., truck and train) are evaluated too. Of
 484 different steps of the supply chain, the transportation of the end-products to the customers imposes the
 485 highest expenses.

Fig. 11. Cost of storing the end products

3.5. The amount of input fossil fuel

Fig. 12 shows the amounts of the input fossil energy in all the steps of the MBCSCN with regard to the corresponding technologies. As it can be seen, the largest amount of the input fossil energy belongs to the transportation of the end-products to the customers and the biofuel production (Jian, Jing, & Peidong, 2015; Karimi, Naini, & Sadjadi, 2021).

Fig. 12. Amount of consumed fossil energy

3.6. Sensitivity analysis

In order to measure the effectiveness and the applicability of the proposed model, it is necessary to study the influence of the critical parameters on it. In this study, the effects of the variation of three parameters on the total cost have been studied. The parameters are the feedstock, the biofuel and co-products transportation costs and the feedstock price. Furthermore, the rate of change for each parameter has been considered to be $\pm 15\%$. The variation of each parameter and its effect on the total cost are presented in Fig. 13.

Fig. 13. Effects of the variations in the feedstock, biofuel and co-products transportation costs and the feedstock price on the total cost

It should be noted that, despite the fact that Iran is one of the largest producers of oil and petroleum products, its industry is significantly depending on transportation. Any changes in the transportation cost can lead to extreme price fluctuation. Therefore, this study has addressed the influence of the transportation cost on the total cost as an important issue. Fig. 13 illustrates the effects of the variation of three parameters on the total cost in one chart. Among all the parameters, the cost of transporting biofuel and co-product (end products) to the customer has had caused the greatest change in the total cost. Due to the vast area of the provinces and the long distance between the end products producers and the customer, more energy has to be consumed, which will cause more expenses. As the transportation cost of the end products increases by 15%, the total cost increases for 8.3%. If the cost of transporting the end products decreases by 15%, the total cost will decrease by 6.7%. The end products transportation is done by truck and train. Since the feedstock transportation is done by truck and train, the changes in its cost will be the same as those in the cost of the end product transportation. However, due to the shorter distance between the feedstock supply market and the cultivation locations, the expected transportation cost is lower than the cost of the end product transportation. Among all the parameters, feedstock prices have the minimum effects on the total cost. Since the feedstock price fluctuation is low and there are various feedstock suppliers with competitive prices, the total cost will have no significant change.

4. Conclusion

In this study, a two-stage framework was proposed to optimize the designed MBCSCN. In the first stage, the locations selected for microalgae cultivation were identified based on the AHP method. In the second stage, a deterministic multi-period, multi-objective MILP model was developed with an objective function of two criteria including economy and environmental impacts. The model was solved using the ε -constraint method. Then, a case study was conducted to specify the effectiveness and the optimality of the model. Based on the results obtained in the first stage, 10 cities were identified and selected as locations for microalgae cultivation in Iran. The model was also implemented to determine appropriate microalgae species, the required quantity of the feedstock, a feedstock supply location, a preprocessing location, a location for biofuel and co-product production, the production capacity, the type of the biofuel and co-product to produce, the required technology, and the transportation modes in each step of the supply chain. This model aims at evaluating the breakeven points of two objective functions including the maximization of profit and the minimization of the environmental impacts of fossil fuel consumption. The results of the study indicate that the cost of producing biofuels should compete with the cost of producing fossil fuels in Iran. The main reason for the lack of competition is the reduction of oil prices, as a competing factor, in recent years. Another finding of this study regards the large share of transportation costs in the total costs of supply chains. Hence, there are certain issues to recommend for future studies. They can consider uncertainty in the price of biofuels and co-products, concentrate more on the production and distribution of microalgae-based co-products, and find ways to reduce the transportation costs in microalgae-based biofuel supply chains.

546 **Declarations**

547 **Ethics approval:**

- 548 • Not applicable.

549 **Consent to participate:**

- 550 • Not applicable.

551 **Consent for publication:**

- 552 • Not applicable

553 **Availability of data and materials:**

- 554 • All data generated or analyzed during this study are included in this published article.

555 **Competing Interests:**

- 556 • Not applicable.

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560 **Authors' contributions:**

- 561 • Study conception and design, data collection, analysis and writing the first draft of the manuscript
562 were performed by Mohammad Ehsan Zerafati. Validation of data and verification of research
563 outputs were performed by Ali Bozorgi-Amiri. Critical review, commentary and revision of
564 translation were performed by Amir Mohammad GolMohammadi. Fariborz Jolai commented on
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567

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