Designing a Multi-echelon and Multi-product Sustainable Biomass Supply Chain Network Considering Input Material Diversity

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Abstract

Biomass sources are receiving increasing attention in the field of academic research and manufacturing as a suitable alternative to fossil fuels due to their renewable capability and economic advantage. This study addresses a multi-echelon and multi-product biomass supply chain network considering input material diversity. The first layer of the considered supply chain consists of five supply centers of Jatropha, Norouzak, Oleander, microalgae, and waste cooking of oil. The second layer dedicated to oil extraction and pre-refining of waste cooking of oil. Biorefineries are considered in the third layer and finally, production centers of the final products including drug, biodiesel, and cosmetics are located in the fourth layer. A mixed-integer bi-objective mathematical programming model is proposed to minimize the total expected cost as well as the environmental impact simultaneously. Besides of solving the problem using data of a case study, sensitivity analysis is conducted to investigate the effect of variations in the capacity of centers as well as demand on two objective functions and the final values of decision variables. The result shows efficiency of the proposed model in solving the problem at hand and providing proper alternatives for managers in different various situations.

Keywords: Biomass, supply chain, sustainability, material diversity, bi-objective model

1. Introduction

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A major portion of the current energy demand is met by fossil fuels. However, such resources are expected to decrease in use by the next century [1]. Additionally, the level of carbon dioxide (CO_2) in the atmosphere has increased due to the burning of fossil fuels, leading to global warming [2]. Thus, researchers constantly emphasize the negative environmental impacts and limited resources related to fossil fuels, highlighting their inappropriateness for sustainable energy production [3].

On the other hand, a variety of products should be made available to customers based on their demands in the current global competitions. Customer demand for high quality and fast service has created unprecedented pressures. Therefore, companies cannot handle all of the tasks on their own anymore. Economic and production enterprises in the competitive market should supervise external resources and elements in addition to dealing with internal organization and resources to achieve competitive advantages or gain a larger market share. Thus, activities such as supply and demand planning, procurement, production and product planning, product maintenance services, inventory control, distribution, delivery, and customer service, which were previously performed at the company level, have now transferred to the level of the supply chain. All of the above-mentioned activities should be managed and controlled in a supply chain properly [4].

Sustainable development is one of the major challenge of countries for success in global competitions around the world. In such condition, beside the economic aspects, the social and environmental impacts of their industries should also be considered [2]. In this way, traditional economic development has been replaced by sustainable one in all of the industries, resulting in guaranteeing economic development alongside environmental and social improvements [5]. Moreover, clean, renewable, and cost-effective energy resources should be supplied properly in sustainable development.

Fossil fuels are one of the most important sources of energy consumption worldwide. Climate change and global warming issues due to the accumulation of carbon dioxide (CO_2) is considered as the most critical environmental concern regarding the consumption of fossil fuels [6]. Therefore, energy researchers and policymakers look for an appropriate alternative for fossil fuel consumption due to their environmental impact, the impending depletion of sources, and the anticipated increase in prices. In this regard, biofuels can reduce environmental impact and contribute to sustainable development. Biofuels are generated from biomass feedstock in various forms such as liquid, solid, or gas. Biodiesel and bioethanol are regarded as the most common liquid biofuels applied as proper substitutes for fossil fuels and gasoline in the transportation sector [7].

There are various processes in producing biomass from vegetable oils and animal fats, in which ester interchange is considered as a key factor for generating environmentally friendly fuels [8]. In all kinds of production process, supply and price of raw materials is regarded as a major constraint on the development of the bioenergy industry [4]. Biofuel is 1.5-2 times more expensive than diesel one with 70-95% of the cost attributed to vegetable oil or animal fat. In addition, some raw materials are considered as food-based and their use for biomass production is criticized by

FAO [3]. Thus, using cheaper feedstock such as non-edible or waste oils can reduce the initial cost of biomass significantly. Microalgae are among the most promising materials for future biomass production, which can meet global demand for transportation fuels.

Majority of the biomass supply chain consist of common stages includes growth, harvesting, transportation, collection, storage, and conversion of biomass into final products. In addition, productivity and technology in each sector affect other sectors. Selection of biomass type, sustainability, and profitability in raw material production, as well as the economies of scale are among the most critical factors in the supply chain. Moreover, the optimal and sustainable design of the biofuel supply chain plays a vital role in cost reduction and commercialization.

According to the abovementioned explanation, this study focuses on designing a biomass supply chain network considering diversity of input materials to determine an optimal location for building a refinery and producing non-food biomass resources such as Jatropha, microalgae, Yellow Oleander, Norouzak, and waste oil. In this way, a bi-objective mathematical model is proposed considering all layers of the biomass supply chain with the aim of minimizing total cost and environmental impact simultaneously. Thus, biofuels is considered as appropriate alternatives to fossil ones [9] given the recent studies focusing on sustainable energy supply over conventional energy sources in various aspects [10].

The rest of the study is organized as follows. The second section focuses on the literature review to identify the research gap. Problem description and the proposed mathematical model is provided in Section 3. Section 4 is dedicated to the solving approach. The case study and result analysis are presented in Section 5 and 6 respectively. Some sensitivity analysis are provided in Section 7. Finally, Section 8 provides a general conclusion and some suggestions for future studies.

2. Literature review

This section discusses the studies conducted in the field of biomass supply chain during the recent years. As evident in the literature, various modeling approaches are used by researchers to design the biomass supply chain, including simulation and mathematical programming. For instance, Hosseinalizadeh et al. [11] developed a comprehensive multi-period and multi-objective model for designing a biodiesel development program by utilizing waste cooking oil (WCO), soybean, sunflower, and canola as primary sources, as well as comparing different compositions of biodiesel and feedstock. They provided a Pareto set applying the augmented ε-constraint method. Based on the results, B5 and B40 were identified as the most appropriate options in the Pareto set. In a similar study, Delkhosh and Sadjadi [1] developed a two-stage approach to commercialize microalgae biofuel supply chain by introducing a second-generation biorefinery concept. The authors used the Best-Worst Method to determine the best cultivation system. Then, a dual-objective mathematical model was presented to optimize economic and environmental objectives simultaneously. In the next step, a robust optimization model was proposed based on scenarios to cope with the uncertain nature of the biofuel supply chain. They were regarded as the first to explore the reuse of gases and wastewater refining as raw materials for different stages in the literature.

Durmaz and Bilgen [12] presented a sustainable multi-objective optimization approach for designing a biomass supply chain. They proposed an optimized network planning of the biomass supply chain, followed by proposing a three-step method and developing a multi-objective programming model to eliminate a real-world obstacle. Afterwards, Mahjoub et al. [13] presented a mixed-integer linear programming (MIP) model for designing the upstream and downstream of biomass supply chain with three types of biomass including second-generation Jatropha, agricultural residues, and animal manure (second generation), as well as microalgae (third generation) for bioenergy production. The proposed model was solved using the augmented ε-constraint method to achieve Pareto-optimal solutions. The results indicated that energy production from microalgae and Jatropha is considered as more sustainable than biomass residues considering the amount of produced bioenergy regardless of its type. In addition, production and investment cost exhibits the greatest effect on the cost of the entire supply chain network, respectively.

Rezaei et al. [14] considered non-edible resources such as Norouzak, Jatropha, and WCO and proposed a robust optimization model based on scenarios for designing biodiesel supply chain networks under uncertainty. Some parameters including demand, supply, costs, and environmental impact are uncertain in their model. Therefore, the uncertain parameter values are estimated based on the scenario planning approach in each scenario and the probabilities of scenario occurrences are determined for the first time in the literature. The results indicate the effectiveness of the proposed approach in designing biodiesel supply chain networks under uncertainties and determine the number, location, and capacity of facilities to minimize the overall supply chain cost.

Guler et al. [15] presented an appropriate modeling approach and sensitivity analysis for establishing biomass energy facilities in order to determine the location of biomass facilities by combining Geographic Information Systems (GIS), fuzzy logic, and BWM method. Puratich et al. [10] provided a bi-objective optimization model for the simultaneous supply of various agricultural and industrial wastes to a co-production system and the promotion of a recyclable bioeconomic system. Duc et al. [16] focused on designing a multi-objective bioenergy supply chain network to minimize the total cost and carbon emissions from transportation. They developed some stochastic and fuzzy models for determining the optimum factory locations as well as material flows and truck types while accounting for demand uncertainty. The authors used the ε-constraint method to generate optimal Pareto solutions. In a similar effort, Ahmadvand et al. [9] developed a bi-objective optimization model for tactical planning of forest-based biomass supply chains to obtain a trade-off between total costs and potential deviations from safety stock. The decision variables include monthly biomass flow, preprocessing, and inventory levels. The results indicated that cost savings of up to 18% are possible in case of inventory level deviation from safety stock.

Ahmadvand and Sowlati [17] optimized a forest-based biomass supply chain for syngas production at the tactical level considering uncertainties. They proposed a robust optimization model to a real case of a Kraft paper pulp mill in British Columbia, Canada. The total supply chain cost is 67% higher than the deterministic one. However, the robust model provides an optimal solution feasible for all of the parameter values within the considered uncertainty intervals. Khadivi [18] focused on gasification as one of the processing technologies for converting biomass into syngas and renewable natural gas. To this aim, economic feasibility and emission reduction were addressed as critical factors influencing investment decisions related to biomass gasification. Identifying the best gas conversion alternative for investment indicated that minimizing costs and emissions in the biomass supply chain is crucial as supply chain costs can account for up to 50% of the total gas conversion cost, and GHG emissions from supply chain activities can be offset.

Shevchenko et al. [19] investigated Production of Biomodified Bleached Kraft Pulp by Catalytic Conversion Using Penicillium verruculosum Enzymes. Their applied research led to resulted the products of sugar solution, mainly glucose, xylobiose, xylose, and a modified complex based on cellulose and xylan. Further, Sani et al. [20] studied a multi-product energy infrastructure for energy production from municipal solid waste in Canada to optimize waste-to-energy technologies. They proposed a two-stage robust optimization model to minimize the total annual cost of waste-to-energy facilities. Based on the results, the robust model can reduce 19.9% of environmental costs.

Mirzaee et al. [21] assessed the supplier selection problem considering green and non-green criteria in a closed-loop supply chain and proposed pollution control mechanisms for the producers. A multi-objective robust optimization model was proposed to balance conflicting objectives and determine the uncertainty of carbon emissions. In another study, Chen and Liu [22] proposed a MILP model for multi-objective sustainable design of a bioenergy-based power supply chain in Hubei Province, China. Finally, Yıldız et al. [23] presented an ideal multi-objective programming model for optimizing the design of a sustainable renewable energy supply chain network based on biomass in multiple stages. The proposed model shows decision-making regarding the optimal number of locations, size of processing facilities and warehouses, as well as the quantities of biomass and final products transported between locations for power generation.

Based on the shortcomings and gaps identified from the literature review (see Table 1), it can be concluded that there is a lack of dealing with the problem of designing the multi-echelon and multi-product sustainable biomass supply chain network considering the variety of input materials. In this way, to address the identified gap in the literature, this study primarily presents an integrated model which simultaneously provides both location and routing in the design of a sustainable biomass supply chain network. In addition, environmental impact is managed by evaluating the distance to ecological management units. The present study proposes a bi-objective model which minimizes the total cost and environmental impact in the supply chain.

{Please insert Table 1 about here.}

It is worth mentioning that, choosing the proper amount of each kind of the input material is an important issue in every sustainable biomass supply chain network due to their different features affecting both the total expected cost and environmental impact. In this regard, the main contribution of this study is twofold: First, it highlights the role of multi-variety input material condition in the problem of designing sustainable biomass supply chain. Second, a bi-objective MIP model is proposed to minimize the total expected cost and environmental impact simultaneously, to investigate their conflict, and to analyze the trade-off between them.

3. Problem description and model formulation

The proposed supply chain network is a four-layer one containing supply centers (Norouzak, Jatropha and Oleander cultivation fields), WCO supply centers, collection centers (oil extraction and WCO pre-refining centers), refining center (bio-refineries, and production centers (biodiesel production, cosmetics and hygiene products manufacturing, and drug production). The presented model is a bi-objective MILP mathematical one which minimizes the supply chain costs including construction, production, inventory maintenance, transportation, and environmental impacts. Figure 1 shows the framework of the proposed model including the symbols used for indices, variables, and model parameters, as well as the considered structure of the supply chain.

{Please insert Figure 1 about here.}

3.1. Assumptions of the model

The main assumptions of the problem at hand inspired by Ahmadvand et al. [9] are as follows:

- The provided supply chain model is a multi-layer and multi-product one. Diesel fuel, cosmetics and hygiene products, and raw materials for medicine are considered as the final products of the proposed supply chain network.
- All of the demands related to biodiesel, cosmetics and hygiene products, and raw materials for medicine should be met, and shortages are not allowed.
- The required raw materials to meet the demand for biodiesel, cosmetics and hygiene products, and raw materials for medicine are sourced from domestic farms of Jatropha, Norouzak, Oleander, and microalgae, as well as WCO, and import of raw materials is not permitted.
- The locations of the consumption centers for biodiesel, cosmetics and hygiene products, and raw materials for medicine are regarded as specified and fixed.
- Potential locations for cultivating Jatropha, Norouzak, Oleander, and microalgae, extraction centers and pre-refining centers for oil, as well as the establishment of a refinery are predetermined.
- Transportation within the biodiesel supply chain is studied only through a road mode.

- The capacity cannot be expanded for farms and all of the existing facilities.
- The opened facilities remain active until the end of the planning horizon.
- All of the parameters are considered as deterministic in nature.
- Inventory holding is only possible for biodiesel in the biorefinery, and the inventory level should be smaller than or equal to the maximum inventory level.

3.2. Notations

Indices, parameters, and variables applied in the mathematical model are described as follows

Indices

j Index related to candidate locations for cultivating Jatropha crops: $j = 1, 2, 3, \ldots, J$

n Index related to candidate locations for cultivating Norouzak crops: $n = 1, 2, 3, \ldots, N$

o Index related to candidate locations for cultivating Oleander crops: $o = 1, 2, 3, \ldots, O$

m Index related to candidate locations for cultivating algae: $m = 1, 2, 3, \ldots, M$

w Index related to candidate locations for supply centers WCO: $w = 1, 2, 3, \ldots, W$

i Index related to candidate locations for collection and extraction centers for Jatropha, Oleander, Norouzak, and algae: $i = 1, 2, 3, \ldots, I$

p Index related to candidate locations for collection and pre-refining WCO centers: $p = 1, 2, 3, \ldots, P$

k Index related to candidate locations for biorefinery centers: $k = 1, 2, 3, \ldots, K$

b Index related to diesel refineries: $b = 1, 2, 3, \ldots, B$

s Index related to cosmetics and hygiene production centers: $s = 1, 2, 3, \ldots, S$

h Index related to medicine production centers: $h = 1, 2, 3, \ldots, H$

t Time period index: $t = 1, 2, 3, \ldots, T$

$\eta = \{j, n, o\}$ Union of indices $\mathrm{j, n, o}$

Parameters

$\mathrm{D}^1_{\mathrm{bt}}$ Demand for diesel refining plants for biodiesel during period "t"

$\mathrm{D}^2_{\mathrm{t}}$ Demand for glycerin during period "t"

$\mathrm{D}^3_{\mathrm{t}}$ Demand for pharmaceutical raw materials during period "t"

Ro_{wt} Amount of waste oil supplied by supply center "w " during period "t "

LF^1_j Minimum land allocated for Jatropha cultivation center in location " j "

UF^1_j Maximum available land for Jatropha cultivation center in location " j "

LF^2_n Minimum land allocated for Norouzak cultivation center in location "n "

UF^2_n Maximum available land for Norouzak cultivation center in location "n "

LF^3_o Minimum land allocated for Oleander cultivation center in location "o "

UF^3_o Maximum available land for Oleander cultivation center in location "o "

LF^4_m Minimum land allocated for Algae cultivation center in location "m "

UF^4_m Maximum available land for Algae cultivation center in location "m "

LC^1_i Lower limit of capacity for oil collection and extraction center in location "i"

UC^1_i Upper limit of capacity for oil collection and extraction center in location "i"

LC^2_p Lower limit of capacity for pre-refining and refining center WCO in location "p"

UC^2_p Upper limit of capacity for pre-refining and refining center WCO in location "p"

LC^3_k Lower limit of capacity for biorefinery center in location "k"

UC^3_k Upper limit of capacity for biorefinery center in location "k"

$Maxu^1$ Maximum number of regions selected for Jatropha cultivation center

$Maxu^2$ Maximum number of regions selected for Norouzak cultivation center

$Maxu^3$ Maximum number of regions selected for Oleander cultivation center

$Maxu^4$ Maximum number of regions selected for Algae cultivation center

$Maxu^5$ Maximum number of regions selected for oil collection and extraction center

$Maxu^6$ Maximum number of regions selected for pre-refining and refining center WCO

$Maxu^7$ Maximum number of regions selected for biorefinery center

μ^1_{jt} Productivity rate of Jatropha per hectare in location " j " during period "t "

μ^2_{nt} Productivity rate of Norouzak per hectare in location "n " during period "t "

μ^3_{ot} Productivity rate of Oleander per hectare in location "o " during period "t "

μ^{4}_{mt} Productivity rate of Algae per unit area in location "m" during period "t"

α^{1} Conversion factor from Jatropha to Jatropha oil

α^{2} Conversion factor from Norouzak to Norouzak oil

α^{3} Conversion factor from Oleander to Oleander oil

α^{4} Conversion factor from Algae to Algae oil

α^{5} Conversion factor from collected WCO to pre-refined one

ρ^{1} Conversion factor from Jatropha, Norouzak, Oleander, and Algae oil to biodiesel

ρ^{2} Conversion factor from pre-refined WCO to biodiesel

ρ^{3} Maximum inventory of biodiesel in the biorefinery

ρ^{4} Demand for diesel refining plants for biodiesel during period "t"

B Demand for glycerin during period "t"

Ω Demand for pharmaceutical raw materials during period "t"

$maxI^{6}$ Amount of waste oil supplied by supply center "w" during period "t"

Cost parameters

FC^{1}_{j} Fixed cost of planting Jatropha in location "j"

FC^{2}_{n} Fixed cost of planting Norouzak in location "n"

FC^{3}_{o} Fixed cost of planting Oleander in location "o"

FC^{4}_{m} Fixed cost of cultivating Algae in location "m"

FC^{5}_{i} Fixed cost of establishing an oil collection and extraction center in location "i"

FC^{6}_{p} Fixed cost of establishing a pre-refining and collection center for WCO in location "p"

FC^{7}_{k} Fixed cost of establishing a biorefinery center in location "k"

VC^{1}_{j} Variable cost of planting Jatropha per hectare in location "j"

VC^{2}_{n} Variable cost of planting Norouzak in location "n"

VC^{3}_{o} Variable cost of planting Oleander in location "o"

VC^{4}_{mt} Variable cost of planting Algae in location "m" during period "t"

VC^5_{it} Variable cost per unit of capacity for oil collection and extraction center in location "i" during period "t"

VC^6_{pt} Variable cost per unit of capacity for WCO collection and pre-refining center in location "p" during period "t"

VC^7_{kt} Variable cost per unit of capacity for biorefinery center in location "k" during period "t"

PC^1_{jt} Cost of producing each unit of Jatropha in location "j" during period "t"

PC^2_{nt} Cost of producing each unit of Norouzak in location "n" during period "t"

PC^3_{ot} Cost of producing each unit of Oleander in location "o" during period "t"

PC^4_{mt} Cost of producing each unit of Algae in location "m" during period "t"

$CCO2_{mt}$ Cost of per unit of CO2 for producing microalgae in location "m" during period "t"

PC^5_{wt} Cost of collecting WCO at supply center "w" during period "t"

PC^6_{it} Cost of producing each unit of Jatropha oil at oil extraction center in location "i" during period "t"

PC^7_{it} Cost of producing each unit of Norouzak oil at oil extraction center in location "i" during period "t"

PC^8_{it} Cost of producing each unit of Oleander oil at oil extraction center in location "i" during period "t"

PC^9_{it} Cost of producing each unit of Algae oil at oil extraction center in location "i" during period "t"

PC^{10}_{pt} Cost of pre-refining WCO in location "p" during period "t"

PC^{11}_{kt} Cost of producing biodiesel at biorefinery location "k" during period "t"

PC^{12}_{kt} Cost of producing glycerin at biorefinery location "k" during period "t"

PC^{13}_{it} Cost of producing each unit of raw materials for medicine at oil extraction center "i" during period "t"

PC^{14}_{it} Cost of producing fertilizer at oil extraction "i" during period "t"

IC^{6}_{kt} The unit cost of maintaining biodiesel inventory at biodiesel refinery location "k" during period "t"

TC^{1}_{jit} Unit cost of transporting Jatropha from cultivation center "j" to oil extraction center "i" during period "t"

TC^{2}_{nit} Unit cost of transporting Norouzak from cultivation center "n" to oil extraction center "i" during period "t"

TC^{3}_{oit} Unit cost of transporting Oleander from cultivation center "o" to oil extraction center "i" during period "t"

TC^{4}_{mit} Unit cost of transporting Algae from cultivation center "m" to oil extraction center "i" during period "t"

TC^{5}_{wpt} Unit cost of transporting WCO from supply center "w" to pre-refining center "p" during period "t"

TC^{6}_{ikt} Unit cost of transporting Jatropha, Norouzak, Oleander, and Algae oils from oil extraction center "i" to biorefinery center "k" during period "t"

TC^{7}_{pkt} Unit cost of transporting pre-refined WCO from pre-refining center "p" to biorefinery center "k" during period "t"

TC^{8}_{kbt} Unit cost of transporting biodiesel from biorefinery center "k" to biodiesel consumption center "b" during period "t"

TC^{9}_{it} Unit cost of transporting fertilizer from oil extraction center "i" to cultivation centers during period "t"

$\boldsymbol{Cpp^{12}_{kt}}$ Unit cost of transporting glycerin from refinery center "k" to customer during period "t"

$\boldsymbol{Cpp^{13}_{it}}$ Unit cost of transporting raw materials for medicine from collection and oil extraction centers "i" to customer during period "t"

Binary decision variables

u^1_j The variable equals 1 when location "j" is selected for the cultivation center of Jatropha; otherwise, 0

u^2_n The variable equals 1 when location "n" is selected for the cultivation center of Norouzak; otherwise, 0

u^3_o The variable equals 1 when location "o" is selected for the cultivation center of Oleander; otherwise, 0

u^4_m The variable equals 1 when location "m" is selected for the cultivation center of Algae; otherwise, 0

u^5_i The variable equals 1 when location "i" is selected for opening the oil collection and extraction center; otherwise, 0

u^6_p The variable equals 1 when location "p" is selected for opening the oil collection and pre-refining center; otherwise, 0

u^7_k The variable equals 1 when location "k" is selected for opening the biorefinery center; otherwise, 0

Continuous decision variables

I^6_{kt} The quantity of biodiesel inventory at the biorefinery center "k" during period "t"

P^1_{jt} The quantity of Jatropha produced at the Jatropha cultivation center in location"j" during period "t"

P^2_{nt} The quantity of Norouzak oil produced at location "n" during period "t"

P^3_{ot} The quantity of Oleander oil produced at location "o" during period "t"

P^4_{mt} The quantity of algae produced at the algae cultivation center "m" during period "t"

$CO2_{mt}$ The amount of CO2 consumed at the algae cultivation center "m" during period "t"

P^6_{it} The quantity of Jatropha oil produced at the oil extraction center "i" during period "t"

P^7_{it} The quantity of Norouzak oil produced at the oil extraction center "i" during period "t"

P^8_{it} The quantity of Oleander oil produced at the oil extraction center "i" during period "t"

P^9_{it} The quantity of algae oil produced at the oil extraction center "i" during period "t"

P^{10}_{pt} The quantity of pre-refined WCO produced at location "p" during period "t"

P^{11}_{kt} The quantity of biodiesel produced at the biorefinery center "k" during period "t"

P^{12}_{kt} The quantity of glycerin produced at the biorefinery center "k" during period "t"

P^{13}_{it} The quantity of raw material for producing medicine at the oil extraction center "i" during period "t"

P^{14}_{it} The quantity of fertilizer produced at the oil extraction center "i" during period "t"

T^{1}_{jit} The quantity of Jatropha transported from the cultivation center "j" to the oil extraction center "i" during period "t"

T^{2}_{nit} The quantity of Norouzak transported from cultivation center "n" to the oil extraction center "i" during period "t"

T^{3}_{oit} The quantity of Oleander transported from cultivation center "o" to the oil extraction center "i" during period "t"

T^{4}_{mit} The quantity of algae transported from the cultivation center "m" to the oil extraction center "i" during period "t"

T^{5}_{wpt} The quantity of pre-refined WCO transported from supply center "w" to the pre-refining center "p" during period "t"

T^{6}_{ikt} The quantity of Jatropha, Norouzak, Oleander, and algae oils transported from the oil extraction center "i" to the biorefinery center "k" during period "t"

T^{7}_{pkt} The quantity of pre-refined WCO transported from the pre-refining center "p" to the biorefinery center "k" during period "t"

T^{8}_{kbt} The quantity of biodiesel transported from the biorefinery center "k" to the consumption center "b" during period "t"

T^{9}_{it} The quantity of fertilizer transported from the oil extraction center "i" to the cultivation centers during period "t"

V^{1}_{j} The area of Jatropha cultivation in location "j"

V^{2}_{n} The area of Norouzak cultivation in location "n"

V^3_o The area of Oleander cultivation in location "o"

V^4_m The area of algae cultivation in location "m"

V^5_{it} The total capacity of the oil collection and extraction center "i" during period "t"

V^6_{pt} The total capacity of the pre-refining center "p" during period "t"

V^7_{kt} The total capacity of the biorefinery center "k" during period "t"

pp^{12}_{kt} The quantity of glycerin sent from the biorefinery center "k" to the customer during period "t"

pp^{13}_{it} The quantity of raw material for medicine sent from the oil collection and extraction centers "i" to the customer during period "t"

3.3. Objective functions and constraints

This section provides two objective functions of the proposed model. The first one minimizes the total expected costs including the fixed, variable, production, inventory, and transportation costs. The second objective function is minimizing the environmental impact. These two functions are presented as (1) and (2) respectively.

- **The total cost objective function**

$$\min z_1 = \sum_j FC^1_j \times u^1_j + \sum_n FC^2_n \times u^2_n + \sum_o FC^3_o \times u^3_o + \sum_m FC^4_m \times u^4_m + \sum_i FC^5_i \times u^5_i + \sum_p FC^6_p \times u^6_p + \sum_k FC^7_k \times u^7_k + \sum_j VC^1_j \times v^1_j + \sum_n VC^2_n \times v^2_n +$$
$$\sum_o VC^3_o \times v^3_o + \sum_m \sum_t VC^4_{mt} \times v^4_{mt} + \sum_i \sum_t VC^5_{it} \times v^5_{it} + \sum_p \sum_t VC^6_{pt} \times v^6_{pt} +$$
$$\sum_k \sum_t VC^7_{kt} \times V^7_{kt} + \sum_j \sum_t PC^1_{jt} \times P^1_{jt} + \sum_n \sum_t PC^2_{nt} \times P^2_{nt} + \sum_o \sum_t PC^3_{ot} \times P^3_{ot} + \sum_m \sum_t PC^4_{mt} \times P^4_{mt} + \sum_m \sum_t CCO2_{mt} \times CO2_{mt} +$$
$$\sum_w \sum_t PC^5_{wt} \times RO_{wt} + \sum_i \sum_t PC^6_{it} \times P^6_{pt} + \sum_i \sum_t PC^7_{it} \times P^7_{it} + \sum_i \sum_t PC^8_{it} \times P^8_{it} + \sum_i \sum_t PC^9_{it} \times P^9_{it} +$$
$$\sum_p \sum_t PC^{10}_{pt} \times P^{10}_{pt} + \sum_k \sum_t PC^{11}_{kt} \times P^{11}_{kt} + \sum_k \sum_t PC^{12}_{kt} * P^{12}_{kt} + \sum_i \sum_t PC^{13}_{it} * P^{13}_{it} + \sum_i \sum_t PC^{14}_{it} \times P^{14}_{it} + \sum_k \sum_t IC^6_{kt} \times I^6_{kt} +$$
$$\sum_j \sum_i \sum_t TC^1_{jit} \times T^1_{jit} + \sum_k \sum_t cpp^{11}_{kt} \times pp^{11}_{kt} + \sum_k \sum_t cpp^{12}_{kt} \times pp^{12}_{kt} + \sum_n \sum_i \sum_t TC^2_{nit} \times T^2_{nit} +$$
$$\sum_o \sum_i \sum_t TC^3_{oit} \times T^3_{oit} + \sum_m \sum_i \sum_t TC^4_{mit} \times T^4_{mit} + \sum_w \sum_p \sum_t TC^5_{wpt} \times T^5_{wpt} +$$
$$\sum_i \sum_k \sum_t TC^6_{ikt} \times T^6_{ikt} + \sum_p \sum_k \sum_t TC^7_{pkt} \times T^7_{pkt} + \sum_k \sum_b \sum_t TC^8_{kbt} \times T^8_{kbt} + \sum_i \sum_t \sum_\eta TC^9_{it} \times T^9_{\eta it} \quad (1)$$

- **Environmental impact objective function**

$$Minz_2 = \sum_i \sum_t \alpha_1 P^6_{it} + \sum_i \sum_t \alpha_{12} P^7_{it} + \sum_i \sum_t \alpha_3 P^8_{it} + \sum_i \sum_t \alpha_4 P^9_{it}$$
$$+ \sum_i \sum_t \alpha_5 P^{13}_{it} + \sum_p \sum_t \rho_1 P^{10}_{pt} + \sum_w \sum_t \rho_2 RO_{wt} + \sum_k \sum_t \rho_3 P^{11}_{kt}$$

$$+\sum_{k}\sum_{t}\rho_4 P_{kt}^{12} + \sum_{i}\sum_{t}\beta P_{it}^{14} \quad (2)$$

3.4. Constraints

All of the constraints used in this research are shown as follows.

$$\sum_k T_{kbt}^{8} = D_{bt}^{1} \quad \forall b,t \quad (3)$$

$$\sum_k P_{kt}^{12} = D_t^{2} \quad \forall t \quad (4)$$

$$\sum_i P_{it}^{13} = D_t^{3} \quad \forall t \quad (5)$$

$$\sum_i T_{jit}^{1} = P_{jt}^{1} \quad \forall j,t \quad (6)$$

$$\sum_i T_{nit}^{2} = P_{nt}^{2} \quad \forall n,t \quad (7)$$

$$\sum_i T_{oit}^{3} = P_{ot}^{3} \quad \forall o,t \quad (8)$$

$$\sum_i T_{mit}^{4} = P_{mt}^{4} \quad \forall m,t \quad (9)$$

$$\sum_p T_{wpt}^{5} \le RO_{wt} \quad \forall w,t \quad (10)$$

$$P_{jt}^{1} \le \mu_{jt}^{1} \times V_j^{1} \quad \forall j,t \quad (11)$$

$$P_{nt}^{2} \le \mu_{nt}^{2} \times V_n^{2} \quad \forall n,t \quad (12)$$

$$P_{ot}^{3} \le \mu_{ot}^{3} \times V_o^{3} \quad \forall o,t \quad (13)$$

$$P_{mt}^{4} \le \mu_{mt}^{4} \times V_{mt}^{4} \quad \forall m,t \quad (14)$$

$$CO2_{mt} = 2 * P_{mt}^{4} \quad \forall m,t \quad (15)$$

$$P_{it}^{6} = \alpha^1 \sum_j T_{jit}^{1} \quad \forall i,t \quad (16)$$

$$P_{it}^{7} = \alpha^2 \sum_n T_{nit}^{2} \quad \forall i,t \quad (17)$$

$$P_{it}^{8} = \alpha^3 \sum_o T_{oit}^{3} \quad \forall i,t \quad (18)$$

$$P_{it}^{9} = \alpha^4 \sum_m T_{mit}^{4} \quad \forall i,t \quad (19)$$

$$P_{pt}^{10} = \alpha^5 \sum_w T_{wpt}^{5} \quad \forall p,t \quad (20)$$

$$P_{kt}^{11} = \beta.\sum_i T_{ikt}^{6} + \omega.\sum_p T_{pkt}^{7} \quad \forall k,t \quad (21)$$

$$P_{kt}^{12} = (1-\beta).\sum_i T_{ikt}^{6} + (1-\omega).\sum_p T_{pkt}^{7} \quad \forall k,t \quad (22)$$

$$P_{it}^{13} = \rho^1 \sum_j T_{jit}^{1} + \rho^2 \sum_n T_{nit}^{2} + \rho^3 \sum_o T_{oit}^{3} + \rho^4 \sum_m T_{mit}^{4} \quad \forall i,t \quad (23)$$

$$P_{it}^{14} = \left(1-\alpha^1-\rho^1\right) \sum_j T_{jit}^{1} + \left(1-\alpha^2-\rho^2\right) \sum_n T_{nit}^{2}$$

$$+\left(1-\alpha^3-\rho^3\right) \sum_o T_{oit}^{3} + \left(1-\alpha^4-\rho^4\right) \sum_m T_{mit}^{4} \quad \forall i,t \quad (24)$$

$$P_{pt}^{10} = \sum_k T_{pkt}^{7} \quad \forall p,t \quad (25)$$

$$I_{kt}^{6} = I_{k,t-1}^{6} + P_{kt}^{11} - \sum_b T_{kbt}^{8} \quad \forall k,t \quad (26)$$

$$P_{it}^{14} = \sum_\eta T_{i\eta t}^{9} \quad \forall i,t \quad (27)$$

$$LF_j^1 u_j^1 \le V_j^{1} \le UF_j^1 u_j^1 \quad \forall j \quad (28)$$

$$LF_n^2 u_n^2 \le V_n^{2} \le UF_n^2 u_n^2 \quad \forall \mathrm{n} \quad (29)$$

$$LF_o^3 u_o^3 \le V_o^{3} \le UF_o^3 u_o^3 \quad \forall \mathrm{o} \quad (30)$$

$$LF_m^4 u_m^4 \le V_{mt}^{4} \le UF_m^4 u_m^4 \quad \forall m,t \quad (31)$$

$$LC_i^1 u_i^5 \le V_{it}^{5} \le UC_i^1 u_i^5 \quad \forall i,t \quad (32)$$

$$LC_p^2 u_p^6 \le V_{pt}^{6} \le UC_p^2 u_p^6 \quad \forall p,t \quad (33)$$

$$LC_k^3 u_k^7 \le V_{kt}^{7} \le UC_k^3 u_k^7 \quad \forall k,t \quad (34)$$

$$\sum_j T_{jit}^{1} + \sum_n T_{nit}^{2} + \sum_o T_{oit}^{3} + \sum_m T_{mit}^{4} \le V_{it}^{5} \quad \forall i,t \quad (35)$$

$$\sum_w T_{wpt}^{5} \le V_{pt}^{6} \quad \forall p,t \quad (36)$$

$$\sum_i T_{ikt}^{6} + \sum_p T_{pkt}^{7} \le V_{kt}^{7} \quad \forall k,t \quad (37)$$

$$P_{it}^{6} + P_{it}^{7} + P_{it}^{8} + P_{it}^{9} \le V_{it}^{5} \quad \forall i,t \quad (38)$$

$$P_{pt}^{10} \le V_{pt}^{6} \quad \forall p,t \quad (39)$$

$$I_{kt}^{6} \le MaxI^{6} \quad \forall k,t \quad (40)$$

$$\sum_j u_j^1 \le Maxu^1 \quad (41)$$

$$\sum_n u_n^2 \le Maxu^2 \quad (42)$$

$$\sum_o u_o^3 \le Maxu^3 \quad (43)$$

$$\sum_m u_m^4 \le Maxu^4 \quad (44)$$

$$\sum_{i} u_i^5 \leq Maxu^5 \qquad (45)$$

$$\sum_{p} u_p^6 \leq Maxu^6 \qquad (46)$$

$$\sum_{k} u_k^7 \leq Maxu^7 \qquad (47)$$

$$\sum_{i} T_{ikt}^6 = P_{it}^6 + P_{it}^7 + P_{it}^8 + P_{it}^9 \qquad \forall t \qquad (48)$$

$$P_{kt}^{12} \leq V_{kt}^7 \qquad \forall k, t \qquad (49)$$

$$All\ of\ the\ continuous\ decision\ variables \geq 0 \qquad (50)$$

$$u_j^1, u_n^2, u_o^3, u_m^4, u_i^6, u_p^6, u_k^7 \in \{0,1\} \qquad (51)$$

Equations (1) and (2) shows two objective functions including minimizing total expected costs and the environmental impacts, respectively. Constraint sets (3), (4), and (5) respectively indicate that all demands of the biodiesel, glycerin, and raw material are met during different periods. Based on Constraint (6), all of the Jatropha seeds produced at the Jatropha cultivation center are transferred to the collection and oil extraction center. Constraint (7) ensures that all of the Norouzak seeds produced at the Norouzak cultivation center are transferred to the collection and oil extraction center. Constraint (8) ensures that all of the Oleander seeds produced at the Oleander cultivation center are transferred to the collection and oil extraction center. As the constraint (9) guarantees, all the algae produced at the algae cultivation center are transferred to the collection and oil extraction center. Constraint (10) says that all of the WCO produced at the supply center is transferred to the WCO collection and pre-refining center. The amount of Jatropha seeds produced in the cultivation region, Norouzak seeds in the cultivation region, Oleander seeds in the cultivation region, and algae in the cultivation region are calculated according to relations (11) to (14) respectively based on their productivity.

Equation (15) calculates the amount of CO_2 consumed at the algae cultivation center. This equation has been defined based on the result of Lin et al. [24] who concluded that two tons of CO_2 are required to produce one ton of biomass. The amount of Jatropha oil produced at the oil extraction center, Norouzak oil at the oil extraction center, Oleander oil at the oil extraction center, algae oil at the oil extraction center, WCO at the collection and pre-refining center, biodiesel in the biorefinery "k", glycerin in the biorefinery "k", raw material in the oil collection and extraction center, and fertilizer in the oil collection and extraction center are determined according to relations (16) to (24) respectively based on their productivity.

Constraint (25) imposes that all of the pre-refined oil produced in the collection and pre-refining center is transferred to the biorefinery center. The inventory level of biodiesel in the biorefinery for each period is calculated as constraint (26). According to constraint (27), all of the fertilizer produced in the oil collection and extraction center is transferred to the planting centers. The allocated area for cultivating Jatropha, cultivating Norouzak, cultivating Oleander, and cultivating algae are determined by the relations (28) to (31) respectively between the minimum and maximum available land.

Constraint sets (32) to (34) determine the total capacity of the oil collection and extraction center, the WCO collection and pre-refining center, and the biorefinery center respectively between the given lower and upper bounds.

The compliance of the amount of transportation of materials with the capacity of oil extraction, pre-refining, and biorefinery centers is controlled by constraint sets (35) to (37) respectively. In addition, constraint (38) represents that the total amount of Jatropha, Norouzak, Oleander, and algae oils should be at maximum equal to the total capacity of the oil collection and extraction center. Similarly, constraint (39) shows that the amount of pre-refined oil produced in the WCO collection and pre-refining center is at maximum equal to its total capacity. The inventory level of biodiesel in the biorefinery center is controlled by constraint (40).

The maximum number of establishment centers for planting Jatropha, Norouzak, Oleander, and algae is controlled by constraint sets (41) to (44) respectively. Similarly, the maximum number of establishment centers for oil collection and extraction, WCO collection and pre-refining, and biorefinery is controlled by constraint sets (45) to (47) respectively.

Based on constraint (48), the amount of oil sent from the oil extraction to the biorefinery center equals the production values of Jatropha, Norouzak, Oleander, and algae oils. Constraint (49) shows that the amount of glycerin produced in the biorefinery center should be at maximum equal to its total capacity. Finally, constraints (50) and (51) represent the types of decision variables.

4. Solving approach

The problem at hand in this study is a bi-objective optimization problem and therefore, we use the following two approaches to implement the proposed model based on the data of a real case study.

4.1. Weighted Sum Method

Since the introducing of multi-objective optimization problems, various approaches have been proposed to solve them. The weighted Sum Method, also called Weighted Linear Combination (WLC) or Simple Additive Weighting (SAW), is the best known and simplest method for solving the optimization problem with more than one objective function.

Suppose that, we deal with a general multi-objective optimization problem as follows:

Minimize $F(x) = [F_1(x), F_2(x), ..., F_k(x)]$

Subject to: $g_j(x) \leq 0; j = 1, 2, ..., m$

Where k is the number of objective functions and m is the number of inequality constraints.

This approach integrates all objective functions into a unified scalar by creating a composite objective function through a weighted sum, as outlined in the subsequent equation (52):

$$F(x) = w_1 F_1(x) + w_1 F_2(x) + ... + w_k F_k(x) \quad (52)$$

A critical aspect in the Weighted Sum Method (WSM) lies in determining the vector of weighting coefficients $(w_1, ..., w_n)$ as the optimal solution significantly relies on the specific weighting coefficients selected. Furthermore, these coefficients must be positive and adhere to the equation (53).

$$\sum_{i=1} w_i = 1 \quad w_i \in (0,1) \quad (53)$$

In the first approach, we focus on the WSM to solve the considered bi-objective model. In addition, in the formation of the objective function, in order for the functions to be aggregate, we descale them. In other words, the objective functions are normalized by divided by their respective maxima, then it becomes easy to set the weights such that they are significant relative to each other and relative to the objective functions values. With the objective functions normalized, both of them are in the range between zero and one.

4.2. Epsilon-constraint method

Epsilon-constraint, the so-called ε-constraint is another well-known exact method for solving the multi-objective optimization problems. In this method, one objective function is selected as the primary one and the remaining ones are converted into constraints considering an upper limit, turning the problem into a single-objective linear programming model, which is then solved employing conventional linear programming methods. The applicability of the above-mentioned method to non-convex solution spaces is regarded as its main advantage over other ones for multi-objective optimization because methods such as weighted sum approaches lose their effectiveness in such spaces. Computation time is considered as a critical feature of any algorithm for evaluation. Using metaheuristic algorithms reduces the computation time significantly since high amount of such time is among the main weaknesses of exact search-based algorithms including the epsilon-constraint method. Pirouz and Khorram [25] proposed a framework which is among the modified versions of the epsilon-constraint method. Based on the above-mentioned method, the single-objective optimization problem is solved for each objective, followed by determining the step size. Then, a set of feasible points is generated, as well as solving the single-objective optimization and estimating the Pareto frontier. The aforementioned method focuses on optimizing one of the objectives, while defining the highest acceptable limit for the other objectives within the constraints. Equation (54) indicates the following mathematical representation for a two-objective problem.

$$\min f_1(x)$$
$$s.t$$
$$f_2(x) \le \varepsilon_2$$
$$x \in s \quad (54)$$

The Pareto edge of the problem is achieved by altering the values on the right side of the new constraints of ε.

5. Case study

The Renewable Energy and Electricity Efficiency Organization was established to improve energy efficiency and increase the use of renewable and clean resources by providing the necessary infrastructure in Iran. Additionally, the above-mentioned organization aims to increase efficiency, ensure energy supply, reduce energy losses in transmission, distribution, and consumption in the country, and utilize renewable and clean electricity generation methods. As evidenced in research, the bioenergy production should be developed from biomass sources to identify methods to access various resources in resource-rich regions of Iran, as well as determining different technologies and technical and operational requirements. For instance, Hamzeh et al. [26] highlighted biomass-derived energy and divided biomass into three main categories including: agricultural residues, animal waste, and municipal solid waste. They emphasized that energy is essential for the economic and social development and improved quality of life in Iran as in other countries. Afterwards, Assadi et al. [27] investigated prioritization of renewable energy resources based on sustainable management approach using simultaneous evaluation of criteria and alternatives. They addressed a case study on Iran's electricity industry and proposed an efficient method for the optimal selection of renewable energy resources to improve the efficiency and effectiveness of sustainable decisions on energy resource planning.

Accordingly, a case study is conducted in this section using information of the Renewable Energy and Energy Efficiency Organization in Iran and two abovementioned references. In this way, Table 2 shows the values of indices and parameters of the considered case study.

The developed model was utilized to solve the real example explained in the abovementioned valid references to investigate its feasibility and analyze the results related to the main variables through the considered parameters. Table 2 details the supplementary data of the considered case study.

{Please insert Table 2 about here.}

6. Results

The proposed model was coded in GAMS and the CPLEX solver is used to find the exact solutions. All experiments are executed on a Pc with a 2.0GHz Intel Core 2 Duo processor and 4GB of RAM. Table 3 represents the results related to the values of P_{kt}^{12} ,, which correspond to the I_{kt}^{6} and, P_{kt}^{11} glycerin production, biodiesel production, and inventory value of biodiesel in the biorefinery "k" during period "t", respectively.

{Please insert Table 3 about here.}

As is evident in Table 3, biodiesel is produced more than glycerin during both time periods although a significant portion always remains as inventory for subsequent periods. For instance, 61777.477 tons of biodiesel is produced at the biorefinery during the first period, out of which 8940 tons are consumed and 52837.477 tons remain as inventory for consumption during the second period. Therefore, a total of 75593.324 tons of biodiesel are produced during the second period with the production of 22755.847 tons of biodiesel (which is regarded as the sum of the remainder from the first period, equal to 52837.477 tons).

Table 4 shows the value of T_{kbt}^{8} , which represents the transportation of biodiesel from biorefinery center "k" to consumption center "b" during period "t".

{Please insert Table 4 about here.}

As perceived, the frequency of transportation between the biorefinery and consumption centers during the second programming period is consistently higher than during the first period. The highest amount of transportation is related to the movement between the refinery and the second consumption center during the second programming period, while the lowest amount is observed in the transportation between the refinery and the first consumption center during the first period. As indicated in Table 5, V_{mt}^{4} , P_{mt}^{4} , and CO_{2mt} represents the amount of algae cultivated, algae produced, and CO_2 consumed at the algae cultivation center in location "m" during period "t", respectively.

{Please insert Table 5 about here.}

As perceived, algae is cultivated only during the first period in both cultivation centers, and the amount of algae cultivation in both centers is zero during the second period. Additionally, the highest algae production is related to the first cultivation center, which occurs during the first programming period. The lowest amount of algae is produced in the first cultivation center during the second period because the highest production occurs in such center during the first period. Based on the production level obtained at the first cultivation center, the CO_2 consumption is higher. Thus, the highest and lowest CO_2 consumption occurs in the first cultivation center during the first and second period, respectively. As shown in Tables 6 and 7, P_{jt}^{1} and T_{jit}^{1} represent the quantity of Jatropha produced in cultivation center "j" and its quantity transported from cultivation center "j" to oil extraction center "i" during time period "t", respectively.

{Please insert Table 6 about here.}
{Please insert Table 7 about here.}

As observed, no value is considered for Jatropha production during the first period based on the calculated amount. A quantity of 411.143 tons of Jatropha is produced only during the second period. Therefore, Jatropha is transported based on its production quantity during the second period. As presented in Table 8, T_{mit}^{4} indicates the quantity of algae transported from cultivation center "m" to oil extraction center "i" during time period "t". The quantity of transported algae is estimated based on the its production quantity at cultivation center "m" during time period "t", which is represented by P_{mt}^{4} .

{Please insert Table 8 about here.}

Table 8 indicates the amount of produced algae transported from cultivation centers. As perceived, algae are transported to the same extent as its production. As shown in Table 9, P_{it}^{6} , P_{it}^{9} , P_{it}^{10} , P_{it}^{13} , and P_{it}^{14} represent the amount of Jatropha oil, algae oil , pre-refined WCO, raw materials for medicine, and fertilizer produced at oil extraction center "i" during period "t", respectively.

{Please insert Table 9 about here.}

Table 10 represents the amount of WCO transported from the supply center "w" to the pre-refining center for the time period "t" considering that the process occurs in two stages. Table 11 presents the amount of WCO transported from the pre-refining center to the biorefinery for different time periods. It is worth noting that the same amount of WCO produced during the time periods is directly transferred to the biorefinery.

{Please insert Table 10 about here.}
{Please insert Table 11 about here.}

As indicated in Table 12, T_{ikt}^{6} represents the amount of Jatropha, Norouzak, Oleander, and algae oils transported from the extraction center "i" to the biorefinery "k" during period "t". As observed, the highest amount of transportation occurs during the second period.

{Please insert Table 12 about here.}

Finally, the total capacity of the oil collection and extraction center "i" is estimated as 5000 units for each period during the first and second time periods. Considering all of the aforementioned factors, the optimal objective function value and cost equals 113521×10^{4} within a time period of 35 seconds.

Table 13 demonstrates computational time of problem solving in different scales. In this way, the problem has been solved in five different values of input parameters. As is evident, as the problem scale increases, the computational time increases dramatically. This result shows the complexity of the problem at hand, which is consistent with the literature.

{Please insert Table 13 about here.}

Finally, Figure 2 demonstrates the Pareto solutions found through the epsilon-constraint method on the test case. For ease of visualization, the horizontal axis is adjusted. The optimality gap in this study is zero due to the model is linear and GAMS can solve it exactly. Nonetheless, the test case was solved with computational time of 3600 seconds. The figure 2 indicates conflicting between two considered objective functions as it is clear that improving of the value of each objective function leads to the worsening of the value of the other objective function. This result provides proper options for choosing by the relevant managers.

{Please insert Figure 2 about here.}

7. Sensitivity analysis

In this section, by changing some of the most important parameters, we examine its effects on objective functions. For this purpose, the fixed and variable costs of planting Jatropha, Norouzak, Olean and Alage and the storage capacity in the fields have been considered. First, for this purpose, we increase the amount of fixed and variable costs for planting biomass crops separately by 10 to 30% and then decrease it to check its effect on the objective function. Table 14 shows the changes of increase and decrease of fixed cost on the value of the objective function. Based on the obtained results, the change on the fixed costs of Olean has the greatest effect and the change on the fixed costs of Jatropha has the least effect.

{Please insert Table 14 about here.}

Also, Table 15 shows the changes of increase and decrease of variable cost on the value of the objective function. Based on the obtained results, the change on Alage variable costs has the greatest impact and the change on Olean variable costs has the least impact.

{Please insert Table 15 about here.}

According to the results obtained in tables 14 and 15, changes on fixed costs have more effects on the objective function than variable costs.

In addition, the extent to which alterations in the influential parameter affect the value of the objective function is studied. To this aim, the maximum capacity of oil collection and extraction centers is reviewed. Applying alterations to the capacity of the aforementioned centers affects the related costs. This section discusses a scenario where the capacity of each center increases or decreases by 100 units. Table 16 presents the capacities of the fields while adding and subtracting 100 units.

{Please insert Table 16 about here.}

In the following, some sensitivity analyses are applied considering two main parameters including the capacity of centers and demand to explore the changes in the values of the objective functions based on changes of the parameters. The analyses are undertaken for the considered case study.

Figure 3 demonstrate changes of the non-dominating solutions based on changes in capacity of centers. The changes in the capacity of facilities are considered in the range of -25%, -10%, 0%, +10%, and +25%. According to the result, it can be said that the increase in the capacity of the centers, which collect, pre-refine, refine, and bio-refine materials, leads to an decrease both in the total cost and environmental impact, and vice versa, a decrease in the capacity of the centers leads to increase in the two objective functions value. However, the largest changes in the Pareto front are observed when the capacity is reduced by 25% of the initial value.

Similarly, Figure 4 represents changes of the non-dominating solutions based on changes in demand. As is evident, the increase in demand leads to increase bot in the total cost and environmental impact, and vice versa, a decrease in demand leads to increase in the two objective functions value. However, the largest changes in the Pareto front are observed when demand decreases or increases by 25% of the initial amount.

In addition, it can be concluded from the result that, the value of the second objective function has not changed significantly with the change in the capacity of centers and demand.

{Please insert Figure 3 about here.}
{Please insert Figure 4 about here.}

8. Conclusion and future works

Biomass supply chain deployment provides sustainable solution for the problems such as energy security, food crisis, rural development, and environmental issues. In this paper, motivated from shortcomings in the literature, an integrated approach based on mathematical programming was developed for designing biomass supply chain network considering the variety of input materials in an efficient way. In the proposed model, real-world assumptions such as variable cultivation, capacity limitation, and input material diversity are considered which led to an application model. The proposed mathematical model, which employs a multi-echelon and multi-product network, can be used as an instrument to improve the efficiency of the supply chain network in order to increase biomass sustainability. Utilizing the multi-echelon and multi-product mathematical model, which accurately and comprehensively assesses all of the factors affecting the supply chain, can improve network efficiency and increase sustainability. In addition, applying such model can reduce the costs and mitigate negative environmental impacts.

The problem at hand was formulated as a bi-objective mixed-integer linear mathematical model for implementation in a multi-echelon and multi-product biomass supply chain. The most significant values which can be calculated using the proposed model include identifying optimal production quantities of glycerin, biodiesel, Jatropha, algae, and WCO in biorefineries, as well as determining optimal quantities of Jatropha and algae oil production. The model can also recognize required amount of raw material for drug production in extraction centers. In addition, predefined the capacity for collection and extraction centers, the costs related to the use of CO2 capture, transfer, and storage technology, as well as the transportation cost through transmission lines to storage sites and its secure storage are regarded in the proposed model.

The proposed integrated approach was implemented to solve an instance using data of a real case in Iran for two periods planning horizon. In addition, some sensitivity analyses were provided considering changes in the key parameters. The result provides a set of solutions as options for decision makers. Another important conclusion of this study is that in biomass supply chain, all echelons from feedstock centers to customer centers should be considered and evaluated under multi-period condition to prevent unnecessary high costs and suboptimal solutions. The acquired results illustrate the usefulness and efficiency of the proposed model in helping policymakers to take suitable strategic and tactical level decisions related to biodiesel supply chain management.

As with any research, this study suffers from limitations. First, the parameters assigned to the proposed model were considered to be deterministic and fixed. However, in the real-world condition, most of the parameters have a nature of uncertainty. Therefore, investigating the problem under uncertainty in key parameters, especially the amount of demand and costs, can be an interesting topic for future studies. Second, this study ignored social objectives such as job creation. Therefore, developing the proposed model in this study by adding proper social objectives can be another important topic for the future efforts. Finally, using other exact methods such as lagrangian and benders decomposition approaches for small- and medium-scaled instances as well as metaheuristics algorithms such as evolutionary for solving the problem in large scales be other interesting topics for future research.

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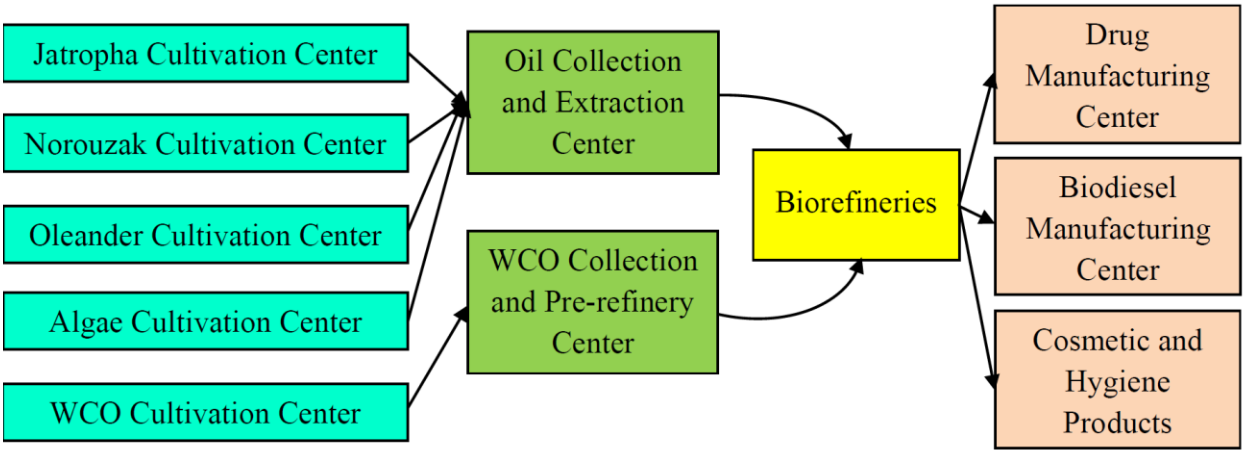

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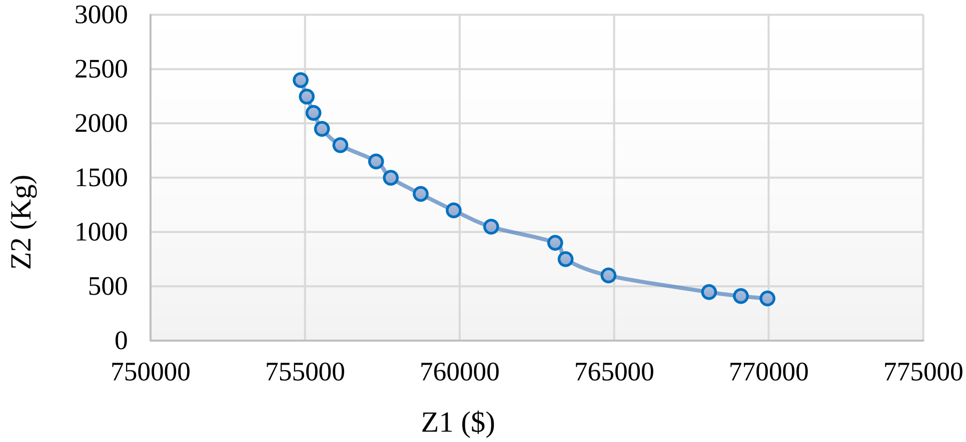

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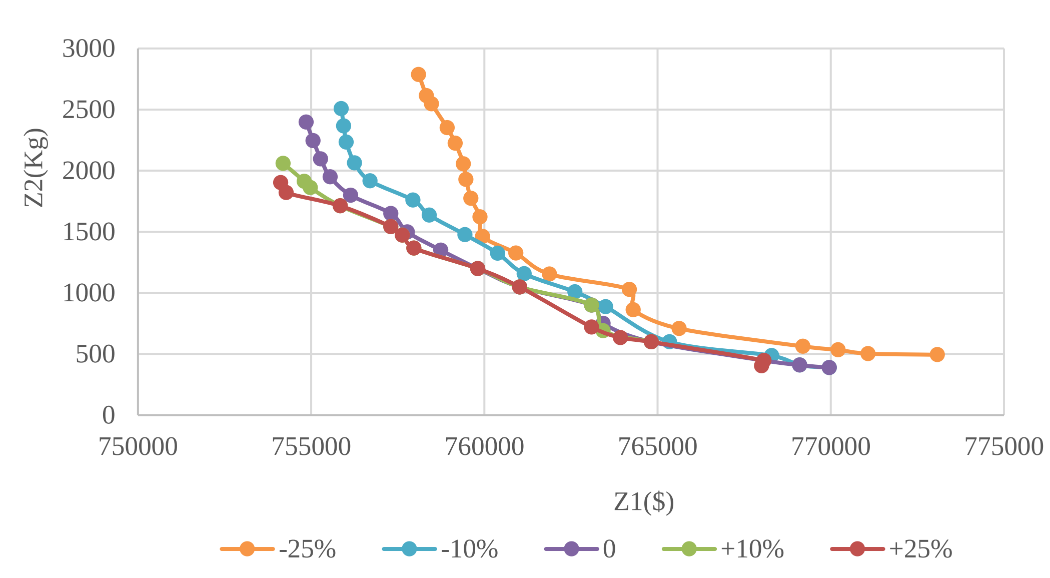

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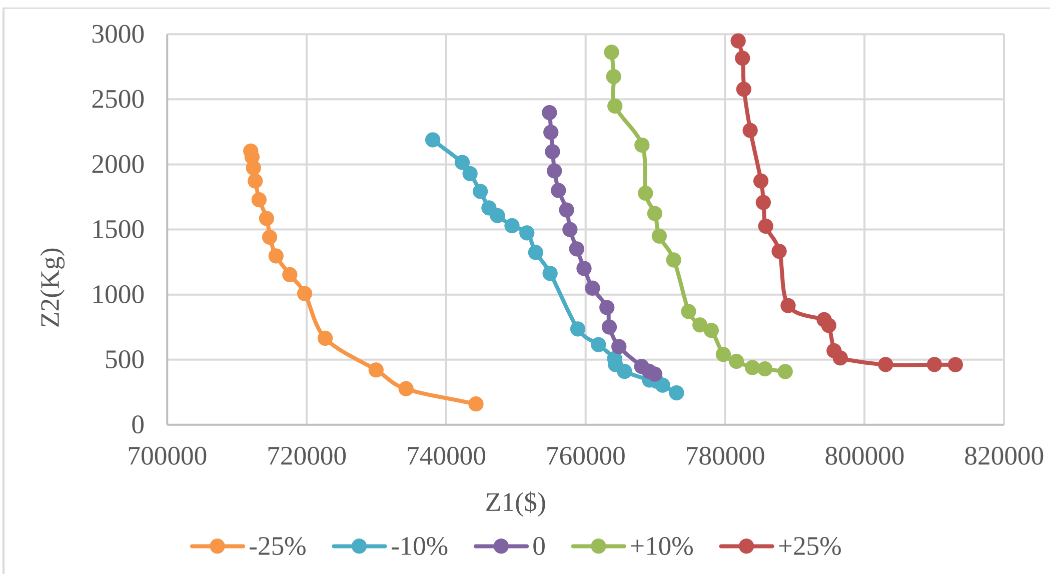

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Table 1. Previous studies on biomass supply chain network

Author	Problem features						Input materials	Product	Objective functions					Solution approach	
	#layers	Multi-product	Multi-period	Diversity of input cases	Product diversity	Uncertainty			Profit	Cost	Pollutant emission	Energy Consumptio	Social	Approximate	Exact
Hosseinalizadeh et al. [11]	One		*	*			Waste oil, Soy, Sunflower, and Canola	Biodiesel product			*	*			$\epsilon - constraint$
Delkhosh and Sadjadi [1]	Two			*	*	*	Gases and sewage	Microalgae		*					Robust
Mahjoub et al. [13]	Two			*			Jatropha, Agricultural waste, and Animal manure	Microalgae		*		*			$\epsilon - constraint$
Rezaei et al. [14]	One			*		*	Norouzakand Jatropha	Biodiesel product		*	*		*	NSGA-II	
Puratich et al. [10]	Two		*				Agricultural waste	Recycling system		*					Weighted sum method

Ahmadvand and Sowlati [17]	One					*	Forest waste	Syngas		*		*			$\epsilon - constraint$
Khadivi [18]	One		*		*	*	Paper pulp	Syngas & natural gas		*	*				$\epsilon - constraint$
Shevchenko et al. [19]	One		*	*			Penicillium verrucosum enzymes	Kraft pulp		*		*			$\epsilon - constraint$
Sani et al. [20]	One	*					Municipal solid waste	Energy production	*						Robust
Chen and Liu [22]	One		*				wastage	Electricity generation		*	*				$\epsilon - constraint$
Yıldız et al. [23]	Two	*					Plant remains	Electricity generation		*	*				$\epsilon - constraint$
This study	Four	*	*	*	*		Norouzak, Jatropha, Oleander , Microalgae, and WCO	Biodiesel fuel, Raw materials for medicine and cosmetic and hygiene products		*	*				$\epsilon - constraint$

Table 2. Predetermined parameters

Value	Symbol	Index
2	j	Index related to candidate locations for Jatropha cultivation centers
2	n	Index related to candidate locations for Norouzak cultivation centers
3	o	Index related to candidate locations for Oleander cultivation centers
1,…,4	m	Index related to candidate locations for algae cultivation centers
1 and 2	w	Index related to candidate locations for WCO supply centers
1	i	Index related to candidate locations for Jatropha, Oleander , Norouzak, and algae collection and oil extraction centers
1	p	Index related to candidate locations for WCO collection and pre-refining centers
1	k	Index related to candidate locations for biorefineries
1 and 2	b	Diesel refineries index
1 and 2	t	Time period index

Table 3. Values of variables P_{kt}^{12}, I_{kt}^{6} and P_{kt}^{11}

Variable	Location $k = 1$	Time period	
		First	Second
P_{kt}^{12}	First biorefinery	10960	13410
P_{kt}^{11}	First biorefinery	61777.477	75593.324
I_{kt}^{6}	First biorefinery	52837.477	117510.801

Table 4. Value of T^{8}_{kbt}

From \ To	First period		Second period	
	Consumption center 1	Consumption center 2	Consumption center 1	Consumption center 2
Biorefinery center	4360	4580	5320	5600

Table 5. Values of variables V^{4}_{mt}, P^{4}_{mt} and CO_{2mt}

Variable	Cultivation centers	Time period	
		First	Second
V^{4}_{mt}	$k=1$	50000	0
	$k=2$	50000	0
P^{4}_{mt}	$k=1$	1567.568	630
	$k=2$	0	900
CO_{2mt}	$k=1$	3135.135	1260
	$k=2$	0	1800

Table 6. Amount of Jatropha produced during two time periods

Jatropha cultivation center	First period	Second period
$j=1$	0	411.143
$j=2$	58.698	102.369

Table 7. Amount of Jatropha transported during each time period

From \ To	Oil extraction center $i=1$	
	First period	Second period
First cultivation center $j=1$	0	411.143
Second cultivation center $j=2$	60.478	120.258

Table 8. Amount of algae transported during the time period "t"

From \ To	Oil extraction center $i=1$	
	First period	Second period
First cultivation center $m=1$	1567.568	630
Second cultivation center $m=2$	0	900
Third cultivation center $m=3$	452	0
Fourth cultivation center $m=4$	900.254	125

Table 9. Values of $P_{it}^{6}, P_{it}^{9}, P_{it}^{10}, P_{it}^{13}$ and P_{it}^{14}

Variable	Location $i=1$	Time period	
		First	Second
P_{it}^{6}	Oil extraction center	0	226.129
P_{it}^{9}	Oil extraction center	987.568	963.900
P_{it}^{10}	Oil extraction center	71749.910	87813.295
P_{it}^{13}	Oil extraction center	580	710
P_{it}^{14}	Oil extraction center	0	41.114

Table 10. Amount of WCO transported from the supply center "w" to the pre-refining center during the period "t"

From \ To	Pre-refining center $p=1$	
	First period	Second period
First supply center $w=1$	333900	311600
Second supply center $w=2$	24849.550	127466.476

Table 11. Amount of WCO transported from the pre-refining center "p" to the biorefinery "k" during the period "t"

From \ To	Biorefinery $i=1$	
	First period	Second period
First pre-refining center $p=1$	71749.910	87813.295

Table 12. Value of T_{ikt}^{6}

To / From	Biorefinery $i = 1$	
	First period	Second period
Oil extraction center $i = 1$	987.568	1190.029

Table 13. Problem parameters in larger scales

Sample	Input values										Value of objective function (× 10^4)	Computation time (second)
	j	n	o	m	w	i	p	k	b	t		
1	2	2	2	3	3	2	2	2	3	3	213256	128
2	2	2	3	4	4	3	2	2	3	3	324689	359
3	2	2	3	4	4	4	3	3	4	3	389657	556
4	3	3	2	3	3	3	4	4	3	3	412569	602
5	3	3	3	4	4	5	3	3	3	3	425698	613

Table 14. The effect of fixed cost changes on the objective function

Product / Changing	Jatropha	Norouzak	Olean	Alage
10%	10520×10^{14}	11621×10^{14}	12521×10^{14}	11369×10^{14}
20%	11452×10^{14}	12369×10^{14}	13469×10^{14}	12478×10^{14}
30%	13672×10^{14}	13478×10^{14}	14369×10^{14}	13258×10^{14}
-10%	9568×10^{14}	10378×10^{14}	11368×10^{14}	10479×10^{14}
-20%	8456×10^{14}	9647×10^{14}	10478×10^{14}	9748×10^{14}
-30%	7258×10^{14}	8465×10^{14}	9639×10^{14}	7369×10^{14}

Table 15. The effect of variable cost changes on the objective function

Product / Changing	Jatropha	Norouzak	Olean	Alage
10%	9362×10^{14}	8457×10^{14}	7456×10^{14}	10326×10^{14}
20%	10325×10^{14}	9678×10^{14}	8456×10^{14}	11247×10^{14}
30%	11247×10^{14}	10325×10^{14}	9647×10^{14}	12364×10^{14}
-10%	6978×10^{14}	6325×10^{14}	6977×10^{14}	9647×10^{14}
-20%	5647×10^{14}	5478×10^{14}	5478×10^{14}	8479×10^{14}

-30%	3648×10^{14}	4452×10^{14}	3256×10^{14}	7412×10^{14}

Table 16. Capacity of fields by adding 100 units

Capacity of current centers $Cap_{current}+100$	
Value of objective function	12452×10^{14}
Capacity of current centers $Cap_{current}-100$	
Value of objective function	12452×10^{14}

Declarations

Conflict of interest: The authors declare that they have no conflict of interest.

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