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RESEARCH PAPER

Designing A Hybrid First/Second Generation Biofuel Supply Chain With Reliable Multimodal Transport: A Mathematical Model

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ABSTRACT
Biofuel production systems are identified as a potential solution to the ever-increasing energy consumption demand. The complexity of conversion process and supply chain of these systems, however, can make the commercialization of biofuels less attractive; therefore, designing and management of an efficient biofuel supply chain network can resolve this issue. Hence, this paper proposes a multi-period hybrid generation biomass-to-biofuel supply chain considering environmental, economic, and technological considerations. The objective is to maximize the total profit that biofuel producers can make with practical constraints including the biomass supply, the capacity of facilities, storage, Greenhouse Gas (GHG) emissions, and transportation with limited capacity. To highlight the applicability of the proposed model, it is applied to a biomass-derived liquid fuel supply system in the southern region of Iran. In the case study, wheat and wheat stem are simultaneously considered as the first- and second-generation feedstocks for biodiesel production. Sensitivity analyses show that the available biomasses can have a significant impact on the profitability of this supply chain. The obtained results demonstrate the efficiency and performance of the proposed model in biodiesel supply chain design.

KEYWORDS: *Biodiesel supply chain; Hybrid first and second generation; GHG emissions; Multimodal transport; Mathematical model.*

1. Introduction

At the early decade of the 1970s, when the world faced its first crisis of energy shortage, international concerns increased on energy security and climate change; therefore, in order to attain sustainable economy and environmental protection, attempts in developing new energy sources increased significantly [1]. Subsequently, in 1990, renewable energy sources such as biomass, aquaculture, heat energy, sun, waves, tides, and wind were introduced as alternatives to fossil fuels such as coal and crude oil [2]. Among these renewable energy resources, biofuels are produced from biomass feedstocks in different forms of liquid, solid, or gas. Biodiesel and bioethanol are the most commonly used liquid biofuels that have been known to be a good substitution for fossil diesel and gasoline, respectively [3].

Nowadays, the production systems of first-generation biofuels such as food, sugars, starch, oil, and animal fats have been successfully commercialized worldwide [4]. These systems have received much attention in recent years as they can prevent the reduction of fossil fuel reserves, avoid increasing oil prices, and provide clean and renewable energy sources. The major problem, however, for the commercialization of biofuels is the complexity of the conversion process and supply chain. Therefore, efficient design and management of a biofuel supply chain network can help improve the economic value for commercialization of biofuel technologies.

Exploring the relevant literature shows that most of biofuel supply chain models have been presented for the first-generation biofuel utilization. Mirhashemi, Mohseni et al. [5] proposed a Mixed-Integer Linear Programming (MILP) model to design a biodiesel supply chain based on Moringa oleifera, which is a fast-growing and drought-resistant tree. The proposed

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model aims to determine the optimal strategic and tactical supply chain decisions. Kostin et al. [6] developed an MILP model to design a sugar-based bioethanol supply chain aimed at simultaneously improving the economic and multiple environmental aspects. However, concerns about the food crisis, water, soil acidification, warming and environmental pollution, the need for new biomass types that can address a number of sustainability related issues have led to a shift in policy towards the second generation, which is related to non-food products or agricultural and forestry wastes, especially in developed countries [7]. Anderson et al. [8] presented a Biodiesel Supply Chain Network Design (BSCND) model using multi-stage MILP. The model examines the competition between sunflowers, soybeans, and Jatropha curcas L. (JCL) to produce biodiesel and optimizes the supply chain network structure and capacities. They considered that JCL represented an appropriate product that could be used instead of current edible energy crops for biodiesel production. Natarajan et al. [9] investigated the potential expansion of the second-generation biodiesel industry in Finland. They minimized the total cost of biodiesel supply chain ranging from biomass supply to biodiesel delivery to determine the number, optimal locations, capacity and configurations of biodiesel production plants. Since the first-generation bioethanol supply chains have already been present and the process of introducing the second-generation bioethanol is ongoing, there is a need to design a hybrid generation bioethanol supply chain to appropriately meet the future bioethanol demand. Some researchers have considered the combination of the first- and second-generation biomasses for biofuels production [10-14].

One of the reasons for low biofuel production is large investment costs and logistical challenges, including location, unit capacity, material flow, inventory level, pre-processing, transportation, production planning, and delivery. Therefore, designing an efficient biofuel supply chain plays a key role in improving the feasibility and competitiveness of biofuels against fossil fuels. The advent of new biofuel technologies has encouraged researchers to study biofuel supply chains leading to attempts such as developing mathematical models and optimization techniques, economic cost, and managing energy supply chains [15]. Gold and Seuring [16] comprehensively reviewed articles published from 2000 to 2009, which covered the interface of bio-energy production and issues of logistics and supply chain management. They classified issues and challenges of designing and operating biomass chains into two categories: 1) the operations harvesting and collection, storage, transport, and pre-treatment techniques; 2) the overall supply system design. Ekşioğlu, Acharya et al. [17] presented a model to minimize the inventory, processing costs, and biomass transportation during a period. They have also determined the numbers, locations, and capacities of the biorefineries. The model was applied in a case study located in Mississippi in the US. An et al. [18] presented a comprehensive review covering strategic, tactical, and operational levels in biofuel supply chains. They pointed out that the second-generation biofuel with non-edible food such as Jatropha is the good selection of first-generation biofuels with edible food. Papapostolou et al. [19] developed a BSCND model, and stated that decision-making on the type of biomass for biodiesel production, demand fulfilling, numbers and locations of facilities, and their corresponding capacities were related to strategic-level decision-making and had an important role in the success of biodiesel supply chain management. Nixon et al. [20] presented a goal programming model for optimizing location, size, amount of plants and materials processed for the supply chain of pyrolysis plants simultaneously based on stakeholders' requirements for electricity and bio-oil production in Punjab, India. Their model was developed as an extension of the research work by Li & Hu [21] so that a supply chain design problem based on a five-echelon single-product system was introduced. The problem considered the numbers, size, location of facilities, and the calculation of the flows between facilities.

To reduce the feedstock transportation cost, it has been suggested that biomass can be converted to bio-oil via fast pyrolysis near harvest sites, and then the bio-oil can be transported to an upgrading plant for the production of transportation fuels [22]. Hence, this paper presents a hybrid production pathway that consists of two parts: 1) Fast pyrolysis facility (i.e., bio-oil is produced by Biomass fast pyrolysis in relatively small processing plants); 2) Refining facility (i.e. bio-oil converted to transportation fuels). In this approach, biomasses converts to bio-oils in relatively small processing plants at distributed locations so that the transportation of bulky biomass over a long distance can be avoided. After mild hydrotreating, the bio-oil is then transported to a centralized gasification facility to produce transportation fuels. This pathway could also simplify syngas cleanup as ashes in biomass played a significant role in the gasification process [23].

Transportation features including transport modes such as trucks, railways, and ships, vehicle capacity and travel distance have a significant impact on shipping costs and supply chain costs [24]. Eriksson and Björheden [25] showed that optimizing the production of biofuels was mainly about the minimization of transportation costs. Searcy et al. [26] investigated the cost of biomass transportation materials by trucks, railways, and ships. Biomass transportation by rail was first investigated by Mahmudi and Flynn [27]. Ghani et al. [28] considered the choice of transportation mode as a tool for reducing GHG emissions. Olivares-Benitez et al. [29] investigated the selection of the transportation channels that are available between nodes in each echelon at different transportation costs and times. They assumed that a faster service is usually more expensive. According to the literature, the capacity of the transportation channel has been assumed to be unlimited, where any capacity can be contracted. In this study, the number and capacity of transportation are considered to be limited.

Recently, with the raising awareness of the need for environmental protection and sustainability, companies try to effectively incorporate sustainability issues into their Supply Chain Management (SCM) plan. Mele et al. [30] worked on the problem of optimizing the sugar-based bioethanol supply chains. Their bi-criteria MILP model addresses the economic and environmental concerns. The model minimizes the total cost of managing the supply chain network and minimizes the environmental impact over the entire product life cycle. You and Wang [31] considered the dual-objective of economic and environmental optimization, which was solved using the ε-constraint method. The environmental performance was measured by the life cycle GHG emissions, and the economic objective was measured by the total annual cost. Gonela et al. [14] developed a Stochastic Mixed-Integer Linear Programming (SMILP) model for designing Hybrid Generation Bioethanol Supply Chains (HGBSC) that aim to maximize the total profit under GHG emissions and irrigation land use restrictions. The results indicated the design of HGBSC changes under different sustainability considerations.

This paper develops a multi-period MILP model to design a supply chain network aimed at maximizing the Net Present Value (NPV) considering economic and environmental criteria. The model is developed to optimize the related strategic- and tactical-level decisions that include production planning decisions including the amount of production, inventory levels in each period, the amount of materials transported between different echelons, and determining the locations of the decentralized fast pyrolysis facilities and gasification facilities and their capacities.

The rest of the paper is organized as follows: In Section 2, the problem statement is described. The proposed MILP is described in Section 3. The details of the solution method are presented in Section 4, and the results are discussed and compared. Finally, Section 5 is devoted to conclusions, suggestions, and future research directions.

2. Problem Statement

In this section, the details of the supply chain network design, assumptions, and biodiesel production process are provided. According to Fig. 1, the considered bio-oil gasification network includes five echelons: 1) Cultivation land, 2) Decentralized fast pyrolysis facilities, 3) Gasification facilities, 4) Warehouses, 5) Transportation, and 6) Demand locations.

2.1. Cultivation land

In this study, wheat and wheat stem as a combination of the first- and second-generation biomasses for biofuel production are considered. Reports of annual wheat production show that the southern regions of Iran have the highest production levels. Therefore, the southern regions of the country are appropriate alternatives of feedstock centers for biofuel production. It is assumed that all the available land is the potential source of supplying first- and second-generation biomasses. However, the amount of biomass in each period can be changed due to different conditions such as climate changes and pest plants.

2.2. Decentralized fast pyrolysis facilities

Biomasses are collected from supply centers and transported to decentralized fast pyrolysis facilities to be converted to bio-oil. In this paper, it is assumed that each fast pyrolysis facility can acquire feedstock from multiple biomass supply locations so that each biomass feedstock supply location can serve multiple fast pyrolysis

facilities. There are losses of biomass resources and bio-oil during transportation and production.
In fast pyrolysis, dry biomass is decomposed in the absence of oxygen into bio-oil, bio-char, and non-condensable gases [32]. This process is run at temperatures between 400°c and 600°c and can produce approximately 70% (by weight) bio-oil [33]. The other 30% is divided into non-condensable gases (e.g., carbon dioxide or methane) and bio-char. The non-condensable gases and bio-char can be used to provide heat for the facility. In addition, bio-char is mostly organic carbon that can be separated or gasified to produce syngas [34]. However, due to the high acidity and viscosity, bio-oil should be upgraded to be used as transportation fuels. On the other hand, biomass gasification requires a relatively mature technology. Therefore, mild hydrotreated bio-oil is transported to a centralized gasification facility to produce transportation fuels [21].

2.3. Gasification facilities

In gasification facilities, biomass gasification runs at a much higher temperature (800°c-1300°c). The syngas produced from the biomass gasification process will typically go through the Fischere-Tropsch synthesis to produce transportation fuels [35]. After processing, the fuels are distributed to gas stations for sale. It is assumed the potential locations of decentralized fast pyrolysis facilities and gasification facilities are known; however, the best locations among them should be determined according to the results of the proposed approach.

2.4. Warehouses

Inventory holding as safety stocks is possible in bio-refineries; therefore, limited amount of the biofuels can be stored to meet future demand.

2.5. Transportation

In this research, the transportation of the product from one facility to another in each echelon of the network is done through two transportation modes, namely road and rail with limited capacity and a certain reliability. The road haulage with tankers is available in all areas. The railroad transportation is available for some demand locations.

2.6. Demand locations

The per capita biodiesel requirement in each demand zone is assumed to be known and deterministic. The total biodiesel requirement is assumed to be proportional to the population in each demand zone.
The goal of this paper is to determine the configuration of a bio-diesel supply chain network and the associated planning decisions with the objective of maximizing the NPV within a defined time horizon considering the cost of production, storage and transportation, the demand for products, the capacity data for plants, the transportation mode, the capacity storage, and capital investment. Fig schematically illustrates the bio-fuel supply chain.

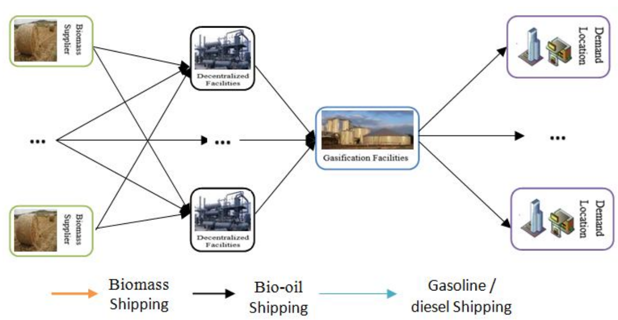

Fig. 1. System schematics of bio-fuel supply chain

3. Model Formulation

To solve the problem, an MILP model is proposed to maximize the total hybrid-generation-based biofuel supply chain profit by determining the optimal level of the various supply chain logistics decision variables.

3.1. Notations

Sets

i	Biomass supply locations
j	Candidate fast pyrolysis facility locations
m	Candidate refining facility locations

c	Biofuel demand zones
l	Fast pyrolysis capacity levels
b	Types of biomass
v	Transportation mode
t	Time periods

Parameters

P_c	Biofuels price at demand zone c
D_c^t	Biofuels demand at demand zone c in time period t
H_m^t	Inventory holding cost of biofuels in refining facility m in period t
Pe_c^t	Shortage cost of biofuels in refining facility for customer c in period t
C_l^{cap}	Capital cost of the decentralized fast pyrolysis facility at capacity level l
U_l	Capacity of fast pyrolysis facility at level l
C^{up}	Capital cost of the centralized refining facility
C^{mo}	Unit conversion cost from dry biomass to bio-oil
C^{OF}	Unit conversion cost from bio-oil to biofuels
C_{ijbv}^{BM}	Unit biomass shipping cost from supply location i to candidate fast pyrolysis facility location j by transportation mode v
C_{jmv}^{BO}	Unit bio-oil shipping cost from supply location j to location m by transportation mode v
C_{mcv}^{BF}	Unit bio-diesel shipping cost from supply location m to location c by transportation mode v
C_{mcv}^{FInv}	Unit bio-diesel shipping cost from inventory m to location c by transportation mode v
ghg_{ijbv}^t	The amount of CO2 Emission while shipping biomass from i to j in period t by transportation mode v
$ghgo^t$	The amount of CO2 Emission per ton of product bio-oil in period t
ghg_{jmv}^t	The amount of CO2 Emission while shipping bio-oil from j to m in period t by transportation mode v
$ghgf^t$	CO2 Emission per ton of product biodiesel in period t
ghg_{mcv}^t	The amount of CO2 Emission while shipping biodiesel from m to c in period t by transportation mode v
GP^t	The amount of GHG emissions permitted in period t
B	Capital budget
β	Sustainability factor
A_{ib}^t	The amount of biomass of type b at place i in period t
Cap^{ref}	Capacity of refining facility
γ	The loss factor of biomass during collection
δ	Availability factor
$Store_m$	Capacity of storage
N_{ijv}^t	The maximum number of vehicles v needed for biomass from i to j during period t
R_{jmv}^t	The maximum number of vehicles v needed for bio-oil from j to m during period t
Q_{mcv}^t	The max number of vehicles v needed for bio-diesel from m to c during period t
Δ	Reliability factor
$C_v^{vehicle}$	Capacity of transportation v

Decision variables

w_{jl}	Whether a fast pyrolysis facility of capacity level l is planned at candidate facility location j (binary variable)
g_m	Whether a refining facility is planned at candidate refining facility location m (binary variable)
X_{ijbv}^t	Amount of biomass transported from supply location i to candidate fast pyrolysis facility location j in period t by transportation mode v
Y_{jmv}^t	Amount of bio-oil transported from candidate fast pyrolysis facility location j to candidate

	refining facility location m in period t by transportation mode v
Z^t_{mcv}	Amount of biofuels transported from refining facility location m to demand location c in period t by transportation mode v
O^t_{mcv}	Amount of biofuels transported from refining facility store m to demand location c in period t by transportation mode v
Inv^t_m	Inventory holding of biodiesel in refining facility m in period t
S^t_c	Amount of shortage of bio-diesel in location c in period t
$bInv^t_m$	Amount of bio-diesel transferred to the warehouse in period t

3.2. Objective function and constraints

The objective function is to maximize the total profit. The total profit is defined as the revenue subtracted by total system costs.

$$Max\, z = Income - Cost \tag{1}$$

Eq. (2) represents the total supply chain revenue by selling the total bio-fuels.

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{v=1}^{V} P_c * (Z^t_{mcv} + O^t_{mcv}) \tag{2}$$

The second objective function is dedicated to the costs.
Eq. (3) denotes the total capital cost for the decentralized fast pyrolysis facility at level l and refining facility with the assumption that facilities have an n-year lifecycle and an interest rate of q denoted in Eq. (2.1).

$$-\left(\frac{(q(q+1)^n}{(q+1)^n - 1}\right)\sum_{j=1}^{J}\sum_{l=1}^{L} C_l^{cap} * w_{jl} + C^{up} \tag{3}$$

Eq. (4) expresses the fast pyrolysis conversion cost from biomass to bio-oil and the conversion cost from bio-oil to biofuel at gasification and biorefinery facilities.

$$-C^{mo} * (1-\gamma) * \sum_{t}^{T}\sum_{i}^{I}\sum_{j}^{J}\sum_{v}^{V}\sum_{b}^{B} X^t_{ijbv} - C^{OF} * \sum_{t}^{T}\sum_{j}^{J}\sum_{m}^{M}\sum_{v}^{V} Y^t_{jmv} \tag{4}$$

Shipping costs are calculated using Eq. (5) that consists of three components including 1) the biomass shipping cost from biomass feedstock locations to fast pyrolysis facility locations; 2) the bio-oil shipping cost from fast pyrolysis facility locations to gasification; 3) biorefinery locations and the biofuel shipping cost from a gasification location to demand locations.

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{v=1}^{V}\sum_{b=1}^{B} C^{BM}_{ijbv} * X^t_{ijbv} - \sum_{t}^{T}\sum_{j}^{J}\sum_{m}^{M}\sum_{v}^{V} C^{BO}_{jmv} * Y^t_{jmv} - \sum_{t}^{T}\sum_{m}^{M}\sum_{c}^{C}\sum_{v}^{V} C^{BF}_{mcv} * (Z^t_{mcv} + O^t_{mcv}) \tag{5}$$

The inventory holding cost of biofuel is calculated through Eq. (6).

$$-\sum_{t=1}^{T}\sum_{m=1}^{M} H^t_m * Inv^t_m \tag{6}$$

Eq. (7) states shortage costs for unmet demand.

$$-\sum_{t=1}^{T}\sum_{c=1}^{C} Pe_c^t * S_c^t \tag{7}$$

Eq. (8) ensures that the sum of the capital costs of decentralized fast pyrolysis facilities and a centralized biorefinery should be less than the total capital budget.

$$C^{up} + \sum_{j}^{J}\sum_{l}^{L} C_l^{cap} * w_{jl} \le B \tag{8}$$

Eq. (9) states that the total amount of biomass transported from supply location i to all of the fast pyrolysis facility locations should not exceed the available feedstock for each supply location.

$$\sum_{j}^{J}\sum_{v}^{V} X_{ijbv}^t \le (1-\beta) * \delta * A_{ib}^t \qquad \forall\, i,b,t \tag{9}$$

There should be no more than one fast pyrolysis facility in each candidate facility location, as illustrated in Eq. (10). In addition, only one centralized refining facility will be constructed in one region as denoted in Eq. (11).

$$\sum_{l=1}^{L} w_{jl} \le 1 \qquad \forall\, j \tag{10}$$

$$\sum_{m=1}^{M} g_m = 1 \tag{11}$$

The facility capacity limits are illustrated in Eqs. (12,13). The loss factor gamma ($\gamma \in [0,1]$) is the fraction weight loss of biomass during the collection and transportation.

$$\sum_{j}^{J}\sum_{v}^{V} Y_{jmv}^t \le Cap^{ref} * g_m \qquad \forall\, m,t \tag{12}$$

$$(1-\gamma) * \sum_{i}^{I}\sum_{b}^{B}\sum_{v}^{V} X_{ijbv}^t \le \sum_{l}^{L} U_l * w_{jl} \qquad \forall\, j,t \tag{13}$$

Eq. (14) expresses the amount of biomasses received from collection centers with the related amount of bio-oil produced at the decentralized fast pyrolysis facility in each period. Eq. (15) states the amount of bio-oils transferred to the refinery with related amount of biodiesel retransferred to customer zone and stored in the gasification facility in each period.

$$(1-\gamma) * \sum_{i}^{I}\sum_{j}^{J}\sum_{b}^{B}\sum_{v}^{V} X_{ijbv}^t = \sum_{j}^{J}\sum_{m}^{M}\sum_{v}^{V} Y_{jmv}^t \qquad \forall\, t \tag{14}$$

$$\sum_{j}^{J}\sum_{m}^{M}\sum_{v}^{V} Y_{jmv}^t = \sum_{c}^{C}\sum_{m}^{M}\sum_{v}^{V} Z_{mcv}^t + \sum_{m}^{M} bInv_m^t \qquad \forall\, t \tag{15}$$

Inventory balance limitations at a centralized biorefinery are denoted by Eqs. (16,17). The constraints ensure that the inventory of biodiesel at a centralized biorefinery in any period is equal to the summation of the inventory of biodiesel from the previous period, the amount of biodiesel produced in that period minus the amount of biodiesel transformed to the demand zone. Eq. (18) states that the inventory of biofuel does not exceed the capacity of store in any period. Eq. (19) considers shortage balance limitation for unmet demands.

$$bInv_m^t + Inv_m^{t-1} = Inv_m^t + \sum_c^C \sum_v^V O_{mcv}^t \qquad \forall\, m, t \qquad (16)$$

$$bInv_m^t = Inv_m^t + \sum_m^M \sum_v^V O_{mcv}^t \qquad \forall\, m, t \qquad (17)$$

$$\mathrm{Inv}_m^t \le Store_m \qquad \forall\, m \qquad (18)$$

$$D_c^t - S_c^t = \sum_m^M \sum_v^V Z_{mcv}^t + \sum_m^M \sum_v^V O_{mcv}^t \qquad \forall\, c, t \qquad (19)$$

Limitations on the reliability of transportation for transporting biomass, bio-oil, and biodiesel are imposed by Eqs. (20-22).

$$\sum_b^B X_{ijbv}^t \le \Delta * N_{ijv}^t * C_v^{vehicle} \qquad \forall\, i, j, v, t \qquad (20)$$

$$Y_{jmv}^t \le \Delta * R_{jmv}^t * C_v^{vehicle} \qquad \forall\, j, m, v, t \qquad (21)$$

$$Z_{mcv}^t + O_{mcv}^t \le \Delta * Q_{mcv}^t * C_v^{vehicle} \qquad \forall\, m, c, v, t \qquad (22)$$

Eq. (23) represents the constraints related to GHG emissions. The estimate of GHG emission in a time period is the sum of the GHG emitted while transporting products, GHG emitted while producing biofuel, and GHG emitted while producing biomass. The constraint ensures that GHG emissions are less than the maximum allowable permit limit in any time period.

$$-\left\{\begin{aligned} &\sum_i^I \sum_j^J \sum_b^B X_{ijb}^t * \left(ghg_{ijb}^t + ghgo^t\right) \\ &+ \sum_j^J \sum_m^M Y_{jm}^t * \left(ghg_{jm}^t + ghgf^t\right) \\ &+ \sum_{c=1}^C \sum_{m=1}^M (Z_{mc}^t + O_{mc}^t) * ghg_{mc}^t \end{aligned}\right\} \le GP^t \qquad \forall\, t \qquad (23)$$

Eqs. (24,25) provide logical binary and non-negative integer boundaries for the decision variables.

$$w_{jl} \in \{0,1\} \qquad \forall\, j, l$$
$$g_m \in \{0,1\} \qquad \forall\, m \qquad (24)$$

$$X_{ijb}^t \ge 0 \qquad \forall\, i, j, b$$
$$Z_{mc}^t \ge 0, O_{mc}^t \ge 0 \qquad \forall\, m, c$$
$$Inv_m^t \ge 0 \qquad \forall\, m \qquad (25)$$
$$S_c^t \ge 0 \qquad \forall\, c$$
$$bInv_m^t \ge 0 \qquad \forall\, m$$

4. Case Study

The proposed hybrid biofuel supply chain design model is applied to a case study in the southern region of Iran. This case example is used to illustrate the efficiency of the proposed model.

Iran is one of the middle-east countries that is rich in fossil fuels and one of the world's largest oil exporters. On the other hand, air quality problems in large cities of Iran have caused some serious problems, such as respiratory, warming up, and a decrease in the quality of living conditions in these cities due to GHG emissions. To deal with these issues, Iran's government has decided to reduce domestic fossil fuels and use biofuels and other renewable energy as an attempt to move towards a more sustainable development. Biodiesel development programs in Iran have been initiated since 2009, and Iran has been planning to substitute about 20% of its diesel consumption with biodiesel [9].

Due to the emerging challenges in biodiesel production from edible sources, it is necessary to use non-edible sources to produce biodiesel. A combination of the first- and second-generation biomasses helps reduce the use of food for biodiesel production. In Iran, one of the most qualified alternatives for biodiesel production includes wheat and wheat stems.

4.1. Data sources

Six cities of Iran are chosen as candidate biomass supply locations, the potential locations for distributed fast pyrolysis facilities, and the candidate location for the centralized gasification facility. The county level wheat production data from 2016 to 2018 are collected (https://www.maj.ir/).

Fixed and variable opening costs of decentralized fast pyrolysis facilities, gasification facility, production and inventory holding costs are taken into account according to own calculations. The collection cost for wheat is different in each city due to the differences in distance and collection quantities. For the collection cost estimation, the regression analysis from Graham et al. was used [36]. Biomass loss factor, which accounts for possible mass loss during collection and transportation, is assumed to be 0.05 in this analysis [37]. Based on [38], the average conversion ratio of biomass to bio-oil on a weight basis in fast pyrolysis is 0.63. Due to the lack of experimental data, the conversion ratio from bio-oil to biofuel is not available; therefore, it is assumed that the conversion ratio from bio-oil to biofuel on a weight basis is 0.60. This study considers 500, 1000, and 2000 metric tons per day for capacity levels of distributed fast pyrolysis facilities, and the centralized gasification plant has a capacity of 550 million Gasoline Gallon Equivalent (GGE) per year.

Transportation distances for biomass, bio-oil, and biodiesel are calculated based on the actual distances between the two locations. Data about road distances gathered in this study are provided by the Ministry of Roads & Urban Development (https://mrud.ir/). In addition, data of the rail distance between cities gathered for this study are provided by Asia Seir Aras Company (http://asiaseiraras.com). The transportation cost of bio-oil via trucks is assumed to be equal to the average truck shipping cost of 0.312 Rial/Metric ton*Miles. The transportation cost of biofuel via train is assumed to be equal to the average train shipping cost, which is 0.250 Rial /Metric ton*Miles. Furthermore, trucks are available for all cities; however, trains are available for some cities.

Gasoline demand for each demand area is assumed to be proportional to the population of the related cities. Therefore, to estimate the amount of biodiesel demands for 24 periods, fossil consumptions are investigated for 24 periods according to historical data. Gasoline prices were obtained from (https://www.eia.gov/).

All of the facilities have a 20-year useful lifetime, and the annual interest rate is assumed to be 10%.

In the following section, to examine the performance and efficiency of the model, the computational results of the case under consideration are presented and analyzed.

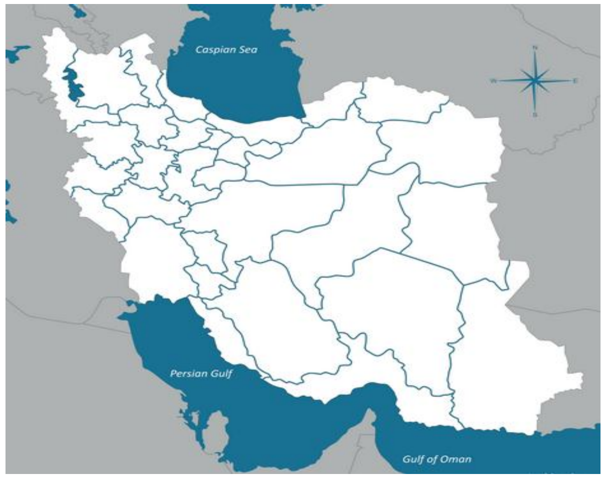

Fig.e 2. The Optimal locations for facilities

4.2. Results and discussion

The proposed model was coded in GAMS® optimization software, and CPLEX solver was used to solve the model. According to the results, due to the budget limit and economies of scale, 3 distributed fast pyrolysis facilities will be planned to be built and are at the highest capacity Level (2000 tons per day). The centralized gasification facility is planned to be built in Fars. Hence, the bio-oil transportation cost and biofuel transportation cost are reduced.

Fig. 1 shows different types of cost. Total capital cost to build fast pyrolysis facility and refinery facility is about 27.10% of the total cost, biomass to bio-oil and bio-oil to biodiesel conversion cost is about 34.05% of the total cost, total shipping for Rail and road transportation cost is about 25.80% of the total cost, and total inventory and shortage cost is about 12.30% and 0.75 of the total cost, respectively.

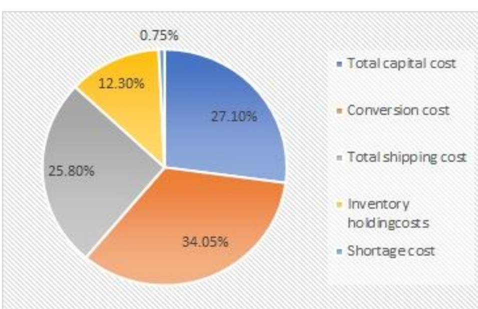

Fig. 1. The total cost of the biofuel supply chain

Although some research works in the literature have examined the environmental subsequences of biomass collection from the land, limited studies have considered social factors such as farmers' willingness to participate. However, farmers' willingness in participating has a direct impact on access to biomass feedstock. Results show that farmers are mostly desired to sell their biomass to the market for consumption, electricity generation, and heating. On the other hand, farmers' environment concerns such as soil erosion, water, climate condition, and loss of nutrients are the main obstacles to biomass collection. Therefore, constant access to biomass is important for product biofuel gasification, and this depends on the farmers' participation. In this case, the impact of farmers' participation is considered as the availability factor δ. It shows the ratio of the available biomass to the collectable biomass. The δ is distributed [0-1]. If the availability factor δ is less than 0.20, which means that, on average, less than 20% of the farmers would participate. In this case, the biofuel supply chain system is not profitable; therefore, it is not optimal to build any facilities. If the δ is between 0.20 and 0.38, the supply chain system is profitable; however, a lot of unmet demand occurs. Results show that the biofuel production target will be satisfied if the availability factor is larger than 0.40. Table 1 presents annual costs and profits for different types of availability factor δ. When the availability factor δ increases from 0.3 to 0.4, the total capital cost, production cost, and total shipping cost increase. The availability factor δ increases from 0.4 to 0.7, the total shipping cost and shortage will decrease and the total capital cost will not change, because it is planned with the same number and capacity of facilities. As a result, annual profits increase.

Tab. 1. Annual costs and profits for different δ

δ	0.4	0.5	0.6	0.7
Profit	70.24	164.53	210.92	242.09
Total capital cost	520.01	609.39	609.39	609.39
Total shipping cost	296.27	328.04	297.13	282.24
Conversion cost	840.14	1020.2	1020.2	1020.2
Inventory cost	150.67	180.16	209.65	219.14
Shortage cost	118.1	111.5	102.9	94.3

5. Conclusion

Biofuels play an increasingly important role in reducing energy dependency and environmental crisis. First, biofuels were produced with first-generation biomass; then, food crises motivated researchers and practitioners to introduce the second-generation biofuel production from non-edible feedstocks as a sustainable and viable solution. Designing an integrated biofuel supply chain network has a significant impact on the commercial feasibility of biofuels.

This paper first reviewed and classified recent research works performed for designing biofuel supply chain networks. Then, after identifying research gaps, a biodiesel supply chain design model was developed under different conditions. A hybrid first/second generation of biodiesel supply chain design model with limited and reliable multimodal transport was proposed to determine capital investment decisions including the numbers, locations, and capacities of fast pyrolysis facility and refinery facility, materials flow, suitable transportation mode, and optimal production. In this study, wheat and wheat stems were considered as the first and second generations of biodiesel production. A case study in southern part of Iran was presented to illustrate how valid the proposed supply chain design model would be. The results showed that factors such as biomass availability, transportation reliability, and biofuel price could be essential in this supply chain design and optimization. In addition, farmers' participation has a significant impact on the decision-making process, and the supply chain design and optimization model will become more profitable when participation increases.

According to the literature and the results of this paper, some future research directions may include the following: firstly, it is assumed that the farmers' participation is the same for all cities. However, this factor may depend on the land characteristics, water, and agricultural management practices. Hence, the factor can be different for different cities, making the assumption more realistic. Secondly, additional constraints such as GHG emissions taxation can be considered to ensure environmental protection. Another important issue is the examination of taking uncertainty in the supply chain into account. To do so, the most common parameters that are prone to uncertainty are availability factor, demands, and costs among others.

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