ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Bioethanol supply chain network design considering land characteristics

Hasti Rahemi [a], S. Ali Torabi [a,*], Akram Avami [b], Fariborz Jolai [a]

[a] School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran
[b] Energy Systems Engineering Group, Department of Energy Engineering, Sharif University of Technology, Azadi Ave P.O. Box, 14565-114, Tehran, Iran

ARTICLE INFO

Keywords:
Bioethanol supply chain network design
Land suitability evaluation
MADM
GIS

ABSTRACT

Biomass is becoming an increasingly widespread source of energy. Yet land, as one of the most important resources in biomass production, is surprisingly understudied in the literature of biomass supply chain planning. This study proposes a novel framework that combines the literature of bioethanol supply chain design with agricultural land planning to simultaneously address optimal supply chain planning and sustainable land use in a bioethanol supply chain. A bi-objective mixed-integer linear programming (MILP) model is proposed to formulate the optimal design and planning of a bioethanol supply chain network considering competition of food and biomass feedstock over the available croplands. The proposed model is capable of making strategic decisions (i.e. locations and capacities of facilities, sourcing and allocation of biomass feedstocks to biorefineries), along with some tactical decisions (i.e. land planning, inventory and production of both biomass feedstock and bioethanol). The model incorporates the two objectives of minimum cost and maximum suitability of crops with their assigned croplands. A novel integration of the FAO framework, the best-worst multi-criteria decision-making method, PROMETHEE II and GIS is used to determine the suitability of available croplands according to the croplands' soil and topographical characteristics. The performance of the proposed model is demonstrated through a multi-feedstock bioethanol supply chain in Fars province, Iran. It is concluded that the proposed integrated land planning-network design framework outperforms hierarchical approaches in which network design and land planning problems are solved separately in a sequential manner. Also, the case study shows that conditional on implementing second generation bioethanol production, Fars province has the potential to satisfy three percent of the fuel demand for transportation in the country.

1. Introduction

With the rapidly increasing energy demand and the destructive environmental implications of fossil fuel consumption, renewable energies (REs) play an important role in protecting the environment for the future. Among all the renewable energy resources, biofuel is very attractive due to its worldwide availability, storage potential, and the efficiency of its conversion technologies [1]. In the recent years, many studies have been conducted on its future contribution to the global energy demand [2,3].

Iran holds the largest natural gas and the fourth largest oil reserves in the world and is within the ten countries with the highest emissions of CO_2 [4]. The country's main primary energy resources include oil (fuel and crude), natural gas, electric power (generated mainly by natural gas, followed by fuel oil, gas/diesel, wind and Hydro), gas/diesel and motor gasoline [4,5]. As reported by Aslani et al. [6], transportation sector is the second most energy-intensive sector, following residential sector, in the country and is currently utilizing gasoline, gas/diesel, natural gas and fuel oil as its main energy resources [4]. Also, as reported by Mousavi et al. [4], transportation has produced the second largest amounts of carbon dioxide, again following residential, on average between 2003 and 2014. Biofuel is one of the few renewable energy resources which can contribute to satisfying the energy demand of the transportation sector [7]. Therefore, biofuel production could potentially play an important role in sustainability of energy consumption and meeting the increasing gasoline demand in the near future in Iran [8,9].

In addition, biofuel production contributes to waste management, specially the extensive agricultural waste produced annually in the country, produces jobs and promotes development specially in rural areas [10]. According to Ghobadian [11], only utilizing the 17.86 million tons of wasted crops in Iran, would be able to produce 4.91 billion liters of bioethanol per year. The availability of land and diversity of climatic situations makes the country suitable for biomass production, so much so that as reported by Ghobadian [11], the country could

* Corresponding author.
E-mail addresses: hasti.rahemi@ut.ac.ir (H. Rahemi), satorabi@ut.ac.ir (S.A. Torabi), avami@sharif.edu (A. Avami), fjolai@ut.ac.ir (F. Jolai).

https://doi.org/10.1016/j.rser.2019.109517
Received 12 April 2018; Received in revised form 2 October 2019; Accepted 22 October 2019
1364-0321/

potentially support the demand for E10 by 2026.

Studies on feasibility and potential of bioethanol in Iran, such as [8, 11] report that the most favorable crops for bioethanol production are wheat, sugarcane, bagasse, rice, barely and corn. These crops are also very high in waste (e.g. on average 50% of wheat turns to be waste) [11] and make very good candidates for second-generation bioethnol production. However, each of these crops require appropriate climatic situations. In this study, we do not consider sugarcane, bagasse and rice since they are not compatible with the climatic situation of our area of study.

The vast available agricultural lands and variability of cultivated crops make the Fars province an attractive region for agriculture. As stated by Agriculture chapter of Statistics Yearbook of Iran [12], 753440 ha of Fars province was under cultivation of more than 30 crops in 2012–2013. About 75% of the cultivated area in 2012–2013 was dedicated to corn, sorghum, wheat, and barley. Therefore, corn, sorghum, wheat, and barley are considered here as the first generation or sugar-based biomass and their residues as the second generation or lignocellulosic biomass.

Nevertheless, scarcity of water resources and the supposed low mineral content of the soil are important concerns for development of biofuels in Iran. Since the land assigned to energy crops could alternatively be assigned to produce food products, it is essential to study the efficient and effective application of available agricultural lands [13]. Therefore, it is important that land is applied in a sustainable manner. According to FAO [14], "sustainability of croplands may only be achieved if lands could be categorized and utilized based upon their different uses". Also, FAO [15] emphasizes that "Efficient, effective, and sustainable usage of croplands could only be achieved through planning the croplands on the basis of their different suitability for different types of crops." Therefore, it is observed that FAO strongly recommends planning the agricultural lands using land suitability evaluation frameworks to accomplish sustainability of croplands.

Due to the importance of government involvement in commercialization of REs, many governments are providing financial aid and/or tax compensation to support them [16]. Rentizelas et al. [17] state that the cost of biofuel supply chains (SCs) is one of the most important barriers in development of a strong bioenergy sector. Therefore, there is an essential need for studies on costs and environmental implications of biofuel production to motivate policy makers in establishing biofuel SCs. Since the supply zones are typically scattered in a broad region, handling and transporting of the bulky and mostly seasonal feedstock induces a variety of economic and environmental implications [18]. Therfore, designing reliable multi-echelon biofuel supply chains is essential for commericialization of biofuels.

In this study, a bi-objective multi-echelon network design model is proposed for a multi-type biomass supply chain by which both the network design related decisions and cropland planning tactical decisions are made simultaneously. The model aims at minimizing the overall supply chain cost and maximizing the suitability of the assigned lands with the crops planted in them. In the literature, studies mostly take the produced crop as the potential feedstock to be fed to biofuel plants. In this paper, a novel methodology is proposed to plan available croplands for producing energy crops while taking into consideration the required food production. In order to plan the agricultural lands for planting these crops, land suitability maps are developed via Geographic Information System (GIS).

The rest of the paper is organized as follows. The relevant literature is reviewed in Section 2. Then, the methodology of the present work is described in Section 3. The results are presented and discussed in Section 4 and Section 5 concludes the paper briefly.

2. Literature review

In this section, we review the literature in two relevant while complementary research streams.

2.1. Biomass supply chain network design

The studies whichthat use mathematical programming to model biomass SCs may be classified according to their decision level (strategic, tactical and operational or an integration of them), the types of biomass, and their geographical aspects.

Zhu and Yao [19] proposed a multi-commodity network flow model in the form of a multi-objective mixed-integer linear programming (MILP) for a multiple-feedstock biomass to bioenergy supply chain. They reported that multiple types of biomass in bioenergy supply chain models are more efficient . Avami [8] developed a model for biodiesel production in Iran. The model integrates the agriculture sector (resource level) into the biofuel production technologies aiming at minimizing the total cost. Avami [20] adapted this model to bioethanol production in Iran. Andersen et al. [21] proposed an MILP model for optimal design and planning of a biodiesel supply chain which considers cropland competition for soybean, sunflower and Jatropha. Gonela et al. [22]. proposed a hybrid generation bioethanol supply chain model that optimizes energy efficiency, environmental sustainability, irrigation land and water usage. The authors implemented their model to a case study in the United States. Similar to this study, they realized the importance of considering both the first and second generation biofuels to analyze cropland implications of biofuel production. Bai et al. [23] proposed a model for biofuel supply chain network design with a multi stakeholder perspective to find a farmland, food, and fuel market equilibrium through a game theory approach. The models presented by Avami [20], Andersen et al. [21], Bai et al. [23] and Gonela et al. [22] have considered cropland competition in terms of pre-fixed available land areas. However, characteristics of the available lands and their feasibility/suitability for specific crops have not been further analyzed.

Many recent studies have addressed different aspects of sustainability in biofuel SCs. Among them, many choose the second-generation biomass as their main feedstock of study (Osmani and Zhang [24], Babazadeh et al. [25]). Osmani and Zhang [26] proposed a multi-objective second-generation feedstock model to optimize a biomass to a bioethanol supply chain under economic, environmental and social objectives. In their model, among other strategic decisions, they determine land allocation to switchgrass. The land model, although very effective in determining switchgrass capacity, does not reflect the competition for land with food agriculture. Ahmed and Sarkar [27] incorporated carbon emission cost in their supply chain model and conclude that the major cost of their second-generation biofuel supply chain can be attributed to the fuel production process. How et al. [28] analyze the bottleneck of sustainability performance in a multiple-feedstock, multiple-product biomass supply chain. Orjuela Castro et al. [29] proposed a multi-objective biodiesel supply chain model in Colombia. They analyze the trade-offs between cost optimization, environmental sustainability and food security in the supply chain. Ren et al. [30] developed a bioethanol supply chain model which aims at optimal sustainability under technical and economical constraints. The authors propose total life cycle ecological footprint to measure sustainability. Land utilization is reflected, along with other measures, in the final life cycle ecological footprint of bioethanol. The model provides a comprehensive sustainability measure but does not reflect on details of a potential land plan. Corsano et al. [31] developed an integrated bioethanol supply chain model to simultaneously address network design, allocation and production planning. Like in this research, they find that studying an integrated model provides a more comprehensive perspective for decision making.

Zhang et al. [32] developed an integration of GIS and biofuel supply chain network design. Mohseni et al. [33] modeled a micro-algae based supply chain in two stages. In the macro stage, they used GIS and AHP to determine candidate locations to establish biodiesel facilities. In the micro stage, they propose a robust mixed-integer linear programming (RMILP) optimization model for planning the supply chain.

Balaman and Salim [34] and Ghaderi et al. [35] conducted reviews on the literature of biomass to energy supply chain network design. They concluded that multi-objective multi-period models were lacking in the literature of biomass network design. Furthermore, they suggested incorporating the tactical decisions in an integrated manner.

2.2. Land evaluation methods

A wider utilization of biofuels implies a more broad use of agricultural lands. The availability of suitable land resources needs to be seriously taken into consideration for the future of biofuel production facilities, specially in those areas with few fertile land resources like Iran. Consequently, land evaluation is a critical step in land-use planning [37]. One of the important ways to increase the yield of crops and making efficient use of the available land is assessment of potential production in a specific cropland area and allocation of crop cultivation according to its suitability for the crop. In this respect, detailed geographical data is essential. During the last few decades, governments in many countries have supported development of large geographical databases describing their territories [36]. GIS is widely used as a powerful computational tool to handle these detailed and large scale geographical data. Integration of land suitability evaluation and multi attribute decision analysis (MADA) tools have been broadly used for the purpose of land planning in recent studies.

Sys et al. [37] provided promising land suitability evaluation approaches for agriculture which was then used by a broad number of other studies. These methods included matching land characteristics with crop requirements within the FAO framework for land suitability evaluation. Ljusa and Pajovic [38], Albaji et al. [13] and Ziaei et al. [39] conducted land suitability evaluation based on Sys method [37] and the tables provided by Givi [40].

Land suitability evaluation processes mostly combine different indices for a wide range of land characteristics using both qualitative and quantitative information. To account for the relative importance of criteria, multi-attribute decision making (MADM) methods such as geometric mean and analytic hierarchy process (AHP) have been used. Hamzeh et al. [41] used a combined fuzzy AHP method for the land suitability evaluation for barley crops in the southwest of Iran.

Briefly, it can be concluded from the extant literature that the impacts of land characteristics in the multiple-feedstock bioenergy SCs has been rarely explored. To the best of our knowledge, most papers in the literature take the available land area as input. To fill the aforementioned gap, this study proposes a novel suitability analysis method for biomass crops for effectively planning of land-use. The proposed cropland suitability analysis method benefits from an integration of FAO framework, PROMETHEE II, and the best-worst method (BWM) [42]. Also, GIS is used for determining the location of candidate plants, storage, and preprocessing sites along with the land characteristics of croplands. Furthermore, a novel multi-objective integrated model is proposed to simultaneously minimize the total cost of biofuel supply chain and maximize the efficiency of land planning. This study incorporates the results of a land evaluation analysis into a supply chain network design to optimally determine the supply of feedstock and production of final product. The results are provided as a land suitability map which classifies the whole region into sub-regions and assigns a suitability index to each sub-region. Afterwards, the suitability index for each region accompanied with its area (i.e. its production capacity) is fed into the optimization model.

3. Methodology

The problem under study concerns both strategic and tactical planning of a biomass for a bioethanol SC aiming at optimizing supply chain cost as well as efficacy of land use. The SC includes a set of harvesting sites (i.e., croplands), preprocessing/storage facilities, and biorefinery plants. The bioethanol SC includes one or more biomass feedstocks that are produced in a number of widely distributed potential harvesting sites. The biomass (crop and crop residue) is transported from the harvesting sites to each preprocessing plant, in which it is dried, densified, and preprocessed. The preprocessed material is then stored in the storage facilities for transportation to biorefineries. The available biomass from crops and residues is converted to bioethanol within two different technological paths: sugar-based or lignocellulosic-based (Fig. 1)). The SC is optimized for two objectives: minimizing the total cost of the SC and maximizing the suitability of croplands with their assigned crops. The coefficients for the second objective (i.e. suitability indexes) are determined using a novel land suitability evaluation process explained in Section 3.1. The optimization problem is then solved through three different scenarios. In the fist scenario, the supply chain as a whole is optimized for the two objectives (i.e. the integrated model). In the second scenario, the problem is broken into two smaller problems which are solved hierarchically. In this scenario, the available croplands are first assigned to cultivating specific crops. Then, other decisions are made by another model (i.e. the Hierarchical Formulation I). In the third scenario, the supply chain network is first designed to derive the optimized land plan. In other words, facility location, material flow, and inventory holding decisions are made in the first model and the cropland allocation decisions are determined by a separate optimization model (Fig. 1). A comprehensive sketch of the proposed framework in this study is provided in Fig. 1. The proposed framework is applied to the real case of Fars province in Iran in Section 4 from where useful managerial insights are also drawn.

3.1. Land suitability evaluation

For parametric land suitability evaluation, the FAO framework proposes dividing the region under study according to specific criteria and index each division (sub-region) as highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N) for a given crop. This procedure results in a number of classifications of agricultural lands in the region of interest. Suitability of a specific cropland for a crop depends on a variety of criteria, shown in Table 1.

In order to obtain a single index for suitability of sub-regions to a given crop, the next step is integrating these indices along the criteria. Sys et al. [37] proposes geometric mean for integrating the indices along the criteria. Land suitability evaluation includes a number of qualitative criteria (e.g. soil texture) and quantitative ones (e.g. soil depth). Additive aggregation of such variety of criteria (as done in AHP or weighted sum method), results in loss of important information because of the compensation occurred for bad performance in some criteria and good performance in others [43]. In this research, the application of PROMETHEE II is proposed for estimating the suitability of sub-regions to a given crop. There is no need to assign quantities to qualitative criteria in this method, which makes it a reasonable choice in the case of dealing with several and diverse qualitative criteria like the problem addressed in this article. Notably, criteria weights (i.e. their relative importance degrees) are calculated using the best-worst method (BWM) [42]. In a practical sense, as shown in Fig. 1, different maps are integrated into a single map.

3.1.1. Determining the criteria weights

The best-worst method (BWM) proposed by Rezaei [42] as the most recent developed multi-criteria decision-making technique is used to estimate the criteria weights and calculating the suitability index of specific crops in each cropland. In this method, an expert determines the most and the least important criteria in suitability of a cropland for cultivation of a specific crop. Then, the expert conducts pairwise comparisons by assigning a number among 1 to 9 (according to Likert scale) as the importance degree of the most important (best) criterion over each criterion and the importance degree of each criterion over the least important (worst) criterion. For cultivating barley, the most and least important criteria were decided to be Salinity & alkalinity and topography, respectively. The results of the two pairwise comparison vectors

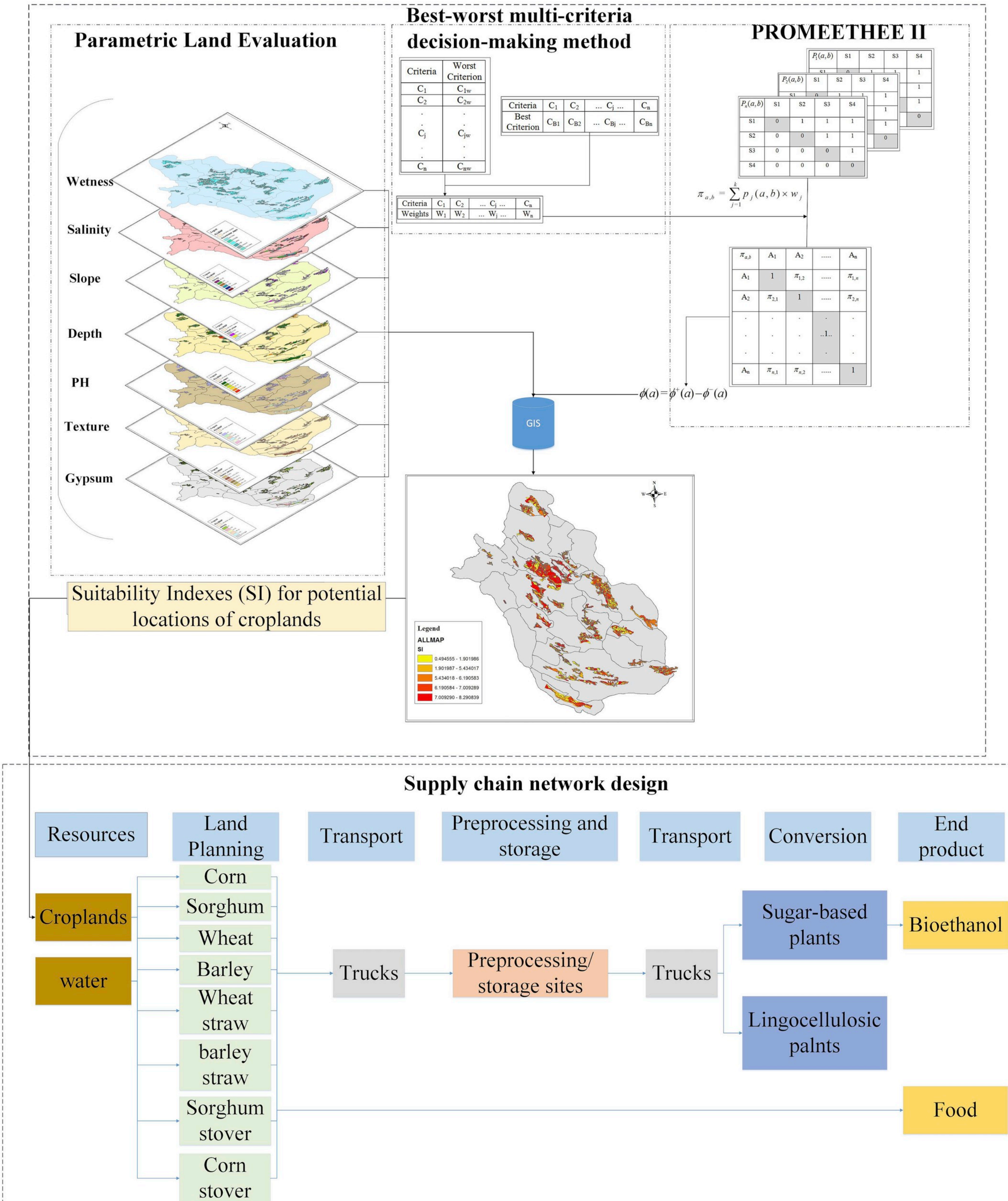

Fig. 1. A schematic representation of the overall proposed framework.

for this case study are shown in Tables 2 and 3. In this way, Table 2 shows the pairwise comparison vector between Topography (as the least important criterion in suitability of a cropland for cultivating barley), and the other criteria. a_{jW} denotes the importance degree of criterion j over the worst criterion (i.e. topography) where 1 indicates that criterion j is of the same importance as topography and 9 indicates that it is extremely more important than topography. For example, topography is of the same importance to itself, so it gets the value 1 and Salinity &

Table 1
The criteria for land suitability evaluation of Fars Province in Iran.

criteria	
Soil depth (cm)	
Soil texture	
Salinity and alkalinity	EC (ds/m)
	ESP (%)
Wetness	Groundwater depth (cm)
	Flooding hazards
Topography	Primary slope (%)
	Secondary slope (%)
	Micro-relief (cm)

Table 2
Pairwise comparison vector for the least important (worst) criterion (Topography) for barley.

Criteria	a_{jW}
Depth	2
Texture	3
Salinity & alkalinity	8
Wetness	7
Topography	1

Alkalinity is much more important than topography, so it gets the very high value of 8. Table 3 is interpreted the same with the difference that a_{Bj} is the importance degree of the best criterion, i.e. Salinity & Alkalinity, over criterion j.

The criteria weights are finally calculated using the following optimization model:

$$\min \ \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_w} - a_{jw} \right| \right\} \text{ s.t. } \sum_j w_j = 1 \ w_j \geq 0 \quad \forall j \tag{1}$$

where a_{Bj} and a_{jw} are extracted from the pairwise comparisons (as provided in Tables 2 and 3) and w_j denotes the weight of criterion j which is calculated upon solving model (1). Also, w_B and w_W denote the weights for the best and the worst criteria, respectively, which are also determined by solving model (1). The results of solving model (1) for barley are presented in Table 4.

As Table 4 shows, Salinity gets the highest weight while Topography gets the lowest.

3.1.2. PROMEETHEE II

PROMETHEE, developed by Brans [44] and further extended by Vincke and Brans [45], is a comprehensive MCDM method used in selecting among finite alternative actions in the presence of conflicting criteria [46]. This method has proved to be very useful due to its simplicity in concept and application in comparison to other MCDM methods [44]. Among different varieties of PROMETHEE, PROMETHEE II is the most frequently applied technique because it guarantees a fully ranked vector of alternatives [46]. Presence of various and heterogeneous criteria in this study makes this method specially suitable. In this section, PROMETHEEII is used to determine the suitability index of each alternative (here cropland) for different kinds of crops considered. The result is a set of suitability indices which will then be used to calculate the efficiency of land planing. For this purpose, two sets of information is required: criteria weights and the preference function chosen for each criterion by the decision maker [46]. The following 5 steps are applied to generate suitability indices of crops for each region (i.e. cropland).

Table 3
Pairwise comparison vector for the most important (best) criterion (Salinity & Alkalinity) for barley.

Criteria	Depth	Texture	Salinity	Wetness	Topography
a_{Bj}	7	6	1	2	8

Table 4
Results of criteria weights for barley in Fars province of Iran.

Criteria	Salinity	Wetness	Texture	Depth	Topography
Weights (w_j)	0.332	0.199	0.066	0.057	0.033

Step 1. The criteria are selected according to the tables provided by Givi [40] (Table 1). Also, given each criterion, a GIS layer is generated for the region (in our case study, we used the database provided by Pakparvar et al. [48] to generate the GIS layers).

Step 2. An evaluation matrix is extracted by merging all the layers. In this matrix, each array $C_{i,j}$ is the value of ith alternative in respect to the jth criterion. Fig. 2 represents the layers in a small region inside the area under study and Fig. 3 represents the merged layer for this small region.

Step 3. Here, for better illustration, we provide a preference matrix for each criterion instead of a preference function. Preference matrices are actually matrix representations of Sys and Givi tables. In Table 5, the array P_j (a,b) represents if cropland a is preferred to b according to the jth criterion (e.g. soil depth in Table 5). That is, if a cropland is preferred to another with respect to its soil depth, the corresponding array gets the number 1 otherwise, 0 is shown in the array. For instance, it can be extracted from the table that a cropland with soil depth in the range 20–50 cm is preferred to a cropland with soil depth of 10–20 cm.

Step 4. After making the preference matrices for each cropland along each criterion for each crop, they are merged to make the aggregated preference indices as follows:

$$\pi_{a,b} = \sum_{j=1}^{k} p_j(a,b) \times w_j \quad \forall (a,b) \in A \tag{2}$$

where $\pi_{a,b}$ denotes the overall preference of alternative a over b, and w_j is the weight associated with criterion j. Note that these weights have already been estimated by BWM in Section 3.1.1.

Step 5. The outranking flows are calculated. For each alternative (e.g. a) when compared with (n-1) other alternatives (where A denotes the alternatives set), the positive and negative outranking flows are calculated as follows:

$$\varphi_a^+ = \frac{1}{n-1} \sum_{x \in A} \pi_{a,x} \quad \forall a \tag{3}$$

$$\varphi_a^- = \frac{1}{n-1} \sum_{x \in A} \pi_{a,x} \quad \forall a \tag{4}$$

where φ_a^+ and φ_a^- denote the positive and negative outranking flows for alternative a, respectively.

Step 6. Net outranking flows are calculated as follows:

$$SI_a = \varphi_a = \varphi_a^+ - \varphi_a^- \quad \forall a \tag{5}$$

The net outranking flow provides each cropland with a land suitability index for each crop which is then fed to the supply chain network design optimization model.

3.2. Biomass supply chain network design

In this section, a bi-objective mixed-integer linear programming (MILP) model is proposed to formulate the optimal design and planning of the bioethanol supply chain network depicted in Fig. 1 considering competition of food and biomass feedstock over the available croplands. The developed model aims at minimizing the total cost and maximizing the total land suitability. Decisions include providing a tactical plan for the available cropland (i.e. the land-use plan, material flow, and inventory levels for each year within a three-year planning horizon) as well as strategic facility location decisions. In order to evaluate whether such integration of strategic and tactical decisions improves former formulations of bioethanol SCs, three modeling scenarios are assessed.

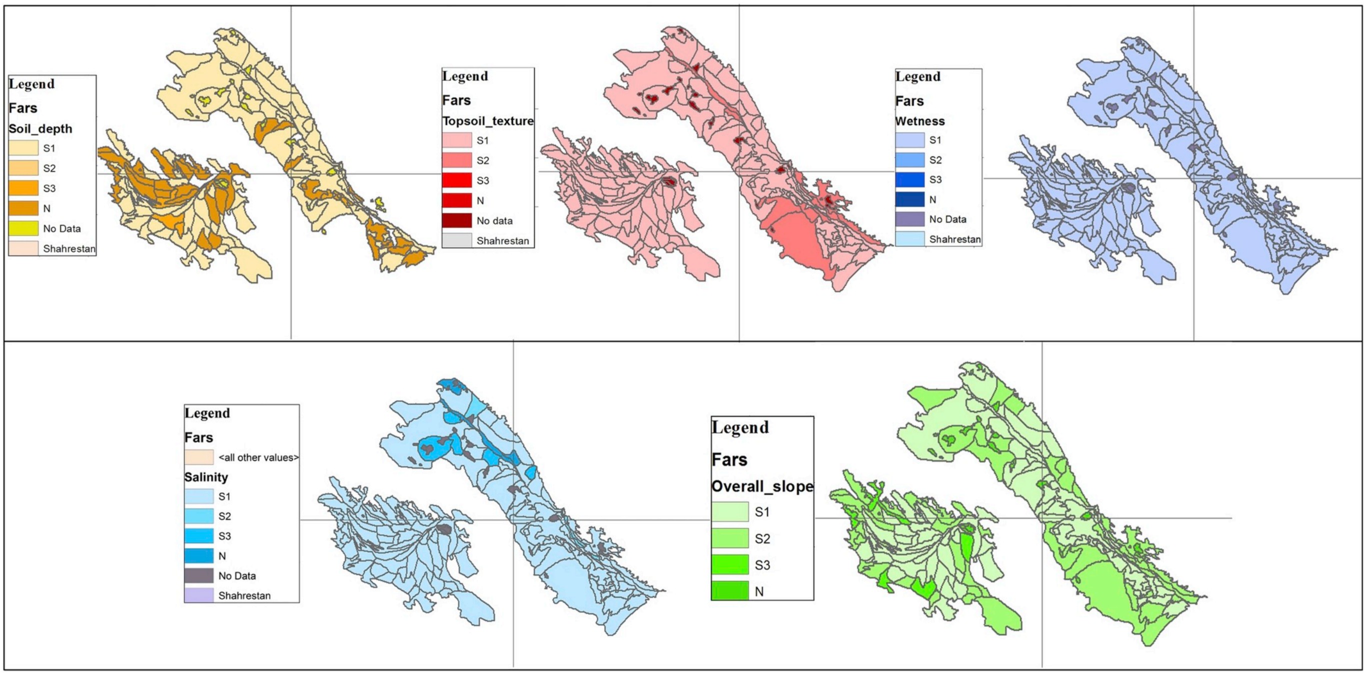

Fig. 2. Criteria Maps of Marvdasht county, Fars province for eight land suitability indexes.

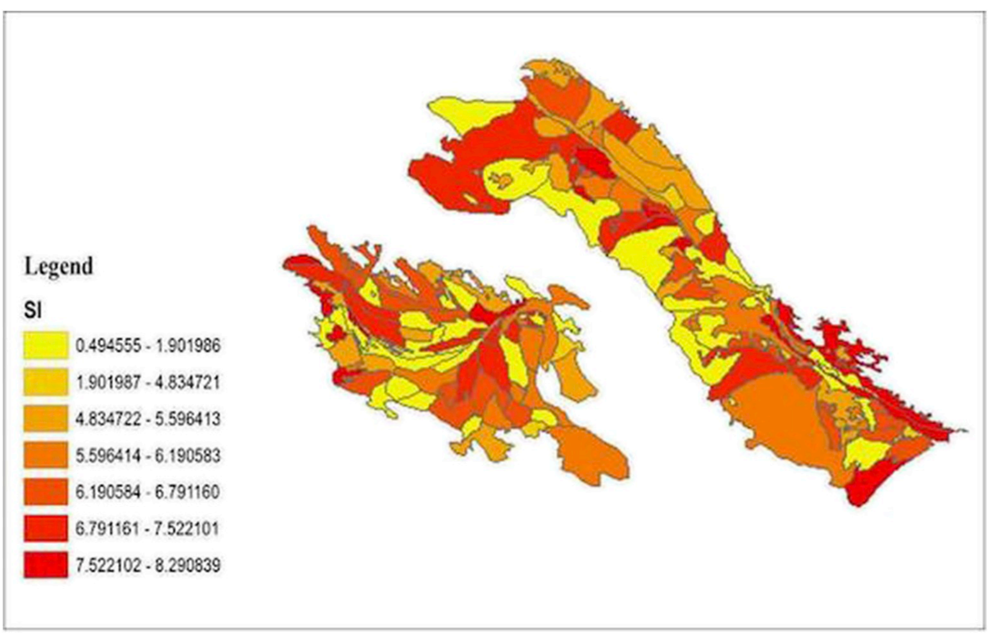

Fig. 3. Aggregated Criteria Map for Marvdasht county, Fars province.

Table 5
Preference matrix for soil depth (sorghum).

$P_j(a,b)$	<10(S1)	10-20 (S2)	20-50(S3)	>50(S4)
<10(S1)	0	1	1	1
10-20(S2)	0	0	1	1
20-50 (S3)	0	0	0	1
>50(S4)	0	0	0	0

In the first scenario, the complete supply chain (as depicted in Fig. 1) is optimized for the aforementioned two objectives. In the second scenario, the land plan is first optimized for the maximum suitability and then the rest of the supply chain is optimized for the minimum cost. In fact, the second model takes the land plan (i.e. available biomass feedstock) as given and designs the supply chain network accordingly (Fig. 1 and Fig. 4). In the third scenario, a bioethanol supply chain network design (BSCND) problem is first solved for the minimum cost and then according to the determined decisions, the land plan is optimized for the maximum suitability. In the next section, after applying the three formulations to a real case study, their performances are evaluated and discussed.

Biomass resource

Inequality (6) restricts croplands to be assigned to only one crop in each time period.

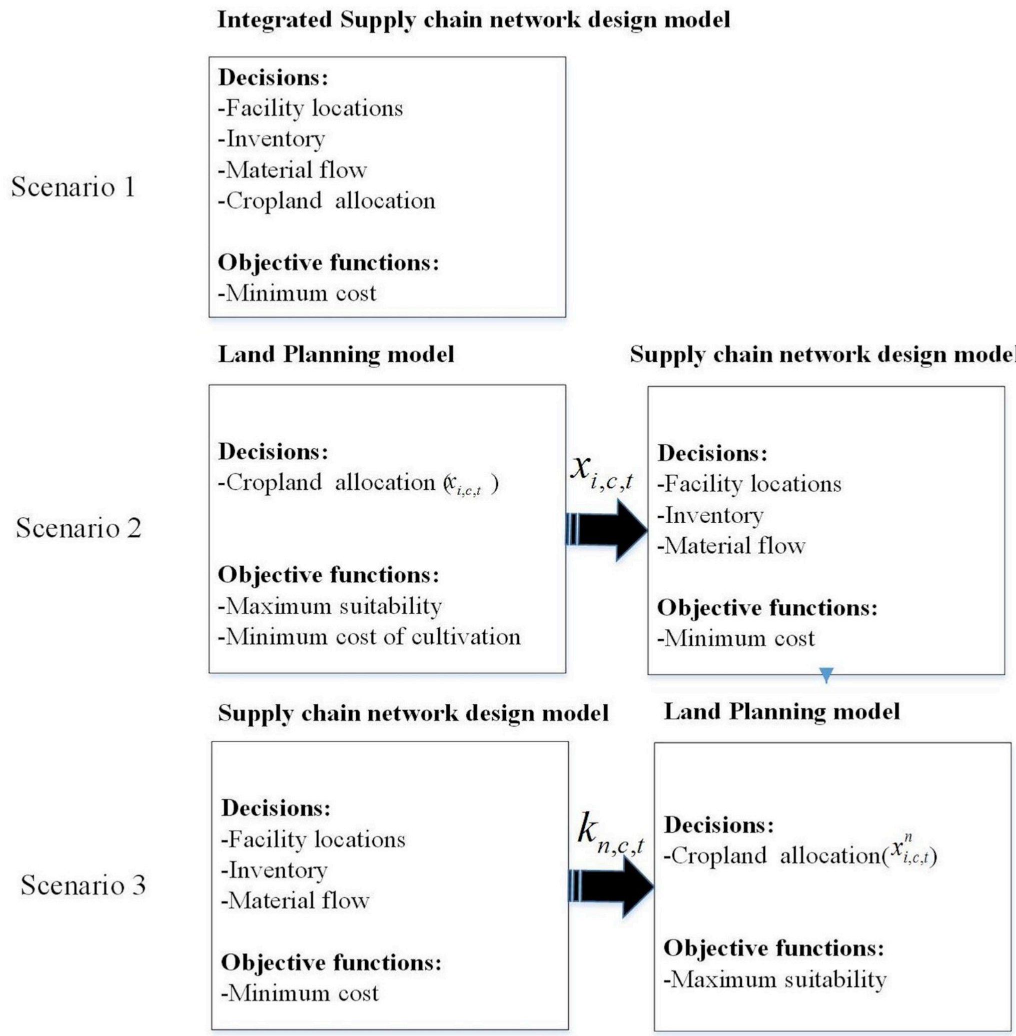

Fig. 4. Description of modeling scenarios for optimization of bioethanol pathway in Fars province of Iran.

$$\sum_c x_{i,c,t} \le 1 \quad \forall i,t \tag{6}$$

Constraints (7) and (8) show that the total amount of harvested main crop or residue of type c in supply zone (cropland) i is constrained by the area of the cropland multiplied by the corresponding crop yield considering the harvest loss of biomass.

$$chrv_{i,c,t} \le x_{i,c,t}.area_i.yl_c.(1-hloss_{c,g}) \quad \text{for} \quad g=1, \quad \forall i,c,t \tag{7}$$

$$rhrv_{i,c,t} \le \mu_c.x_{i,c,t}.area_i.yl_c.(1-hloss_{c,g}) \quad \text{for} \quad g=2, \quad \forall i,c,t \tag{8}$$

As crop production implies a high amount of water consumption, Constraint (9) limits the water consumption in the process with the maximum sustainable use of renewable water in the region.

$$\sum_i\sum_c win_c.chrv_{i,c,t} \le mw_t \quad \forall t \tag{9}$$

This constraint and the relative data are extracted from Gerbens-Leenes et al. [49].

Constraint (10) states that for first generation biomass (main crops), the harvested main crop should be assigned to both food purposes ($food_{i,c,t}$) and biomass feedstock for bioethanol production ($hf_{i,c,g,t}$). Constraint (11) states that the second generation biomass feedstock for bioethanol production in a supply zone cannot exceed the amount of harvested residue from the supply zone ($rhrv_{i,c,t}$). Also, constraint (12) enforces that the amount of cultivated main crop assigned to food satisfies the food demand.

$$hf_{i,c,g,t} + food_{i,c,t} \le chrv_{i,c,t} \quad \text{for} \quad g=1, \quad \forall i,c,t \tag{10}$$

$$hf_{i,c,g,t} \le rhrv_{i,c,t} \quad \text{for} \quad g=2, \quad \forall i,c,t \tag{11}$$

$$\sum_i food_{i,c,t} \ge fd_{c,t} \quad \forall c,t \tag{12}$$

In the case study, it is assumed that the food demand for crop c is the same as the current cultivation of crop c for food purposes (derived from Annual Statistics on Agriculture published by Iran's Organization of Statistics (2013) [47]) and grows linearly by the same growth rate as the average of the past five years.

Transportation of biomass to preprocessing/storage sites

As stated in inequality (13), the amount of transported biomass produced in supply zone i and transported to preprocessing sites collectively may not exceed the harvested biomass assigned to bioethanol production feedstock in each time period.

$$\sum_s htr_{i,c,g,s,t} \le hf_{i,c,g,t} \quad \forall i,c,g,t \tag{13}$$

Mass balances of raw and preprocessed biomass in preprocessing/storage sites

Constraint (14) indicates that the amount of harvested biomass shipped into preprocessing/storage site s during time period t ($htr_{i,c,g,s,t}$) plus the inventory from the previous time period ($hinv_{c,g,s,t-1}$)

considering deterioration equals the inventory of raw biomass in time period t plus the amount of raw biomass which is preprocessed ($bfp_{c.g.s.t}$).

$$\sum_i htr_{i,c,g,s,t} + (1 - drate_{c,g})hinv_{c,g,s,t-1} = hinv_{c,g,s,t} + bfp_{c,g,s,t} \quad \forall s, c, g, t \neq 1 \tag{14}$$

Constraint (15) indicates that the amount of preprocessed biomass in site s in time period t plus the inventory of preprocessed biomass at the end of time period t-1 equals the inventory at the end of time period t plus transported preprocessed biomass to refinery sites collectively.

$$pb_{c,g,s,t} + pinv_{c,g,s,t-1} = pinv_{c,g,s,t} + \sum_r ptr_{c,g,s,r,t} \quad \forall c, g, s, t \neq 1 \tag{15}$$

Constraint (16) limits the amount of preprocessed biomass by the amount of raw biomass which is preprocessed multiplied by the conversion factor in preprocessing sites ($\theta_{c,g}$).

$$pb_{c,g,s,t} \leq \theta_{c,g}.bfp_{c,g,s,t} \quad \forall c, g, s, t \tag{16}$$

Opening and capacity determination of preprocessing/storage sites

Constraint (17) shows that if preprocessing/storage site s with capacity sc is opened, the amount of preprocessed biomass in a certain time period may not exceed the selected capacity level.

$$\sum_c \sum_g pb_{c,g,s,t} \leq \sum_{sc} scap_{sc}.sl_{s,sc} \quad \forall s, t \tag{17}$$

Constraint (18) indicates that only one capacity level may be selected for a preprocessing/storage site.

$$\sum_{sc} sl_{s,sc} \leq 1 \quad \forall s \tag{18}$$

Conversion of preprocessed biomass to biorefinery

Constraint (19) indicates that the amount of bioethanol produced in biorefinery r may not exceed the amount of dry matter in transported preprocessed biomass from storage sites to biorefinery r multiplied by ethanol yield in the biorefinery.

$$\sum_s \sum_c ptr_{c,g,s,r,t}.eyl_{c,g}.dm_{c,g} \geq ef_{r,g,t} \quad \forall r, g, t \tag{19}$$

Opening and capacity determination of biorefineries

Constraint (20) enforces that if candidate biorefinery site r, for generation (technology) g and the capacity level rc is selected, the amount of bioethanol produced in a certain time period may not exceed the selected capacity level.

$$ef_{r,g,t} \leq rl_{r,g,rc}.rcap_{rc} \quad \forall r, g, rc, t \tag{20}$$

Constraint (21) shows that only one capacity level and technology type may be selected for a biorefinery.

$$\sum_g \sum_{rc} rl_{r,g,rc} \leq 1 \quad \forall r \tag{21}$$

Demand satisfaction

Constraint (22) shows that the demand fulfillment of bioethanol:

$$\sum_r \sum_g ef_{r,g,t} \geq ed_t \quad \forall t \tag{22}$$

3.2.1. Scenario 1: integrated formulation

In this scenario, the supply chain (Fig. 1) is optimized for the two objectives as a whole. Constraints (6)–(22) define the feasible region. The first objective aims to economically optimize the supply chain and the second objective maximizes the suitability of croplands to the crops cultivated in them in each time period.

The total cost of the supply chain includes the cost of production and cultivation of biomass, pre-processing, holding costs, conversion and transportation. Equation (23) calculates the cost of harvesting the biomass. Equation (24) states the cost of pre-processing which includes the fixed and variable costs of investing in a pre-processing site, which depend on the capacity of the site, and the operating cost, which depends on the material flow that goes through the site. Equation (25) calculates the inventory holding cost of both harvested and preprocessed biomass in the preprocessing/storage facilities. Equation (26) shows the investment (fixed and variable) cost of opening biorefineries plus operating cost of producing bioethanol in those sites. Equation (27) adds up transportation costs in the supply chain, including cost of moving the harvested biomass to pre-processing sites and moving the preprocessed material to the biorefineries. Finally, Eqeq (28) adds up all the costs to form the total cost objective function for this model.

$$C_{hrv} = \sum_t \sum_c \sum_g \sum_t hf_{i,c,g,t}.hcst_{c,g} \tag{23}$$

$$C_{sp} = \sum_s \sum_{sc} (sfocst_{sc} + svo\ cost_{sc}.scap_{sc})sl_{s,sc} + \sum_s \sum_c \sum_g \sum_t pop\ cost_{c,g}.pb_{c,g,s,t} \tag{24}$$

$$C_{inv} = \sum_s \sum_c \sum_g \sum_t invh\ cost_{c,g}.(hinv_{c,g,s,t}.hvol_{c,g} + pinv_{c,g,s,t}.pvol_{c,g}) \tag{25}$$

$$C_{rfn} = \sum_r \sum_{rc} (rfo\ cost_{rc} + rvo\ cost_{rc}.rcap_{rc}).rl_{r,rc} + \sum_r \sum_g \sum_t rop\ cost_{c,g}.ef_{r,g,t} \tag{26}$$

$$C_{tr} = \sum_l \sum_s \sum_c \sum_g \sum_t (lucst_{c,g} + htrcst_{c,g}.dis_{i,s}).htr_{i,c,g,s,t} + \sum_s \sum_r \sum_c \sum_g \sum_t (lupcst_{c,g} + ptrcs_{c,g}.dis_{s,r}).ptr_{c,g,s,r,t} \tag{27}$$

$$Min \quad Z_1 = C_{hrv} + C_{sp} + C_{inv} + C_{rfn} + C_{tr} \tag{28}$$

Furthermore, the total suitability of croplands to their crops is estimated as a weighted sum of suitability indices of croplands for crops. Notably, the suitability indices ($SI_{i,c}$) are calculated as described in Section 3.1.2, Eq. (5). In Fact, the methodology described in Section 3.1 was used to calculate suitability indices (SI) for every crop c and cropland i.

$$Max \quad Z_2 = \sum_i \sum_c \sum_t x_{i,c,t}.SI_{i,c}.area_i \tag{29}$$

3.2.2. Scenario 2: Hierarchical Formulation I

In the Hierarchical Formulation I, two MILP models are sequentially solved (Fig. 4). The first one determines the optimum land plan and the second one optimizes the rest of the supply chain (i.e. the SCND model). This perspective is specially useful if the total capacity of biofuel production is sought in a region according to land limitations. In this perspective, the total available agricultural lands are planned and then the planned cultivated crops are assigned to be used as biofuel feedstock or food. The second model solved in this scenario, takes the available biofuel feedstock as input and optimizes facility locations and capacity levels, as well as material flow between facilities for the cost objective.

First model (Tactical land planning): In the tactical land planning model, the constraints include inequalities (6)–(12) and (30). The land suitability objective function is the same as equation (29). In this model, the suitabilities are maximized and the cost of cultivating and harvesting biomass is minimized. Equation (31) represents the cost objective for the land planning model. Also, inequality (30) makes sure that enough biomass feedstock will be available for the rest of the supply chain.

$$\sum_{i,c,g} hf_{i,c,g,t}.\theta_{c,g}.eyl_{c,g}.dm_{c,g} \geq ed_t \quad \forall t \tag{30}$$

$$Min \quad Z_3 = \sum_i \sum_c \sum_g \sum_t hf_{i,c,g,t}.hcost_{c,g} \tag{31}$$

Second model (Supply chain network design): In the supply chain network design model, the rest of the supply chain is optimized for the lowest cost of facilities establishment, transportation, and inventory holding. The constraints for this model includes inequalities (14)–(22) and the objective function is presented as Equation (32).

$$Min \quad Z_4 = C_{hrv} + C_{sp} + C_{inv} + C_{rfn} + C_{tr} \tag{32}$$

where C_{hrv}, C_{sp}, C_{inv}, C_{rfn}, C_{tr} are calculated by Equations (23)–(27).

3.2.3. Scenario 3: Hierarchical Formulation II

In the Hierarchical Formulation II, two MILP models are solved sequentially (Fig. 4). The first one optimizes the decisions regarding facility locations, inventory holding, and material flow between facilities for the cost objective and the second one optimizes the land plan for the maximum suitability. In this perspective, the network is designed and the required feedstock is determined in the first model. Then, the land plan is determined to fulfill the required feedstock by the second model.

First model (Supply chain network design): In the first model of Hierarchical Formulation II, the supply chain network is designed for optimum cost. As the cultivation plan for croplands is not determined in this model, there is no need to include detailed information of croplands. Therefore, the croplands are collapsed into counties. The counties are indexed with symbol n and the model determines the optimal area in each county for cultivation of each crop. Then, the determined areas are fed into the second model to determined the detailed land plan.

Inequality (33) makes sure that the area assigned to the cultivation of crops does not exceed the available area of agricultural lands.

$$\sum_c K_{n,c,t} \le A_n \quad \forall n, t \tag{33}$$

where $K_{n,c,t}$ denotes the area in county n in which crop c is cultivated in period t. Also, A_n is the area of county n. The total amount of harvested main crop or residue of type c in supply zone (county) n is constrained by the total area of all the croplands that fall into the county multiplied by the corresponding crop yield and considering the harvest loss of biomass (constraints (34) and (35)). Inequality (36) restricts the total amount of water. Constraints (37)–(39) represent the same concept as the inequalities (10)–(12). Constraints (40) and (41) balance the flow of harvested biomass to preprocessing/storage sites. The rest of the constraints are the same as constraints (15)–(22).

$$cchrv_{n,c,t} \le k_{n,c,t}.yl_c.\left(1 - hloss_{c,g}\right) for \quad g = 1, \quad \forall n, c, t \tag{34}$$

$$crhrv_{n,c,t} \le \mu_c.k_{n,c,t}.yl_c.\left(1 - hloss_{c,g}\right) \quad for \quad g = 2, \quad \forall n, c, t \tag{35}$$

$$\sum_n \sum_c win_c.cchrv_{n,c,t} \le mw_t \quad \forall t \tag{36}$$

$$chf_{n,c,g,t} + cfd_{n,c,t} \le cchrv_{n,c,t} \quad for \quad g = 1, \forall n, c, t \tag{37}$$

$$chf_{n,c,g,t} \le crhrv_{n,c,t} \quad for \quad g = 2, \quad \forall n, c, t \tag{38}$$

$$\sum_n cfd_{n,c,t} \ge fd_{c,t} \quad \forall c, t \tag{39}$$

$$\sum_s chtr_{n,c,g,s,t} \le chf_{n,c,g,t} \quad \forall n, c, g, t \tag{40}$$

$$\sum_n chtr_{n,c,g,s,t} + \left(1 - drate_{c,g}\right) hinv_{c,g,s,t-1} = hinv_{c,g,s,t} + bfp_{c,g,s,t} \quad \forall c, g, s, t \ne 1 \tag{41}$$

$$pb_{c,g,s,t} + pinv_{c,g,s,t-1} = pinv_{c,g,s,t} + \sum_r ptr_{c,g,s,r,t} \quad \forall c, g, s, t \ne 1 \tag{42}$$

$$pb_{c,g,s,t} \le \theta_{c,g}.bfp_{c,g,s,t} \quad \forall c, g, s, t \tag{43}$$

$$\sum_c \sum_g pb_{c,g,s,t} \le \sum_{sc} scap_{sc}.sl_{s,sc} \quad \forall s, t \tag{44}$$

$$\sum_{sc} sl_{s,sc} \le 1 \tag{45}$$

$$\sum_s \sum_c ptr_{c,g,s,r,t}.eyl_{c,g}.dm_{c,g} \ge ef_{r,g,t} \quad \forall r, g, t \tag{46}$$

$$ef_{r,g,t} \le rl_{r,g,rc}.rcap_{rc} \quad \forall r, g, rc, t \tag{47}$$

$$\sum_g \sum_{rc} rl_{r,g,rc} \le 1 \quad \forall r \tag{48}$$

$$\sum_r \sum_g f^{ethanol}_{r,g,t} \ge ed_t \quad \forall t \tag{49}$$

The total cost objective function in this model is as follows:

$$\begin{aligned} Min \quad Z_5 = & \sum_n \sum_c \sum_g \sum_t chf_{n,c,g,t}.hcst_{c,g} + \sum_s \sum_{sc} (sfocst_{sc} + svo\ cost_{sc}.scap_{sc}) sl_{s,sc} + \\ & \sum_s \sum_c \sum_g \sum_t pop\ cost_{c,g}.pb_{c,g,s,t} + \\ & \sum_s \sum_c \sum_g \sum_t invh\ cost_{c,g}.\left(hinv_{c,g,s,t}.hvol_{c,g} + pinv_{c,g,s,t}.pvol_{c,g}\right) + \\ & \sum_r \sum_{rc} (rfo\ cost_{rc} + rvo\ cost_{rc}.rcap_{rc}).rl_{r,rc} + \sum_r \sum_g \sum_t rop\ cost_{c,g}.ef_{r,g,t} + \\ & \sum_n \sum_s \sum_c \sum_g \sum_t \left(lucst_{c,g} + htrcst_{c,g}.cdis_{n,s}\right).chtr_{n,c,g,s,t} \\ & + \sum_s \sum_r \sum_c \sum_g \sum_t \left(lupcst_{c,g} + ptrcst_{c,g}.dis_{s,r}\right).ptr_{c,g,s,r,t} \end{aligned} \tag{50}$$

Second model (Land planning): In the second model Hierarchical Formulation II, the land plan is determined given the locations and the material flow determined by the first model. Constraint (51) restricts the total area assigned to cultivation to be less than the determined total area that was determined for cultivation in the first model. Also, $K^*_{n,c,t}$ denotes the determined optimal area in county n to cultivate crop c in period t which is obtained from the first model. Furthermore, constraint (52) makes sure that no cropland is assigned to more than one crop.

$$\sum_i x^n_{i,c,t}.area_i \le K^*_{n,c,t} \quad \forall n, c, t \tag{51}$$

$$\sum_c x^n_{i,c,t} \le 1 \quad \forall n, i, t \tag{52}$$

where $x^n_{i,c,t}$ is 1 if cropland i, which is in county n, is assigned for cultivation of crop c in time t. The objective function in this model (53) is the same as the second objective value in the integrated formulation. In this model, the overall suitability of crops with croplands is maximized.

$$Max \quad Z_6 = \sum_n \sum_i \sum_c \sum_t x^n_{i,c,t}.SI_{i,c}.area_i \tag{53}$$

3.3. Solution methodology

The resulted bi-objective MILP models are solved using the well-known Augmented Ɛ-Constraint (AUGMECON) method. AUGMECON, developed by Mavrotas [48], is an extension to the Ɛ-constraint method for solving Multi-Objective Mathematical Programming (MOMP) problems. This method avoids weakly Pareto optimal solutions and makes finding the efficient solutions faster than Ɛ-constraint method. Consider the following bi-objective problem:

$$\begin{aligned} &min\{f_1(x), f_2(x)\} \\ &s.t. \quad x \in S \end{aligned}$$

where x is the vector of decision variables, $f_1(x)$ is the first objective function and $f_2(x)$ is the negative form of the second objective function as it is of maximization type. A feasible solution x is efficient if there is no feasible solution like $x' \neq x$ such that $f_i(x') \le f_i(x)$ for i = 1,2 and at least there is one i for which $f_i(x') < f_i(x)$. The AUGMECON method for the bi-objective problem guarantees efficiency of solutions. In order to implement AUGMECON, the following steps are taken:

Step 1: First, the ranges of objective functions should be calculated. The minimum values of objective functions, or their positive ideal solutions (PIS), are easily attainable through separately optimizing each objective. Calculating the worst values (i.e. nadir values), however, would be more challenging as we are only interested in the efficient set. We need to make sure that the obtained solutions would be Pareto optimal, so we need to make sure that in the instance of optimality in one objective, the other objective is at its best value. Therefore, as proposed by [48], we calculate the Lexicographic optimization model for each objective. Let x_1^* and x_2^* be the optimal solutions for the first and second objectives, respectively and $f_1(x_1^*)$ and $f_2(x_2^*)$ be the corresponding objective functions' minimum values. Therefore, the Lexicographic optimization models take the following form:

$$\begin{aligned} &SOP_i \\ &min \quad f_i(x) \\ &s.t. \\ &f_j(x) \le f_j\left(x_j^*\right) \quad j \neq i \\ &x \in X \end{aligned} \tag{54}$$

Model (54) searches through the solutions which make the objective function j optimal and chooses the best ones in terms of objective function i. The obtained value for objective function i is in fact the negative ideal solution (NIS).

Step 2: Vary the value of ε in the range of PIS and NIS of the second objective and plug the obtained values in model (43). Often, the range is segmented into equal parts, and the grid points are used as the values of ε [50].

$$\begin{aligned} &min \quad f_1(x) - eps \times s_2 \\ &s.t. \\ &f_2(x) + s_2 = \varepsilon \\ &x \in X; s_2 \in R^+ \end{aligned} \tag{55}$$

where ε is the satisfaction level of the second objective, eps is a chosen parameter in the range of 10^{-3} and 10^{-6} and s_2 is a slack variable. By varying the satisfaction level, more efficient solutions could be obtained. According to the Proposition offered in Ref. [51], the optimal solutions obtained from (55) are efficient.

4. Results and discussion

We considered five preprocessing site capacities, namely, 221, 294, 442, 883, 1472 Gigagrams for cultivated biomass per year (as proposed by Lambert & Middleton [52]) and three biorefinery capacities 127, 316, 633 million liters (as proposed by Festel et al. [53]). Two conversion technology paths are considered for sugar-based and lignocellulosic biomass. The demand for bioethanol is considered to be blended by 3% with fossil fuels (E3), to satisfy the transportation demand of the country. The time horizon was considered three years, during which bioethanol demand is considered to grow with a constant rate. Harvested and preprocessed biomass may be stored at the end of each year. The area, which consists of 19 counties, is divided into 3000 sub-regions each of which performs differently in terms of suitability to different crops. The results for the three scenarios are presented in the following sections.

4.1. Scenario1-integrated formulation

In the integrated formulation, the BSCND is optimized for the two objectives of minimum cost and maximum suitability. The resulted amounts of PIS and NIS for the case study are presented in Table 6. Then, the amounts of ε are calculated and the respective MILP Single Objective Problems (SOP) are solved. We considered six different amounts for ϵ, and therefore 6 SOPs are solved and 6 series of results are obtained. Fig. 5 presents the estimation of the Pareto front obtained from solving the 6 SOPs. In this figure values of the optimum results are normalized. This figure shows how one objective is improved by slight changes in the other objective, in other words the trade-off between the two objectives. The results of land assignment and network design for one of the solutions, namely Solution #2, is presented in Figs. 6–9. Fig. 6 represents the determined cropland allocations and facility locations in solution #2. While the optimal solution specifies only 316 million liters per year to bioethanol production from 1st generation biomass, it allows more than 1000 million liters of bioethanol production from 2nd generation biomass. Although there is a substantial cost gap between the 1st and 2nd generation bioethanol, the land and water limitations in Fars province, restricts the harvestable agricultural products for energy use. As can be seen, wheat is the most cultivated product due to its high demand for food purposes in the region. In 2014, wheat contributed to roughly 20% of total cultivation in Fars province [47]. Fig. 7 represents the determined portion of cultivations to food and energy and Fig. 8 illustrates the proportion of different biomass types used in producing bioethanol. It can be seen that the most recommended biomass feedstock in the region is the waste and residual of wheat. Also, the first generation wheat and corn, are not recommended, which is consistent with their high demand as food. This implies that high production of wheat for food purposes and high percentage of waste (50%) in wheat production, makes this crop an attractive feedstock for biofuel production. Also, barely is the most attractive among the first-generation resources.

The current land allocations for counties inside the region and proposed land area allocations for the counties by the model are presented

Table 6
Results of positive and negative ideal solutions for objective functions of integrated model in Scenario1.

Objective Function	Positive Ideal Solution (PIS)	Negative Ideal Solution (NIS)
Z_1	2.3702E+9 (min Z_1,s.t. $x \in X$)	2.7779E+9 (min Z_1,s.t. $Z_2 \ge Z_2^*$, $x \in X$)
Z_2	2.799E+11 (min Z_2,s.t. $x \in X$)	1.539E+11 (min Z_2,s.t. $Z_1 \ge Z_1^*$, $x \in X$)

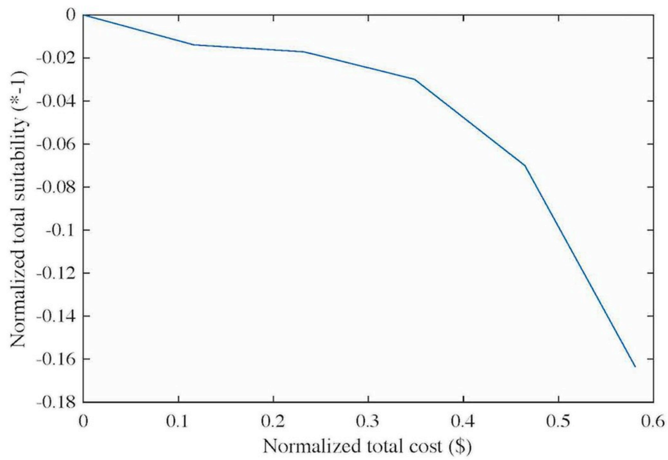

Fig. 5. The pareto front of integrated model in Scenario 1.

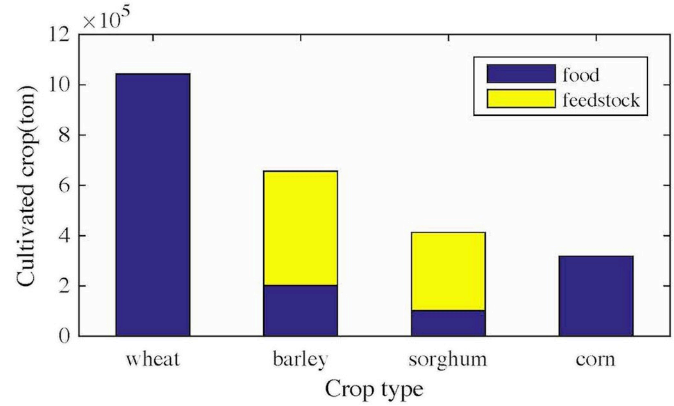

Fig. 7. Tons of cultivated main crops used as food or feedstock in Solution #2 of Scenario 1.

in Fig. 9 and Fig. 10. The three counties of Laar, Marvdasht, and Shiraz are assigned to provide a noticeable proportion of the produced crops in all of the solutions. This result is probably due to the vast area of available agricultural lands and their overall high compatibility with studied crops. This is consistent with the current high amounts of crop production in these counties (Appendix A). As shown in Fig. 9 and Fig. 10, in both scenarios Solution 2 is the most similar one to the current land area assignment in the region. This shows that a slight modification in land planning in the region could improve the cost and sustainability of agriculture in the region and make biomass production more feasible. Also, Fig. 11 shows that in exchange for a small increase in the overall cost of the supply chain, land assignment could be determined much more efficiently. To be precise, while Solution 1 only considers the cost objective, Solution 2 also considers the land suitability and as a result, the suitability objective in Solution 2 is 16% higher than Solution 1, whereas its cost is only 1.2% higher.

4.2. Scenario 2- Hierarchical Formulation I

In Hierarchical Formulation I, the first model (i. e. Land planning model), is optimized according to the two objectives of minimum cost and maximum suitability. A similar Augmented Ɛ-Constraint procedure is used in solving the bi-objective problem of this scenario. The results of PIS and NIS of the two objectives for this model are presented in Table 7. As the second objective (suitability) is the same in the land planning model in Hierarchical Formulation I and the integrated model, the two models may be compared on the basis of the first objective (Table 8). In other words, if with the same level of sustainability in both formulations, the one which is lower in the total cost, outperforms the other one.

As described in Table 8, the cost objective is lower in the integrated model for all ε amounts. This clearly shows that solving an integrated land plan-network design problem results in lower costs for the whole supply chain. It can be concluded that the results obtained in the Hierarchical Formulation I represent a sub-optimal solution for the supply

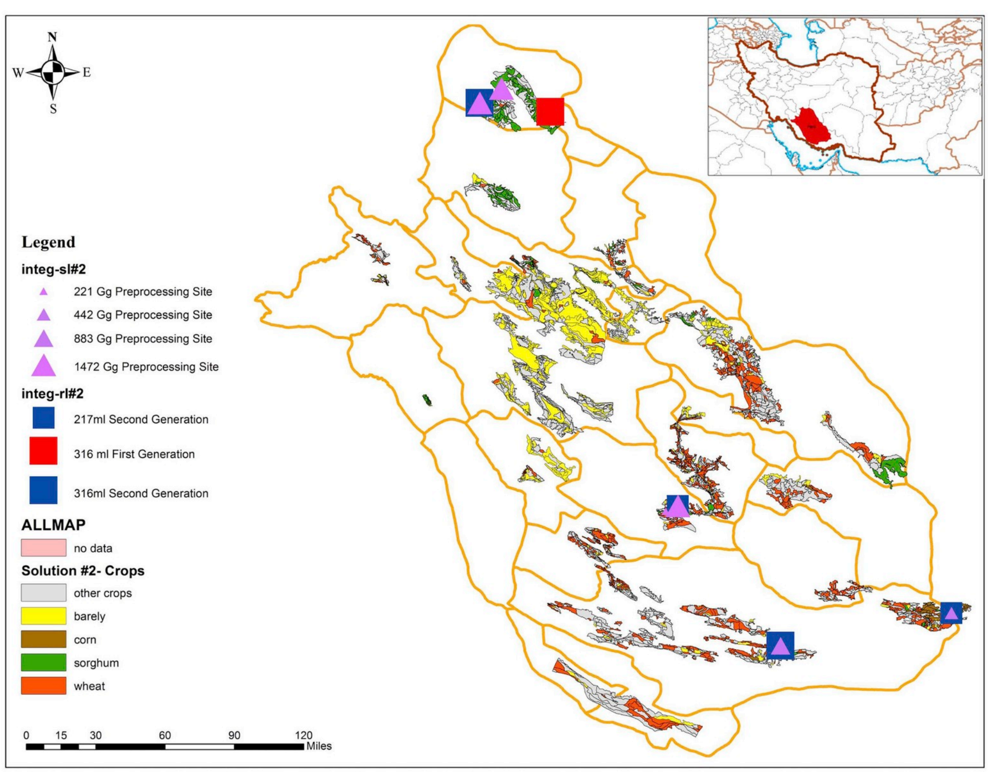

Fig. 6. The land allocation results of Solution #2 in Scenario 1 for the fist year.

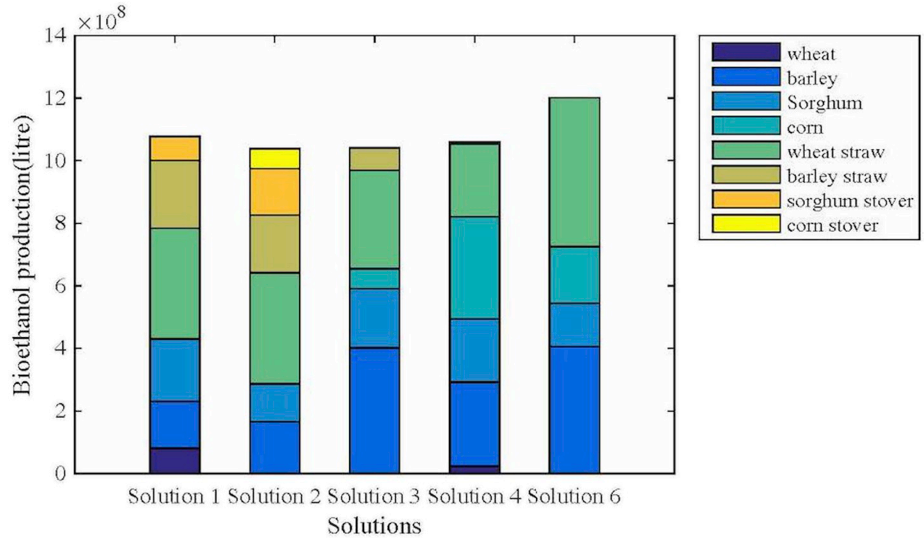

Fig. 8. Bioethanol production by different resources in Scenario 1 in year 1.

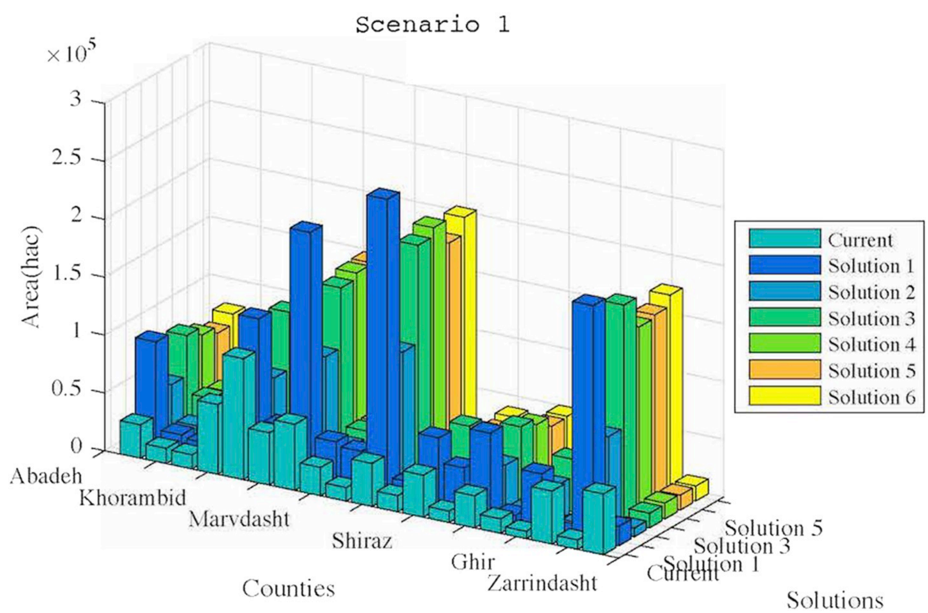

Fig. 9. Total cultivation in counties according to land allocation results for year 1 (Scenario 1).

chain network design problem. Fig. 12 presents the estimation of the Pareto front obtained from solving 6 SOPs in Scenario 2. In this figure values of the optimum results are normalized. In Fig. 13, the left side figure shows the land plan for Solution #2 determined by the first model; and the right side figure shows the determined facility locations by the second model. The DM may prefer one of the Pareto solutions according to the importance of the economic objective versus the land suitability objective. Using the method provided here the DM optimizes the suitability of croplands as well as the cost of the supply chain simultaneously. Overall, it seems that the 2nd solution would be a good choice, since it does not significantly change the agricultural landscape of the region, yet, it performs very well in both suitability and economic terms.

The results of this scenario suggests wheat and corn to be of the highest harvest amounts and sorghum to be the lowest. Unlike in Scenario 1, barely is not considered an attractive crop in this scenario. The difference is that in the land planning phase in this scenario, the cost objective is not considered. This could mean that although barely makes a cost-effective candidate for the first-generation biofuel production, it is not as consistent with the region as wheat and corn. Nevertheless, consistent with the results obtained from Scenario 1, Laar, Marvdasht, and Shiraz are the most attractive counties for crop production.

4.3. Scenario 3 - Hierarchical Formulation II

In Hierarchical Formulation II, two single objective problems are sequentially solved. The first one determines the facility locations, inventory levels, and material flow for the minimum cost while the second one determines the land plan for maximum suitability according to the results obtained from the first model. In Fig. 14, the left side figure shows the amount of the assigned level of cultivation in counties and the determined locations of facilities by the first model and the right side figure shows the determined land plan by the second model. Table 9 represents the obtained solutions of all scenarios including Scenario 3. Appendix B shows the determined cultivation areas in hac in each of the three scenarios (see Fig. 15).

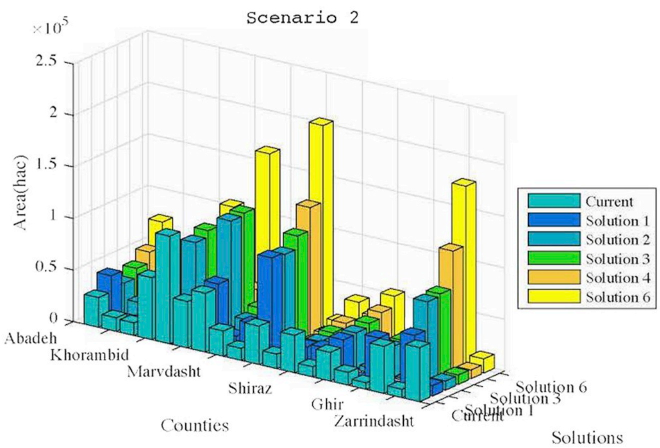

Fig. 10. Total cultivation in counties according to land allocation results for year 1 (Scenario 2).

In this scenario, first the areas to be assigned to cultivation of each crop is determined according to the minimum cost objective, and then the specific land plan is determined according to the suitability objective. The logic behind this procedure is that if all the decisions are not determined simultaneously, first the long-term decisions, (i.e. facility locations and capacity determination), should be made and then the tactical decisions (i.e. land plan), should be made accordingly. As Table 9 shows, this scenario outperforms Scenario 2 in the economic objective function, yet it is dominated by Scenario 1 which proves to induce the best results for the whole problem. This means that integrating land planning and network design improves the result of the whole supply chain.

Consistent with the results obtained from Scenarios 1 and 2, Laar, Marvdasht, and Shiraz are the highest cultivated counties. Also, consistent with scenario 1, wheat is the most attractive crop in this scenario.

4.4. Insights and policy recommendations

The results of the case study contain important policy making insights. As opposed to the common belief that enough agricultural resources are not available in Iran for proliferation of biofuel, it can be seen that solely in the Fars province, there is enough fertile agricultural

Table 7
Results of positive and negative ideal solutions for objective functions in Scenario 2.

Objective Function	Positive Ideal Solution (PIS)	Negative Ideal Solution (NIS)
Z_3	7.542189E+08 $minZ_3, s.t.x \in S$	1.013053E+09 $minZ_3, s.t.Z_2 \geq Z_2^*, x \in S$
Z_2	2.80E+11 $maxZ_2, s.t.x \in S$	1.46E+11 $maxZ_2, s.t.Z_3 \leq Z_3^*, x \in S$

Table 8
Computational results of the proposed model under different ε limits for Scenarios 1 and 2.

Solution	ε limit	Total Cost	
		Hierarchical I	Integrated
1	$Z_2 \geq 1.46E+11$	3.72E+09	2.37E+09
2	$Z_2 \geq 1.73E+11$	3.72E+09	2.40E+09
3	$Z_2 \geq 1.99E+11$	3.79E+09	2.41E+09
4	$Z_2 \geq 2.26E+11$	3.88E+09	2.44E+09
5	$Z_2 \geq 2.53E+11$	3.98E+09	2.54E+09
6	$Z_2 \geq 2.80E+11$	3.98E+09	2.78E+09

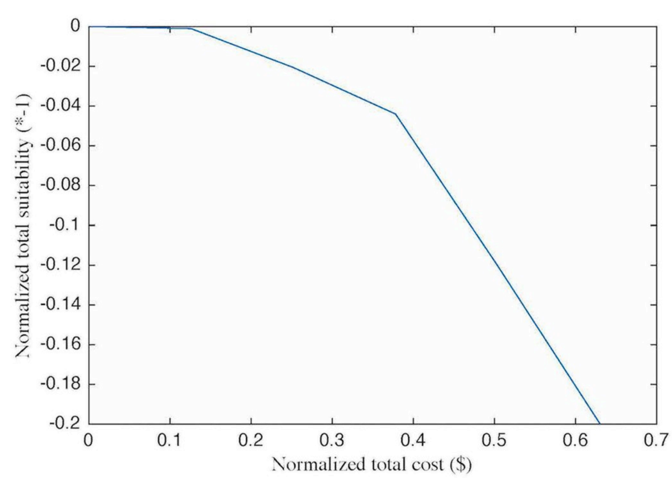

Fig. 12. The pareto front of integrated model in Scenario 2.

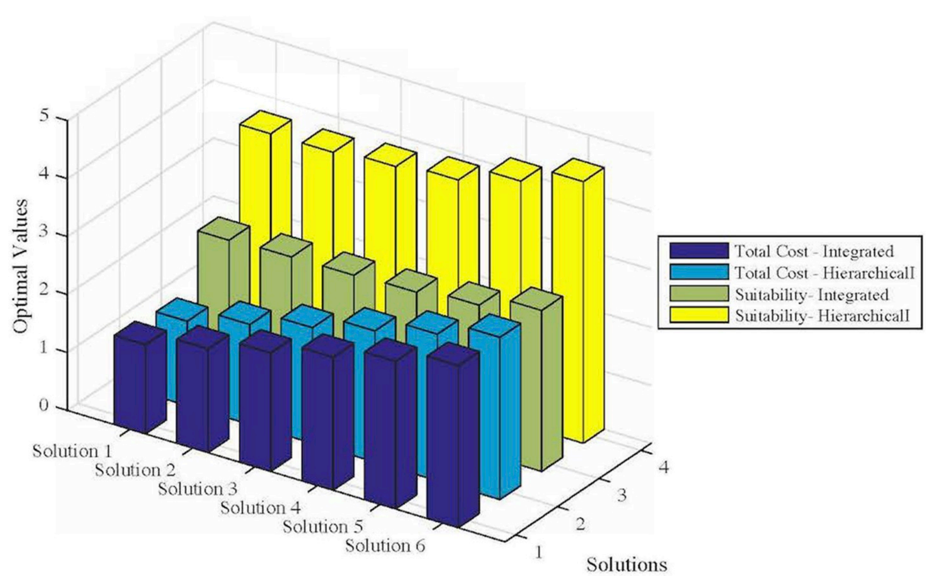

Fig. 11. Optimal values in integrated and hierarchical formulation I.

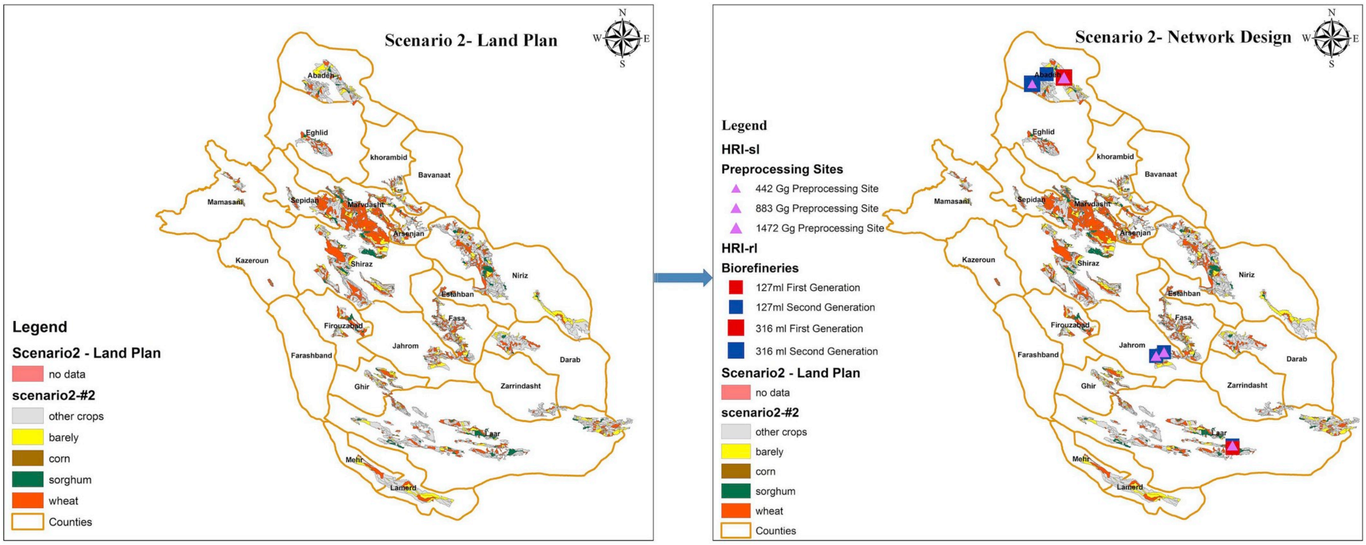

Fig. 13. Results of Hierarchical Formulation I for solution #2.

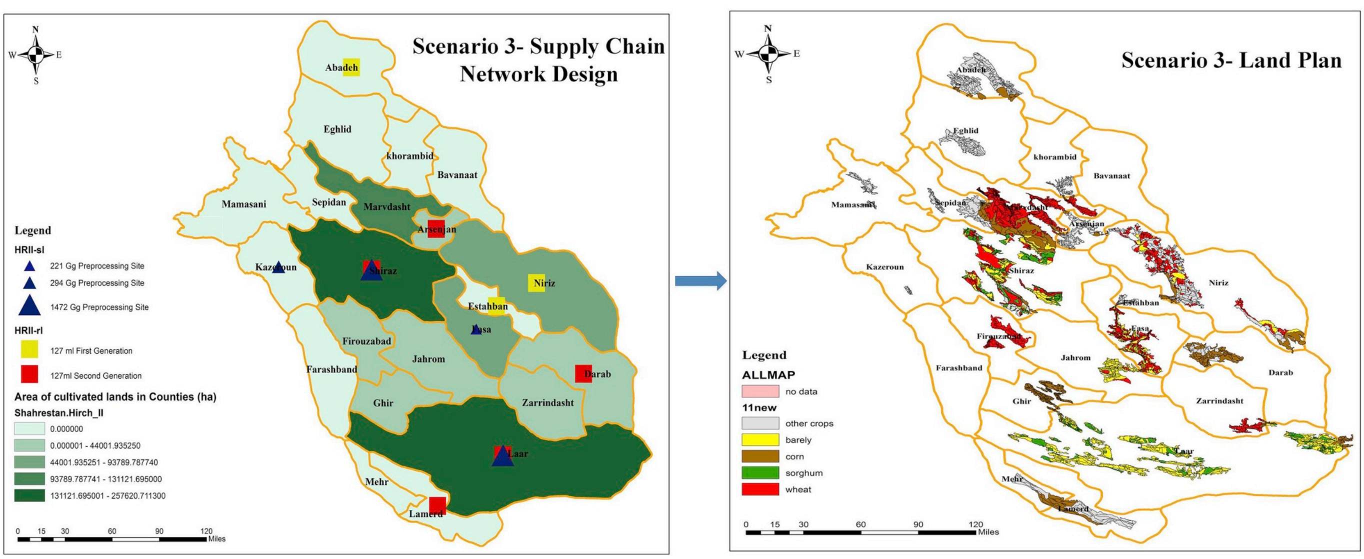

Fig. 14. Results of hierarchical formulation II.

land and renewable water to produce 1000 million liters of bioethanol without effecting the region's capacity of food production. This is possible by using the water and land resources of the region effectively and using the enormous amount of agricultural residue, which is mostly wasted, to produce second-generation bioethanol. This implies that policies promoting bioethanol production do not necessarily undermine cropland and soil sustainability as long as the policy maker is able to motivate agriculture according to cropland suitability. Also, as discussed elaborately in the previous sections, the Pareto front shows that with the expense of a marginally higher cost, far greater land utilization efficiency could be obtained. This means that with proper financial incentives in the form of tax and subsidy, a policy maker could motivate more sustainable land planning.

As can be seen in Table 9 and the descriptions provided in the last section, the resulted objective values in all the scenarios show that Scenario 1 outperforms the two other scenarios. The optimum results obtained in the first scenario dominates the second scenario in terms of cost and are better than the third scenario in terms of both cost and suitability. This shows the importance of integrating the strategic and tactical decisions in biofuel supply chains. This also shows that if bioethanol capacities are already in place, a policy maker who cares about the cost efficiency, would benefit from motivating the farmers to plan their croplands according to the optimal land plan (Scenario 3), for example by facilitating biofuel plants to buy locally. Also, a policy maker who cares about cropland sustainability, could benefit from incentivizing bioethanol plants to choose locations according to the Scenario 2 solutions. Assuming that extra local demand would be generated after construction of biofuel facilities, this practice would incentivize more sustainable land planning on the farmers' part.

This study points out the importance of considering the competition between food and biomass production and how by prioritizing food production, waste and crop residues could potentially be used as feedstock for biofuel production. In the future, studies can investigate the issue further by considering food and energy supply chains jointly. One of the most important results of this paper is that, no matter the geographical region, it is vital to consider the quality of land and how it could be sustainably utilized for food and energy production. Therefore, simultaneously considering energy, food and ecology would be most beneficial in local policy making.

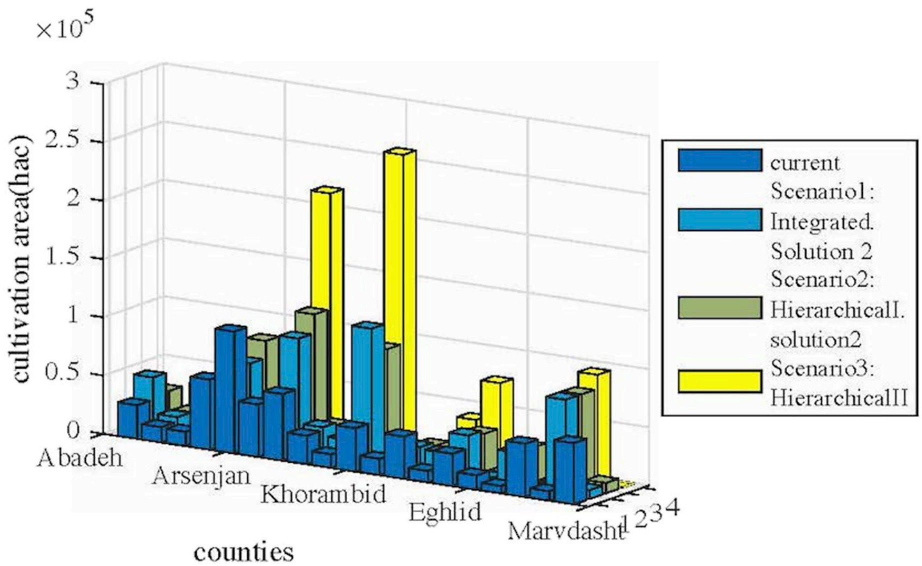

Fig. 15. The Land plan for the three scenarios.

Table 9
Comparison of results for different scenarios.

Scenarios	Scenario 1: Integrated	Scenario 2: Hierarchical I	Scenario 3: Hierarchical II
Cost ($)	2.37E+09	3.72E+09	2.9027E+9
	2.40E+09	3.73E+09	
	2.41E+09	3.8E+09	
	2.44E+09	3.9E+09	
	2.54E+09	3.98E+09	
	2.78E+09	4.52E+09	
Suitability	1.54E+11	1.46E+11	1.86E+11
	1.79E+11	1.73E+11	
	2.04E+11	1.99E+11	
	2.30E+11	2.26E+11	
	2.55E+11	2.53E+11	
	2.80E+11	2.8E+11	

5. Conclusion

This paper makes use of a combination of MCDM (multi-criteria decision making) and optimization techniques to define a novel biomass supply chain planning problem in which in addition to the usual supply chain design decisions, cropland allocation is also considered. Sustainability of land, as one of the most important production inputs in agriculture and consequently biofuel production, is widely neglected in the literature of biofuel production planning. This is especially significant in countries like Iran, where cropland considerations have been making even the sustainability of food agriculture a topic of debate. This paper is an attempt to draw attention to this important gap in the literature and constructs a framework to effectively address this matter. In this paper, an integration of biofuel supply chain network design decisions and those of sustainable tactical cropland planning is proposed. However, as supply chain network design problems are usually very large in scale, there is a need to justify the importance of this integration. For this, we investigate three different problem scenarios. In the first scenario, all the decisions are determined simultaneously and in the other ones they are determined through two separate models which are solved hierarchically. The two hierarchical models represent the usual course of decision making in biofuel SCs. It is evident from the results that the integrated model outperforms the hierarchical ones considerably in both objectives. Notably, the integrated model represents a bi-objective MILP model for integrated network design and crop planning of a hybrid sugar-based and lignocellulosic biofuel supply chain. The model determines biomass cultivation, sourcing and allocation, locations, capacity levels, and technology types of biorefinery facilities, inventory levels, production amounts, and shipment flows in the network. The results imply that such integration leads to better use of land as well as economic utilization of resources. In this paper, a well-known and widely used method of land planning, i.e. parametric suitability analysis, combined with MCDM methods are used to model land sustainability. We believe that the significant improvement achieved by using a mixture of decision making tools and information systems like GIS (which can store enormous amount of data in a meaningful way) as proposed in this paper is promising for policy makers. A noticeable direction of improving the research is considering the dynamics of land suitability and cultivation. As soil and land characteristics are abundant and in some cases their dynamics are very complex, it would be helpful to perform empirical studies. Also, given the length of strategic decisions considered in this paper and the intrinsic uncertainty in natural phenomena like water and soil, incorporating uncertainty in the model would be a good extension possibility for this paper.

Disclaimer

For specific applications of this paper, please contact the authors regarding the scope of the model.

Appendix A

Nomenclature

Indices

i	Biomass supply zones (candidate cropland locations)
s	Candidate locations for preprocessing/storage sites

k	Candidate locations for bio-refineries
c	Crops (e.g. wheat, corn, sorghum, barley)
g	Biomass generations and production technologies (1 for first generation, 2 for the second generation)
sc	Preprocessing/storage capacity levels
rc	Biorefinery capacity levels
t	Time periods
n	Counties

Parameters

yl_c	Average yield of crop c (ton/ha)
$area_i$	Area of cropland i
$dm_{c,g}$	Dry matter ratio of crop c of generation g
μ_c	Crop residue to crop main produce ratio for crop c
win_c	Water input needed to cultivate 1 ton of crop c (ton)
mw_t	Maximum amount of water (ton) available for use in time period t
$hloss_{c,g}$	Harvest loss of generation g biomass type c
$fd_{c,t}$	Food demand for main crop c in time t (ton)
$drate_{c,g}$	Deterioration rate for crop c of generation g
$\theta_{c,g}$	Conversion factor in preprocessing site c with technology g
$scap_{sc}$	Capacity of level sc preprocessing site (ton/year)
$eyl_{c,g}$	Ethanol yield (lit/ton) of crop c of generation g
$rcap_{rc}$	Capacity of biorefinery with capacity level rc (ton/year)
$hcst_{c,g}$	Cost of production and harvest ($/ton) of crop c of generation g
$lucst_{c,g}$	Loading and unloading cost of wet biomass ($/wet ton) of crop c of generation g
$htrcst_{c,g}$	Transportation cost of harvested biomass ($/wet ton/km) of crop c of generation g
$sfocst_{sc}$	Storage/preprocessing site annualized fixed opening cost ($/year)
$lupcst_{c,g}$	Loading and unloading cost of preprocessed biomass ($/ton)
$svocost_{sc}$	Storage/preprocessing site with capacity sc annualized variable opening cost ($/ton)
$popcost_{c,g}$	Operation cost of storage/preprocessing site with capacity sc for generation g crop c ($/year)
$invhcost_{c,g}$	Inventory holding cost of g generation crop c($/$m^3$)
$bvol_{c,g}$	Volume of 1 ton of g generation biomass type c
$pvol_{c,g}$	Volume of 1 ton of preprocessed g generation biomass type c
$rfocost_{rc}$	Annualized fixed opening cost ($/year) of a biorefinery with capacity rc
$rvocost_{rc}$	Annualized variable opening cost ($/ton) of a biorefinery with capacity rc
$ropcst_{c,g}$	Refining operation cost of g generation crop c ($/year)
$ptrcst_{c,g}$	Transportation cost of preprocessed biomass ($/ton/km) c of generation g

Variables

$x_{i,c,t}$	1 if crop c is cultivated in cropland i in period t; 0 otherwise
$rhrv_{i,c,t}$	Amount of harvested residue c produced in cropland i in period t
$chrv_{i,c,t}$	Amount of harvested main crop c produced in cropland i in period t
$hf_{i,c,g,t}$	The amount of biomass c from cropland i used as bioethanol production feedstock
$food_{i,c,t}$	Amount of crop c cultivated for food purposes in i
$htr_{i,c,g,s,t}$	Transported harvested g generation crop c from cropland i to preprocessing/storage site s in period t
$hinv_{c,g,s,t}$	Inventory level of g generation crop c at the end of period t in preprocessing/storage site s
$bfp_{c,g,s,t}$	Amount of biomass preprocessed in site s in time t
$pb_{c,g,s,t}$	Amount of preprocessed biomass in site s in time t
$pinv_{c,g,s,t}$	Inventory level of preprocessed g generation crop c at the end of period t in preprocessing/storage site s
$ptr_{c,g,s,r,t}$	Transported g generation preprocessed feedstock c from storage/preprocessed site s to biorefinery site r
$sl_{s,sc}$	1 if storage site s is selected for sc capacity level; 0 otherwise
$ef_{r,g,t}$	Amount of bioethanol produced in biorefinery r with technology g in time t
$rl_{r,g,rc}$	1 if location r is selected to open a biorefinery for g generation biofuel production; 0 otherwise
$K_{n,c,t}$	The area in county n in which crop c is cultivated in period t
$crhrv_{n,c,t}$	Amount of harvested residue c to be produced in county n in period t
$cchrv_{n,c,t}$	Amount of harvested main crop c to be produced in county n in period t
$chf_{n,c,g,t}$	The amount of biomass c from county n used as bioethanol production feedstock
$cfd_{n,c,t}$	Amount of crop c cultivated for food purposes in county n
$chtr_{n,c,g,s,t}$	Transported harvested g generation crop c from cropland n to preprocessing/storage site s in period t
$cdis_{n,s}$	Distance from the center of county n to location s

Appendix B. Results of land area allocation(ha) to biomass feedstocks in the counties

Counties	Current	Hierarchical II	Solution #1		Solution #2		Solution #6	
			Hierarchical I	Integrated	Hierarchical I	Integrated	Hierarchical I	Integrated
Abadeh	28834		44433	92722.29	31603.57	47919.44	74143.50	78028.25
Arsenjan	13193	35031.07	4489.73	17022.23	16271.74	17043.17	29655.03	29710.77
khorambid	12321		9818.86	14416.78	8753.73	7168.08	11066.52	11419.64
Eghlid	60252		1327.58	35675.85	14710.59	17611.21	24134.88	25354.62
Marvdasht	104508		22622.90	131123.04	87048.96	72331.57	104780.13	112793.16
Sepidan	45128		11207.83	43545.65	28271.09	25636.16	35798.59	38363.88
Shiraz	57126	215092.8	60493.78	215092.78	116070.25	100007.55	164529.43	160031.23
Firouzabad	24502		13793.25	38884.015	23845.97	27102.13	37889.79	36945.19
Ghir	11702		29787.48	35262.55	18983.28	19323.59	23291.74	24580.15
Laar	37234	257620.7	97850.51	257620.71	95641.68	117909.35	204092.18	203365.14
Zarrindasht	14059		1296.41	17452.72	2966.17	10071.39	17452.72	16869.49
Darab	36348		19659.66	60766.79	19090.57	22516.98	40474.73	39671.34
Jahrom	9927	39423.32	22633.81	39423.32	17199.72	20687.89	30917.61	30503.97
Fasa	27833	74113.42	34392.97	74113.42	35568.21	38792.29	54407.92	50000.61
Estahban	12467		285.90	7936.64	4888.25	5517.23	6139.20	5517.23
Lamerd	6401		44254.86	48202.77	29827.98	30309.02	42023	42023
Kazeroun	45783			2391.34	2159.89	2202.1	2301.87	2281.91
Niriz	8153	93789.79	54817.25	202963.85	81866.53	81985.94614	177322.29	173232.59
Mamasani	52593		10057.31	16858.39	8895.42	7574.63	13696.86	12933.096

References

[1] Iakovou E, Karagiannidis A, Vlachos D, Toka A, Malamakis A. Waste biomass-to-energy supply chain management: a critical synthesis. Waste Manag 2010;30:1860–70.

[2] Yamamoto H, Fujino J, Yamaji K. Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. Biomass Bioenergy 2001;21(3):185–203.

[3] Parikka M. Global biomass fuel resources. Biomass Bioenergy 2004;27(6):613–20.

[4] Mousavi B, Stephen N, Lopez A, Bionab JBM, Chiuc A, Blesla M. Driving forces of Iran's CO2 emissions from energy consumption: an LMDI decomposition approach. Appl Energy 2017;206:804–14.

[5] Hessari FA. Sectoral energy consumption in Iran. Renew Sustain Energy 2005;9:203–14.

[6] Aslani A, Naaranoja M, Zakerib B. The prime criteria for private sector participation in renewable energy investment in the Middle East (case study: Iran). Renew Sustain Energy 2012;16(4):1977–87.

[7] U.S. DOE. National algal biofuels technology roadmap. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program; 2010.

[8] Avami A. A model for biodiesel supply chain: a case study in Iran. Renew Sustain Energy 2012;16:4196–203.

[9] Mohammadnejad M, Ghazvini M, Mahlia TMI, Andriyana A. A review on energy scenario and sustainable energy in Iran. Renew Sustain Energy 2011;15:4652–8.

[10] Hajhasan A, Avami A. Comparative assessment of bioethanol supply chain: insights from Iran. Biofuels 2018.

[11] Ghobadian B. Liquid biofuels potential and outlook in Iran. Renew Sustain Energy 2012;16:4379–84.

[12] Statistical Center of Iran. Iran statistical yearbook 2013-2014. 2015. 07.18.17, https://www.amar.org.ir/english/Iran-Statistical-Yearbook/Statistical-Yearbook-2013-2014.

[13] Albaji M, Naseri A, Papan P, Boroomand Nasab S. Qualitative evaluation of land suitability for Principal crops in west shoush plain. Bulgarian J Agric Sci 2009;15(2):135–45.

[14] Guidelines FAO. Land evaluation for irrigated. Rome: Soils Bull 1985;No:55.

[15] FAO (Food and Agriculture Organization of the United Nations). A framework for land evaluation. Rome: Soils Bulletin; 1976. p. 32.

[16] Weea H, Yang W, Chou C, Padilan M. Renewable energy supply chains, performance, application barriers, and strategies for further development. Renew Sustain Energy 2012;16:5451–65.

[17] Rentizelas AA, Tolis AJ, Tatsiopoulos IP. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew Sustain Energy 2009;13:887–94.

[18] IPCC (Intergovernmental Panel on Climate Change). Special report on renewable energy sources and climate change mitigation. Cambridge and New York: Cambridge University Press; 2011.

[19] Zhu X, Yao Q. Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. Bioresour Technol 2011;102(23):10936–10945.

[20] Avami A. Assessment of optimal biofuel supply chain planning in Iran: technical, economic, and agricultural perspectives. Renew Sustain Energy 2013;26:761–8.

[21] Andersen F, Iturmendi F, Espinosa S, Diaz MS. Optimal design and planning of biodiesel supply chain with land competition. Comput Chem Eng 2012;47:170–82.

[22] Gonela V, Zhang J, Osmani A. Stochastic optimization of sustainable industrial symbiosis based hybrid generation bioethanol supply chains. Comput Ind Eng 2015;87:40–65.

[23] Bai Y, Ouyang Y, Pang JS. Enhanced models and improved solution for competitive biofuel supply chain design under land use constraints. Eur J Oper Res 2016;249:281–97.

[24] Osmani A, Zhang J. Economic and environmental optimization of a large scale sustainable dual feedstock lignocellulosic-based bioethanol supply chain in a stochastic environment. Appl Energy 2014;114:572–87.

[25] Babazadeh R, Razmi J, Pishvaee MR, Rabbani M. A sustainable second-generation biodiesel supply chain network design problem under risk. Omega 2017;66(B):258–77.

[26] Osmani A, Zhang J. Multi-period stochastic optimization of a sustainable multi-feedstock second generation bioethanol supply chain : a logistic case study in Midwestern United States. Land Use Policy 2017;61:420–50.

[27] Ahmed W, Sarkar B. Impact of carbon emissions in a sustainable supply chain management for a second generation biofuel. J Clean Prod 2018;186:807–20.

[28] How BS, Yeoh TT, Tan TK, Chong KH, Ganga D, Lam HL. Debottlenecking of sustainability performance for integrated biomass supply chain: P-graph approach. J Clean Prod 2018;193:720–33.

[29] Orjuela-Castro JA, Aranda-Pinilla JA, Moreno-Mantilla CE. Identifying trade-offs between sustainability dimensions in the supply chain of biodiesel in Colombia. Comput Electron Agric 2019;161:162–9.

[30] Ren J, Manzardo A, Toniolo S, Scipioni A, Tan S, Dong L, Gao S. Design and modeling of sustainable bioethanol supply chain by minimizing the total ecological footprint in life cycle perspective. Bioresour Technol 2013;146:771–4.

[31] Corsano G, Fumero Y, Montagna JM. Integrated decision making for the optimal bioethanol supply chain. Energy Convers Manag 2014;88:1127–42.

[32] Zhang F, Wang J, Liu S, Zhang S, Sutherland J. Integrating GIS with optimization method for a biofuel feedstock supply chain. Biomass Bioenergy 2017;98:194–205.

[33] Mohseni S, Pishvaee MS, Sahebi H. Robust design and planning of microalgae biomass-to-biodiesel supply chain: a case study in Iran. Energy 2016;111:736–55.

[34] Balaman SY, Selim H. Biomass to energy supply chain network Design: an overview of models, solution approaches and applications. In: Handbook of bioenergy. Springer International Publishing; 2015. p. 1–35.

[35] Ghaderi H, Pishvaee MS, Moini A. Biomass supply chain network design: an optimization-oriented review and analysis. Ind Crops Prod 2016;94:972–1000.

[36] Bodaghabadi AB, Casanovas P, Khakili P, Masihabadi M, Gandomkar H. Assessment of the FAO traditional land evaluation methods, A case study: Iranian Land Classification method. Soil Use Manag. 2015;31(3):384–396.

[37] Sys C, Van Ranst E, Debaveye J. Land evaluation, part I: principles in land evaluation and crop production calculationvol. 7. Brussels, Belgium: General Administration for Development Cooperation, Agric. Pub.; 1991. p. 1–265.

[38] Ljusa M, Pajovic I. Land evaluation in the province of larache- Morocco. In: 22nd course professional master. "Geomatics and natural resources evaluation, vol. 22. Florence, Italy: IAO; 2002. p. 60–70.

[39] Ziaei Javid A, Goychaili S. Qualitative land suitability classification for major crop products in Tabriz plain, eastern Azerbaijan province, Iran. Intl J Agric Crop Sci 2014;7(9):620–3.

[40] Givi J. Qualitative evaluation of land suitability for field and fruit crops. Iran. Soil and Water Res Inst 1997;1015:23–72.

[41] Hamzeh S, Mokarram M, Alavipanah SK. Combination of Fuzzy and AHP methods to assess land suitability for barley: case Study of semi arid lands in the southwest of Iran. Desert 2014;19(2):173–81.

[42] Rezaei J. Best-worst multi-criteria decision-making method. Omega 2015;53:49–57.

[43] Macharisa C, Springaelb J, De Bruckerc k, Verbekea A. PROMETHEE and AHP: the design of operational synergies in multicriteria analysis. Eur J Oper Res 2004;153(2):307–17.

[44] Brans JP. Lingenierie de la decision. Elaboration dinstruments daide a la decision. Methode PROMETHEE. In: Nadeau R, Landry M, editors. Laide a la Decision: nature, Instruments et Perspectives Davenir. Quebec, Laval, Quebec: Presses de Universite Laval; 1982. p. 183–214.

[45] Vincke JP, Brans P. A preference ranking organization method. The PROMETHEE method for MCDM. Manag Sci 1985;31:641–56.

[46] Abedi M, Torabi SA, Norouzi GH, Hamzeh M, Elyasi GR. Promethee II: acknowledge-driven method for copper exploration. Comput Geosci 2012;46: 255–63.

[47] Brans JP, Vincke Ph, Mareschal B. How to select and how to rank projects: the PROMETHEE method. Eur J Oper Res 1986;24:228–38.

[48] Pakparvar M, Hassan Shahi H. Land classification for fars province, GIS data. Organization of Agriculture Jahad Fars; 2008.

[49] Gerbens-Leenes W, Hoekstra AY, Van Der Meer THH. The water footprint of bioenergy. Proc Natl Acad Sci 2008;106(25):10219–23.

[50] Bairamzadeh S, Pishvaee MS, Saidi-Mehrabad M. Multiobjective robust possibilistic programming approach to sustainable bioethanol supply chain design under multiple uncertainties. I & EC Res 2016;55(1):237–56.

[51] Mavrotas G. Effective implementation of the e-constraint method in Multi-Objective Mathematical Programming problems. Appl Math Comput 2009;213: 455–65.

[52] Lambert DK, Middleton J. Logistical design of a regional herbaceous crop residue-based ethanol production complex. Biomass Bioenergy 2010;3(4):91–100.

[53] Festel G, Würmseher M, Rammer C, Boles E, Bellof M. Modelling production cost scenarios for biofuels and fossil fuels in europe. ZEW 2013; Discussion Paper No. 13-075, http://ftp.zew.de/pub/zew-docs/dp/dp13075.pdf.