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Optimal design and planning of biodiesel supply chain considering non-edible feedstock

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ABSTRACT

The rapid expansion of first-generation biodiesel production from vegetable edible oils and animal fats has triggered a sense of concern among policymakers and development practitioners about farm land allocation, food supply, and food market equilibrium. In this respect, utilization of second-generation biodiesel from non-edible feedstocks has been attracted many interests in recent years. To accelerate transition towards large-scale and economic viable biofuels, systematic design and optimization of entire biofuel supply chains is crucial. In this paper, firstly the presented works for biofuel supply chains optimization are systematically reviewed and categorized. Secondly, a multi-period and multi-product biodiesel supply chain network design model is developed. The proposed model is capable to determine the optimum numbers, locations, capacity of facilities, suitable transportation modes, appropriate technology at bio-refinery, material flow, and production planning in different periods. The proposed model is applied in a real case in Iran. We consider Jatropha seeds and waste cooking oil as non-edible feedstocks for second-generation biodiesel production in the studied case. The acquired results demonstrate the efficiency and performance of the proposed model in designing biodiesel supply chain network.

1. Introduction

In recent years, concerns about energy security, food crisis, environmental issues, and standards of living have led to search for renewable and cleaner sources of energy. Among various sectors demanding energy, transportation sector consumes significant amount of energy which in turn causes to fossil fuel depletion and environmental pollution [38]. In response to urgent need for cleaner and renewable energy in transportation sector, researchers, policymakers and development practitioners have introduced biofuels utilization in large-scales from biomass, forestry residues, energy crops, waste oils, and municipal wastes [28,8]. In this respect, China has built up more than 2000 biodiesel production factories by 2007 [68]. U.S. has targeted to produce 36 billion gallons of biofuels by 2022 [66].

Bioethanol and biodiesel have been recognized as promising biofuels providing sustainable and viable solution to the mentioned problems. Bioethanol is produced from the feedstocks containing glucose, cellulous, and starch such as sugar cane, wheat, corn, sorghum, cassava, sugar beet, wood chips, and rice straw [67]. Biodiesel is produced from oleaginous feedstocks such as soybean, palm, sunflower, castor, cotton, rapeseed, and Jatropha [48]. Currently, most of feedstocks used for biodiesel production are provided from vegetable oils and animal fats which have edible nature [38].

The rapid increase of the biofuel industry implies a large amount of agricultural crops affecting farm land allocation, feedstock and food market equilibrium, food supply and agricultural development in rural areas [8]. In Malaysia utilizing edible palm oil for biodiesel production has risen price of palm cooking oil by 70% [62]. Another problem arising from biodiesel production from edible feedstocks is related to biodiesel commercial feasibility. Indeed, high edible feedstocks' prices for biodiesel production needs remarkable amount of subsides granted by governmental policymakers to be comparable with fossil diesel in energy markets. It is worthy to note that feedstock costs comprise about 80% of biodiesel total production costs [48,65]. To deal with food supply concerns and high prices of edible feedstocks for biodiesel production, researchers have found new sources of biofuel feedstocks such as Jatropha and waste cooking oil that have non-edible nature and don't compete with food crops to seize fertile lands [14]. Biodiesel production from non-edible oil would help to biodiesel feasibility without granting subsides and lead to food supply improvement.

Jatropha plant is the most promising non-edible energy crop which has attracted many interests due to high oil content for biodiesel production, perennial drought tolerant, soil reclamation, desert reduction, rural development and environmental benefits [2].

Jatropha seed kernel has high oil content circa 30–40% [49]. After

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palm, Jatropha has the highest oil content among edible and non-edible energy crops. Biodiesel produced from Jatropha has low acidity and good oxidation ability compared to soybean oil, low viscosity compared to castor oil and better cooling properties compared to palm oil [61]. Jatropha is carbon neutral due to existing balance between the amount of carbon dioxide emitted from the corresponding biodiesel combustion and the amount of carbon dioxide absorbed by agro-forestry of Jatropha. As now, successful utilization of Jatropha for biodiesel production in large scales have been reported in Malaysia, Indonesia, and India [33,37,58]. It is expected that about 1.72 million hectares of land would be allocated for Jatropha cultivation in India [38]. Notably, although other non-edible feedstocks such as Sal, Mahua, Neem, and Pongamia have been specified for biodiesel production, the following features make Jatropha plant prominent respect to other ones [32].

According to the literature, the main contributions of Jatropha could be stated as follows [18,2,31,32,49,55,7]:

- Growth in marginal lands and soil reclamation
- Preventing soil erosion and improving water infiltration
- Drought tolerant and low water and nutrient requirement
- High seed oil content with good quality for biodiesel production
- Reduction of greenhouse gas effects
- Opportunity for rural poor areas and contribution to poverty reduction
- Useful by-products used as manure, hygienic and medicinal material production
- High resistance against pests and diseases
- Do not compete with food supply

Transesterification process is commonly used for converting the oleaginous feedstock to biodiesel [23]. The most important by-product of transesterification process is glycerin which is widely used in hygienic and medicinal industries. Biodiesel is usually blended with fossil diesel with specified blends for example B2 to B20 to improve its combustion and reduce its destructive environmental effects. B20 blend means blending 20% biodiesel with 80% petro-diesel. Blending biodiesel and diesel up to 20% (B20) does not need any modification in the current diesel engines [46].

Another interesting non-edible feedstock for biodiesel production is waste cooking oil [69]. Utilizing waste cooking oil for biodiesel production provides good feedstock and helps to solve its disposal problem. Edible oils are vastly used for cooking in homes and restaurants, and also for different food production in corresponding factories. About 25% of these oils are lost as waste. This amount of waste should be disposed and could not be recovered to be used for cooking purposes. Therefore, suitable planning helping to collect and utilize theses used oils provides an appropriate feedstock for biodiesel production with very low price [60].

Supply chain network design (SCND) problem is related to strategic level decisions affecting on overall performance of supply chain management [9]. The main concerns in a SCND problem are determining the numbers, locations, capacity of locations, and material flows [10,5]. Also, production planning decisions such as amount of production and inventory level in different periods, which are categorized as tactical level decisions, may be integrated with the strategic level decisions to prevent sub-optimal solutions. Meanwhile, integrated models have higher complexity and thus need more computational efforts than separated ones [11]. Recently, rapid extension of biofuel industry has encouraged researchers to study biofuel supply chain through developing optimization mathematical models [3]. An et al. [3] note that determining the optimal structure of a biofuel supply chain from feedstocks sources to final biofuel consumers will significantly help to commercial feasibility of biofuels.

In this study, firstly, the recently presented mathematical models for optimizing biofuel supply chains (SCs) are reviewed and systematically categorized to explore the literature gaps. Secondly, motivated from the shortcomings from the literature an integrated mixed-integer linear programming (MILP) model for designing biodiesel supply chain network is developed to optimize the related strategic and tactical level decisions. In the proposed model, strategic level decisions are attributed to determining the numbers and locations of facilities in each echelon of the SC and their capacities, transportation mode, and production technology in bio-refineries. Tactical level decisions are related to production planning decisions including the amount of production and inventory levels in different periods and the amount of material transported between different echelons in different periods. The proposed model consists of five echelons including feedstock centers, collection and preprocessing centers, bio-refineries, distribution centers, and customer zones. The model is applied in a real case in Iran for 10 years planning horizon.

The body of this paper is structured in 5 sections. In Section 2, the recently presented mathematical models for designing biofuel supply chain network are reviewed and systematically categorized. The concerned biodiesel supply chain network design model, inspired by a real case in Iran, is described and formulated in Section 3. The proposed model is implemented in a real case in Iran and the acquired results are discussed in Section 4. Finally, Section 5 concludes this paper and presents some useful managerial implications and future research directions.

2. Literature review

In this section the most recent studies in biofuel SCs optimization are reviewed and systematically categorized to clearly show the literature gap and open practical future research directions. As now, many researchers have studied SCND problem for variety of industries [41]. Biofuels supply chain network design extensions return back to the recent decade along with increasing international attentions for biofuel utilization. An et al. [3] presented a comprehensive review covering strategic, tactical, and operational levels in biofuel SCs. Moreover, the biofuel supply chain models are classified according to upstream, midstream, and downstream levels in biofuel supply chain management. They mentioned that first-generation biofuels with edible feedstocks are being replaced by second-generation biofuels with non-edible feedstocks such as Jatropha. Yue et al. [66] reviewed and described the key challenges and opportunities in modeling and optimization of biofuel SCs. In addition to reviewing operational to strategic time frame decisions in biofuel SCs, integration of current bio-refineries with fossil fuel refineries are investigated. Moreover, sustainability issues i.e. economic, environmental and social aspects of biofuels and the approaches dealing with uncertainty of biofuel supply chain are studied.

Banos et al. [12] reviewed different optimization methods including mathematical programming methods, approximate methods, heuristic and meta-heuristic methods applied to renewable and sustainable energy field. Hoekman et al. [30] studied composition, properties, and specifications of different types of biodiesel produced from vegetable oils and animal fats. Sajjadi et al. [59] presented a comprehensive review on properties and specifications of biodiesel produced from edible and non-edible vegetable oils. They Also studied different prediction models presented to quantify biodiesel specifications. Datta and Mandal [20] investigated production, performance and emissions from a compression ignition engine using biodiesel. Verma and Sharma [64] studied the various technical aspects of biodiesel production methodology and determined the optimum ranges for parameters of biodiesel production process. Gold and Seuring [24] reviewed the supply chain and logistics issues of bioenergy production from the works published from 2000 to 2009. They note that biofuel feedstock costs and continuous feedstock supply are the main concerns in biofuel supply chain management.

Generally, biofuel SCs comprise five major echelons including