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Robust design and planning of microalgae biomass-to-biodiesel supply chain: A case study in Iran

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ABSTRACT

Microalgae have emerged as one of the most promising sources for biodiesel production because they yield a substantial amount of oil. In order to accelerate the commercialization of microalgal biodiesel, this paper proposes a two-stage model for the design and planning of a microalgae-based biodiesel supply chain. The macro-stage performs a spatial filtering using GIS and AHP to identify the most suitable candidate locations to establish biodiesel production facilities. These potential locations are later applied in the supply chain design model of the micro-stage. Consequently, the macro-stage obviates the need to consider a large set of candidate locations which is the main reason for the computational complexity of the supply chain optimization problems. In the micro-stage, a robust mixed-integer linear programming (RMILP) optimization model, which provides a trade-off between system cost and reliability, is elaborated to determine the strategic and tactical supply chain decisions that remain optimal for almost all possible realizations of the uncertain parameters. The applicability of the proposed framework is demonstrated through a case study considering different uncertainty settings. The results show that the proposed model outperforms the traditional supply chain design models in terms of solution robustness and computational time.

1. Introduction

Spurred by the rapid depletion of fossil fuel reserves, ever increasing energy demand and environmental issues, many countries have been interested in renewable biofuels and provide support schemes to accelerate the development of biofuels industry [1,2]. First generation biofuels which are chiefly extracted from food crops like oil seeds and cereals are now being produced on an industrial scale all around the world [3]. Their potential of supporting common goals such as economic growth, sustainable development and greenhouse gas mitigation, however, is subject to controversy due to the growing competition between biofuel and food production, and also lack of reliable evidence acknowledging their positive impacts on the environment [4]. Such concerns have triggered a surge of interest in the development of biofuel production from non-food biomass sources. Microalgae are considered as one of the most promising energy crops due to the following advantages: (1) high biomass yield per unit of land; (2) effective lipid accumulation; (3) ability to grow in open ponds or photobioreactors on unsuitable lands for traditional agriculture; (4) using water sources unusable for human consumption and agricultural purposes, such as saline-, brackish- and wastewater; (5) utilizing water contaminants as nutrients and helping the wastewater treatment process; and (6) removing carbon dioxide from industrial emissions [4–6].

As microalgal biofuel demand increases, the planning and managing of microalgal biofuel supply chain operations is increasingly taking more attention. Efficient and effective design of supply chain contributes to a drastic decrease in total cost by integrating and aligning strategic and tactical supply chain decisions, which can expedite the implementation of algal biofuel production systems in the real world. Generally speaking, strategic long term decisions, which are related to supply chain configuration, determine the numbers, locations and capacities of facilities while tactical mid-term decisions optimize the material flow through the logistics network [7,8]. In recent years, supply chain

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modeling and optimization has been extensively employed by researchers and practitioners to determine the production capacity and locations of biofuel plants [9,10], biomass collection and storage strategies [11,12], the allocation of forest biomass to heating plants [13]. A major difficulty supply chain design faces, especially for supply chains with wide geographical extension, is identifying candidate locations where facilities may be sited. This is more underlined in the case of microalgae biofuel supply chain in which the location of production facilities is highly affected by numerous geographical, physical and weather factors. Furthermore, for successful large-scale algal biofuel production, the production facilities should be located close to water, CO_2 and nutrient resources, posing additional restrictions on finding the candidate locations [14].

Even though the position of candidate locations strongly influences the physical network structure and consequently supply chain costs and performance, most of previous studies on supply chain design (SCD) did not elaborate on how to determine the candidate locations. Some of the studies considered a large set of candidate locations to cover the potential area more appropriately. However, this approach is not able to ensure the selection of optimum locations all through the planning area and also increases the computational burden significantly. As an alternative solution, some other researchers developed continuous facility location models which assume that facilities can be located anywhere in the continuous space [15]. But these models are typically confined to one or two levels with few number of components. Furthermore, due to computational complexity, their functionality is drastically limited when the extent of the planning area increases [16]. In a nutshell, the traditional SCD models usually focus on a few candidate locations without taking into account the geographical traits of the area being studied, resulting in their incompetence in designing the microalgae biofuel supply chain.

Geographic Information System (GIS) is a computer based analytical tool utilized to capture, manipulate, integrate and analyze geographical data. GIS plays an important role in policy making and planning process by interactively solving spatial decision problems; understanding spatial patterns; and performing sophisticated geographical analysis [17,18]. Such capabilities have motivated researchers to put GIS technology in practice for determining capable locations of algal biofuel production facilities [19–21]. To benefit from the capabilities of GIS and mathematical optimization in supply chain design, this study proposes a two-stage sequential framework that employs spatiotemporal filtering and supply chain modeling synergistically to design and optimize microalgae-based biodiesel supply chain in a nationwide scale. In the macro-stage, GIS is integrated with Analytical Hierarchy Process (AHP), one of the most popular Multi-Criteria Decision Making (MCDM) techniques, to restrict the studied area to a number of most suitable areas for production facilities by taking into account the importance of criteria which influence the location of facilities. In other words, the macro-stage aims to remove parcels of land unsuitable for production facilities by performing a pixel by pixel filtering according to site selection factors combined in GIS environment in a weighted, hierarchical fashion. In addition, integration of AHP in GIS provides a suitability index for the appropriate areas [22], allowing supply chain designers and managers to determine and prioritize the candidate locations across the suitable areas. The candidate locations with high suitability scores are then delivered to micro-stage as feasible geographical regions for network optimization. Through the micro-stage a mixed-integer linear programming (MILP) model is utilized to find the best configuration of algal biofuel supply chain, while taking into consideration a realistic range of network design assumptions and characteristics.

Treatment of uncertainty is another important subject addressed in the micro-stage. As highlighted in the related literature, the dynamic nature of biomass supply chain results in the majority of parameters being tainted with a high degree of uncertainty [1,23,24]. Despite the fact that if supply chain decisions do not incorporate adequate hedging against uncertainty, the SCD model would not be reliable and practical for real-world applications, few studies have taken uncertainty into consideration in supply chain decision making (e.g., [24–27]). In these previous studies, stochastic programming is the dominant approach to capture uncertainty. But in the context of supply chain optimization, stochastic programming suffers from major drawbacks (see Section 3.2) limiting its practicality in real-world applications. Alternatively robust optimization technique overcomes these limitations and obtains a solution that is ensured to be feasible and robust for almost all possible realizations of the uncertain parameters [28]. Moreover, this technique allows the decision makers to make a trade-off between economic performance and system reliability [29]. Accordingly, the micro-stage extends the proposed deterministic MILP model to a robust MILP model providing a more stable supply chain structure and enabling us to reach robust supply chain decisions which are less sensitive to small changes in supply chain parameters (e.g., supply and demand variability).

The remaining of this paper is structured as follows: The paper is started with a short description of the problem in Section 2. Then, Section 3 addresses the proposed two-stage model. This is followed by formulating the deterministic and robust models in Section 4. Thereafter, Section 5 evaluates the performance of the proposed model in a real-world environment. Finally, Section 6 discusses the observed conclusions and recommends some promising avenues for future research.

2. Problem statement

This research studies a microalgae-based biodiesel supply chain as illustrated in the micro-stage of Fig. 1. It consists of the following layers:

2.1. Feedstock sources

According to many studies on the resource requirements of microalgae cultivation, sufficient and stable supply of water, nitrogen (N), phosphorus (P) and CO_2 is required to have a metabolic maintenance and efficient growth [14,30]. Given the fact that large-scale algal production requires large inputs of these resources which imposes negative effects on agriculture and other related markets, input supply for achieving a more economically and environmentally sustainable production is managed as follows:

- Water: today's technology consumes a considerable amount of water (189–1655 gal) to produce a gallon of biodiesel, depending on the location and the method of cultivation [20,31]. Evidently, fresh water cannot be our only water source if algal biofuel is to address a chief portion of petroleum-based fuel consumption. As this paper aims to design a supply chain which is compatible with large scale production, saline and waste water would be additional sources of water.
- N and P: another obstacle in the way of algae cultivation at large scale is high consumption of nitrogen and phosphorus and their current high costs [30]. Here, N and P requirements is satisfied by (1) purchasing N and P fertilizers from local markets, and (2) municipal wastewater as a source of nutrients, which is transported from waste water treatment plants (WTPs). Not only can the wastewater utilization strategy decrease the potential