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Model-based optimisation of biodiesel production from microalgae

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ABSTRACT

This work presents a superstructure-based optimisation model to optimise the microalgae to biodiesel production flowsheet for the minimum net annualised life cycle cost (ALCC) of biodiesel. The model includes the important processing steps of converting microalgae into biodiesel, viz. microalgae growth, harvesting, lipid extraction, and transesterification of lipid. Different options to perform these steps are considered. The mass and volumetric balance for each process and equipment, and the equipment capacity limitations constitute the important model constraints. The decision variables include growth duration, medium, as well as the techniques and specifications to be followed in each of the downstream steps. The mixed integer linear programming model was applied to a case study of producing 30,000 kg/d biodiesel from *Chlorella*. The minimum ALCC was US $ 13.286/l for the flowsheet and equipment details recommended by the model. Sensitivity analysis showed that lipid extraction was the most crucial step in the flowsheet.

1. Introduction

Among different bio-energy sources, microalgae have emerged as a promising option. The rationale for microalgae's potential as a large-scale energy alternative can be attributed to their high productivity per unit area, which is 13.69 l/m^2 oil yield as compared to less than 0.6 l/m^2 oil yield for various other sources such as soybean, coconut, and palm oil (Chisti, 2007). Unlike food-crops, large-scale usage of microalgae is least likely to engender any food-security problem as microalgae can grow even on degraded lands and on salt water. Microalgae can harness carbon from industrial flue gases and use nutrients from waste water for growth (Brennan and Owende, 2010; Mata et al., 2010). Moreover, they are sources of different value-added products such as polysaccharides, ω-3 oil, carotenoids, and β-carotene, thereby enhancing their economic potential (Harun et al., 2010; Mata et al., 2010).

In spite of these potential benefits, large-scale implementation of microalgal biorefinery has not yet been realised (Hannon et al., 2010; Amaro et al., 2011; Christenson and Sims, 2011; Lam and Lee, 2012). The chief drawback is the highly cost-intensive processes involved in generating products for end-use from microalgae (Sen Gupta et al., 2014). Current estimates of biodiesel production cost from microalgae lie between US $ 2.38–10.58/l (Amaro et al., 2011). Average baseline lipid (triacylglycerol) production cost has been estimated to be US $ 3/l based on results from multiple studies (Sun et al., 2011). It has also been reported that the cost of microalgal biofuel must reduce by a factor of 10 to make it cost-competitive with other energy sources (Wijffels and Barbosa, 2010). This can potentially be addressed by designing integrated biorefineries that produce fuel along with other value added products (Singh and Gu, 2010), and optimising the design as well as operational protocols for the biorefinery, thereby improving the economics of the entire system. As a first step towards this broad objective, this article presents work on designing an economically optimal flowsheet for producing biodiesel from microalgae.

The design of an integrated biorefinery is not trivial (Subhadra, 2010). The schematic in Fig. 1 highlights the central idea of an integrated microalgae biorefinery. The necessary system inputs and the end-products can be interfaced with other industries in the form of industrial flue gases and waste water upstream of the biorefinery and a variety of value-added end-products downstream. The main challenge in designing the integrated biorefinery is to select the best combination of unit processes and operations from a multitude of alternatives for microalgae cultivation and processing steps, while considering market economics and the diverse environmental constraints. The primary hurdle in such an approach is that different processes in microalgae biorefinery are at different maturity levels, leading to a significant lack of understanding about the optimal microalgae biorefinery configuration. Adaptation of an interdisciplinary approach and the development of new computing tools based on modelling and systems engineering is essential to address this challenge (Taylor, 2008). A systematic approach is to

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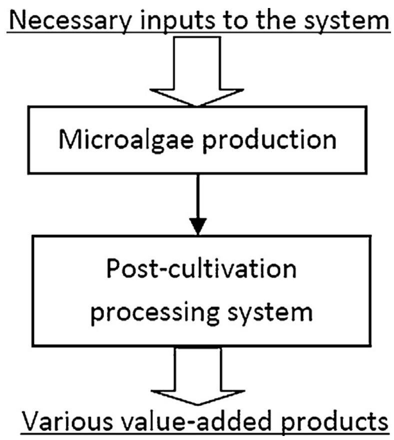

Fig. 1. Integrated microalgae biorefinery: the central notion.

undertake a comprehensive optimisation study to determine the best flowsheet by incorporating various options at each stage of the entire process, to quantify sensitivities to model parameters, to identify trade-offs among different objectives, and to provide comprehensive decision support. In this work, we propose to apply a superstructure-based approach, utilising information on various alternative routes to select the optimum combination of process decisions and to identify the major hurdles in the process that need to be addressed for overall improvement in process performance.

Superstructure-based optimisation studies have been extensively employed in energy sector, such as for thermochemical based conversion of hybrid coal, biomass, and natural gas to liquid fuels (Baliban et al., 2012), and ethanol production via gasification of switchgrass (Martin and Grossmann, 2011). Recently, this approach has been reported for sustainable design of microalgal biorefinery for simultaneous hydrocarbon biofuel production and carbon sequestration (Gebreslassie et al., 2013) and also for finding out an optimal pathway to produce biodiesel from microalgae (Rizwan et al., 2013). Computational studies to determine the economic potential of the microalgae-derived products and its sensitivity with respect to various model uncertainties have also been reported (Davis et al., 2011). Moreover, research is in progress to acquire greater insights on the microalgae-derived product system with the help of life cycle analysis (LCA) (Campbell et al., 2011; Yang et al., 2011). There have also been model-based studies on multi-criteria analysis for finding out the optimal topology for microalgae-based biodiesel production (Torres et al., 2013).

In context of superstructure based optimisation applied to microalgae biorefinery, a MINLP based approach has been developed (Rizwan et al., 2013) to achieve optimal biodiesel production protocol from microalgae for different objectives, considering mass conservation across the different steps of the process. The objectives being studied are maximisation of biodiesel production, maximisation of gross operating margin, and simultaneous maximisation of gross operating margin and minimisation of waste. However, the study ignores the economically critical step of algal growth and focuses only on post-cultivation unit operations. In a more recent study (Rizwan et al., 2015), the same authors expanded the superstructure to include the process of growth alongside considering processing of lipid depleted biomass for different energy products in order to realise the potential of an integrated biorefinery to a greater extent. The mass balance and energy balance across the different steps are modelled as constraints. However, the details on the equipment in the process steps which is a critical concern in terms of the practical large-scale implementation are not considered. In a separate study, Gebreslassie et al. (2013) modelled an algae-based hydrocarbon biorefinery, considering bio-mitigation of carbon dioxide of power plant flue gas for different objectives. Different technological alternatives have been considered to upgrade the extracted algal oil. Although the study presents details of process engineering as well as the optimisation framework, the quantity of different cell constituents as well as the efficiencies of operations such as extraction, and reaction are assumed to be independent of process alternatives whereas in reality, these parameters are strong functions of operational decisions. Researchers have also focused on the prospect of simultaneous mitigation of carbon dioxide and production of biofuel in connection with microalgae system through a multi-objective life cycle optimisation (Gong and You, 2014a). Life cycle environmental impact has been modelled as constraints alongside mass, energy and economic constraints. Efficient global optimisation strategies have been proposed to solve the corresponding superstructure-based non-convex MINLP model with 7800 alternate processing pathways for microalgae. Along similar lines, the feasibility of microalgae as a possible mean of carbon sequestration and utilisation has been analysed by the same researchers (Gong and You, 2014b). Global optimisation strategies have been applied to solve the non-convex MINLP model.

These detailed studies notwithstanding, there is a significant research gap on four counts;

(1) The state of the microalgae cell has not been factored into the design. For example, the impact of variation in growth condition on the constituents of the microalgae cells needs to be studied as that would directly impact all the post-cultivation steps as well as the final product yields.
(2) The efficiency of the processing steps has been assumed constant regardless of the process conditions. In reality, variation in process conditions such as duration, and amount of reactant in case of reaction affects the efficiency of the specific operation.
(3) Scheduling of the various operations associated with the system has been ignored. Since most of the intermediate process steps are batch in nature, their optimal scheduling is very critical for design of the integrated system.
(4) Factors such as number and size of equipment, their operating strategy and such operational decisions have not been considered in detail in the previous studies, thereby limiting the usefulness of the models as decision support tools.

The goal of this work is to address these research gaps by developing an optimisation model to perform process synthesis while considering the detailed design issues. As a first step towards this broad objective, this article presents design for an economically optimal flowsheet for producing biodiesel from microalgae. Specifically, a mixed integer linear programming model is developed to minimise the cost of biodiesel production for a fixed demand for a particular microalgae, *Chlorella*. The salient features of this study are as follows-

- A superstructure model is developed for a large-scale commercial production of biodiesel whose demand is fixed, from microalgae.
- At each process step, operational parameters as well as the equipment specifications are optimised.
- The variation in constituents of the microalgae cell as a function of growth conditions is considered in the model. Similarly, the variation in the efficiency and yields of an operation as a function of operating parameters has also been included for other processing steps.
- The batch time for the post-cultivation steps is optimised, in addition to the sequence of steps, to obtain a preliminary idea of the protocol of operation and the schedule for a sustained production of biodiesel.