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Optimal design of microalgae-based biorefinery: Economics, opportunities and challenges

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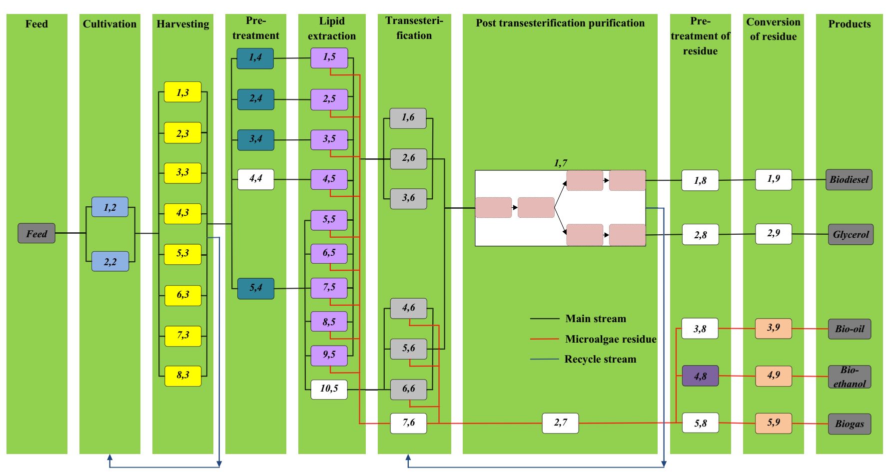
HIGHLIGHTS

- A superstructure based optimization model is developed.
- Optimal structures of microalgal biorefinery are determined.
- The optimization problem is formulated as an MINLP model.
- Two different optimization scenarios are investigated.
- Sensitivity analysis elaborates potential improvements.

GRAPHICAL ABSTRACT



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ABSTRACT

Microalgae have great potential as a feedstock for the production of a wide range of end-products under the broad concept of biorefinery. In an earlier work, we proposed a superstructure based optimization model to find the optimal processing pathway for the production of biodiesel from microalgal biomass, and identified several challenges with the focus being on utilizing lipids extracted microalgal biomass for economic and environmentally friendly production of useful energy products. In this paper, we expand the previous optimization framework by considering the processing of microalgae residue previously treated as wastes. We develop an expanded biorefinery superstructure model, based on which a mixed integer nonlinear programming (MINLP) model is proposed to determine the optimal/promising biorefinery configurations with different choices of objective functions. The MINLP model is solved in GAMS using a database built in Excel. Economic sensitivity analysis is performed to elaborate the potential improvements in the overall economics, and set the targets that must be achieved in the future in order for microalgal biofuels to become economically viable.

1. Introduction

Microalgae have received significant attention lately as a promising renewable feedstock for producing a wide range of

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products, including biofuels and a variety of value-added chemicals, owing to its high quantity of lipids, proteins, carbohydrates, vitamins, pigments, and enzymes [1]. These biofuels also contribute to the quality of the environment by producing less net amounts of carbon dioxide than fossil fuels [2], and may reduce dependency on fossil fuels. Microalgae also offer many potential advantages over terrestrial food crops, including their extremely rapid growth (with the typical doubling time of less than 24 h) and ability to be grown in non-arable land [3]. They can also utilize CO_2 as a carbon source, and hence their large-scale cultivation can contribute to restoration of the carbon balance in the atmosphere [4]. Microalgae are composed of three main components; lipids, proteins, and carbohydrates. After extraction, lipids are mainly used for the production of biodiesel through the transesterification process (a well-known process for biodiesel production). One of the major challenges in the production of biodiesel from microalgae is its cost-effectiveness. Microalgal biodiesel is not cost-effective at current time, as indicated in our previous study [5]. This challenge can be addressed by utilizing all the components of microalgae, not just the lipids, under the broad concept of biorefinery where the lipid contents can be utilized for the production of biodiesel, and (lipid-extracted) residue can be used for the production of value-added products including various biofuels, valuable chemicals, and other useful industrial intermediates [3,6].

'Spent microalgal biomass' or 'microalgae residue', in this work, mean the residuals left over after the extraction of the lipids; they mainly contain proteins and carbohydrates. These microalgae residues account for approximately 70% of the whole microalgal biomass (on dry basis) and thus, have potential to serve for a number of applications [7]. Therefore, proper exploitation and utilization of microalgae residue can enhance the overall economics of biofuels production from microalgae. Unlike the lipid contents of microalgal biomass, the spent microalgal biomass has not been studied extensively and its applications are not well-documented [8]. According to a baseline study [8], spent microalgal biomass can be used to produce many products such as bio-ethanol, bio-hydrogen, bio-oil, bio-methane, fertilizer, plastics, nutrients, animal feed, sorbents, etc. Therefore, their processing can be considered under the overall frame of biorefinery.

Despite the various benefits associated with the concomitant utilization of microalgal biomass and its residue, an economic feasibility of microalgae-based biorefinery has not yet been evaluated fully [9]. A systems engineering approach can be applied to address the challenges associated with the microalgae-based biorefinery, for example, by developing a systematic methodological framework to locate the promising biorefinery configurations in terms of cost-effectiveness, robustness, and environmental sustainability [10,11]. These challenges include: (1) existence of a huge number of processing pathways for the production of biofuels and chemicals from microalgae due to many technological alternatives available at each processing step and (2) inconsistent, uncertain, and preliminary nature of technological and economic data. The research in the field of microalgae-based biorefinery is in an early phase of development and yet to mature enough to produce a consistent and reliable dataset regarding the various technological alternatives for each step of microalgae processing. Therefore, the developed framework should have the capability to consider and address the inconsistent nature of the data, and give a set of promising production routes with high potential to become sustainable from both economic and environmental viewpoints.

Systems approaches to process synthesis and optimization of processing networks have been proposed and described in many studies [12–14]. Based on these studies, many researchers developed systemic methodologies for a number of applications including the optimal synthesis of biogas production from organic and animal waste [15], processing of soybean oil [16], processing of waste palm oil for biodiesel and fatty alcohol production [17], processing of lignocellulousic biomass [18–20], and processing of microalgal biomass [5,21–25]. Davis et al. [26] investigated and established the baseline economics for microalgae cultivation via open ponds and photobioreactors, and then further conversion to green diesel via hydrotreating. Delrue et al. [27] developed an economic, sustainability and energetic model for the production of biodiesel from microalgae. In their follow-up study [28], the techno-economic viabilities of hydrothermal liquefaction, oil secretion and alkane secretion have been evaluated. Slegers et al. [29] proposed a model-based combinatorial optimization approach for energy efficient conversion of microalgae into biodiesel. The performance is expressed in terms of net energy ratios. In a recent review on the application of process synthesis to biorefinery processes [30], process synthesis is recognized as a powerful tool to generate a cost-effective process for the production of bio-based products from biomass derived feedstocks, with high conversion efficiency. It also provides a detailed review of the studies on the process synthesis of biorefineries. Martin and Grossman [22] evaluated a superstructure for the production of biodiesel from cooking oil and algae by formulating an MINLP problem considering heat and water integration. Gebreslassie et al. [23] proposed a superstructure based optimization of algae based biorefinery for simultaneous production of hydrocarbon biofuels and carbon sequestration. A multi-objective MINLP model is developed that simultaneously maximizes the net present value (NPV) and minimizes the global warming potential (GWP). Gong and You [24] formulated an MINLP model to minimize the unit carbon sequestration and utilization cost for algae-based biorefinery processes. In their follow-up study [25], a generic modeling framework for global superstructure optimization is developed for the synthesis and sustainable design of algae processing networks for CO_2 mitigation and biofuels production, considering the entire lifecycle. A multi-objective MINLP is developed to simultaneously optimize the unit annualized cost and GWP.

Despite several contributions focusing on optimal design of biorefiney configurations: (1) no modeling framework addresses the integration of microalgal biodiesel production with the processing of microalgae residue in a comprehensive manner, i.e., by incorporating a number of potential technological alternatives available for the pre-treatment and further conversion of microalgae residue into biofuels and other useful products; (2) no biorefinery superstructure is developed based on the process data solely applicable to a specific microalgae species by considering the fact that dataset is strain-specific, and every strain has its own dataset starting from the cultivation to the final products. The coupling of residue processing with biodiesel production will enhance the overall economics of biofuels production from microalgae. It is thus the objective of this paper to address these research gaps by developing a systemic methodology to handle simultaneous production of biodiesel and other useful energy products from *Chlorella vulgaris* using a dataset of preliminary nature.

In our previous work [5], we proposed a superstructure based modeling framework for the production of biodiesel from the lipid contents of microalgal biomass. In this work, we extend the optimization framework by adding models for the processing of microalgae residue into useful products so that the overall economics of the biofuels production from microalgae could be improved. The extended framework also accommodates the recycling of water and solvents. The biorefinery superstructure model is developed for the particular species of *C. vulgaris* but it can easily be extended to consider other species given that data of similar nature can be collected. In addition, the optimization formulation is not strain specific. The optimization results give insight about the promising configurations and cost-effectiveness of microalgae-based biorefinery. Due to the preliminary and inconsistent