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Economic and life-cycle greenhouse gas optimization of microalgae-to-biofuels chains

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ABSTRACT

The new microalgae-to-biofuels chains for producing diesel and ethanol simultaneously are presented. The techno-economic analysis shows that the break-even prices of diesel and ethanol are estimated about US$0.49/kg and US$2.61/kg, respectively, the internal rate of return (IRR) is close to 29.21%, and the commercial prices and yield of products dominate the profitability of this project. According to life cycle analysis (LCA) standards, the life-cycle greenhouse gas (GHG) emissions for producing diesel and ethanol are 0.039 kg CO_2-eq/MJ FAME and 0.112 kg CO_2-eq/MJ EtOH, respectively. It is verified that the process integration of the heat recovery scheme, the entrainer recovery tower, and CO_2 recycling can effectively reduce life-cycle GHG emissions of this design. Through a specific optimization algorithm under different lipid contents and 180 scenario combinations for the cultivation and pretreatment processes, the compromise solutions between the maximum total revenue and the minimum environmental impact can be found.

1. Introduction

Algal biomass is considered as emerging alternatives for biofuel production because its composition reveals a remarkable presence of lipids and carbohydrate which are the main sources of biofuels. Microalgae species do not require the high use of land, do not need freshwater, can grow faster in a very short period of time, and the produced oil is not a threat to food security (Bwapwa et al., 2017). In general, 1 kg of dry algal biomass utilizes about 1.83 kg of CO_2 (Brennan and Owende, 2010), so it effectively reduces the impact of climate change and global warming. Microalgae exhibit a great variability in lipid content such as Chlorella species with 20–50% of oil contents due to different growing conditions and methods of extraction of lipids. Moreover, Chlamydomonas, Scenedesmus, and Spirulina would contain over 50% of starch and glycogen (Cardona-Alzate and Sanchez-Toro, 2006; Martin and Grossmann, 2013). The triglycerides-enriched feedstock is commonly applied to biodiesel production and sugar-enriched feedstock usually produces bioethanol, biobutanol, and biopropanol. For algal biofuel production process, the cultivation of biomass does not require complex treatment methods in comparison with lignocellulose-enriched biomass (Nigam and Singh, 2011). However, the third generation biofuel using algal biomass is not competitive in the biofuel markets and has not yet become a popular raw material for the generation of engine fuels due to the lack of works at optimizing of the cultivation system, harvesting methods, and biofuel production processes (Voloshin et al., 2016).

Regarding the biodiesel production from microalgae, the process design and optimization of microalgae cultivation, lipids extracted from microalgae, and the transesterification process were essential technologies (Faried et al., 2017). A few studies showed that lipid extracted from immobilized microalgae biomass has a high potential for biodiesel production (Lam and Lee, 2012), and the vapor recompression and heat integration were utilized to optimize the performance and reduce the energy consumption of wet microalgae drying and oil extraction (Song et al., 2016). Regarding the economic studies of the production of biodiesel, the main economic criteria were a capital cost, manufacturing cost, and biodiesel break-even price. For a case of producing biodiesel by alkali- or acid-catalyzed transesterification, the prices of feedstocks and biodiesel and the plant capacity were found to be the most significant factors affecting the economic viability of biodiesel manufacture (Zhang et al., 2003). A sensitivity analysis of the TAG-enriched biomass production cost was performed and scenarios with reduced production costs were also discussed (Benvenuti et al., 2017). The economic risk analysis was performed for a biodiesel production plant with regard to the estimated total risk with 50% uncertainty (Sajid et al., 2016).

A recent review of the bioethanol production from algae indicated that some species of microalgae have high amount of carbohydrates, it

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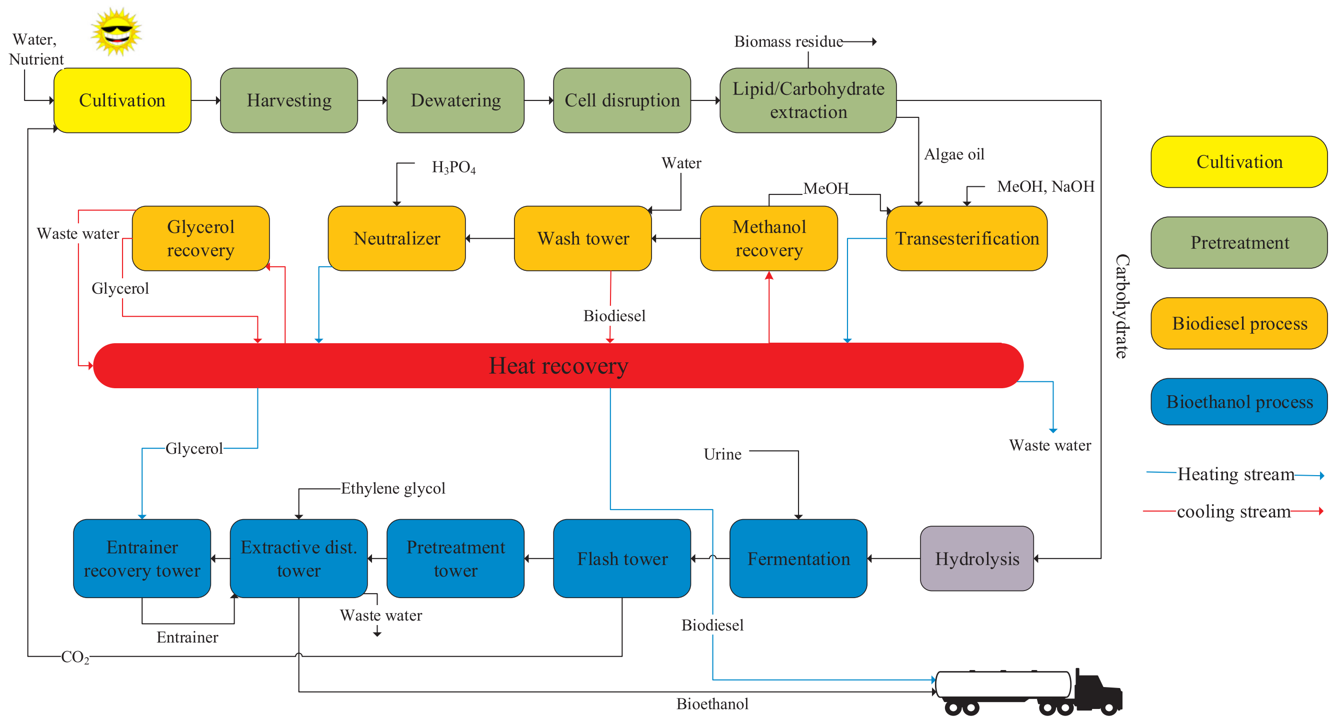

Fig. 1. Process flow diagram of microalgae-to-biofuels chains.

has a great possibility and significance in global sustainable development (Sirajunnisa and Surendhiran, 2016). Regarding the algae bioethanol process, the pretreatment, hydrolysis, and fermentation of algae biomass are required, but it is not economically feasible due to the cost of algae production and harvesting (Ziolkowska, 2014). The commercialization should encounter the challenges of the techno-economic constraints such as the enzymatic hydrolysis and chemical hydrolysis of algal biomass and distillation technologies (Li et al., 2014). For a case study of polygeneration plants, a bioethanol production system integrated with a combined heat and power (CHP) plant can reduce the bioethanol production cost (Song et al., 2014). Through the optimization and heat integration for the simultaneous production of bioethanol and biodiesel, the biofuel production cost can be reduced around 20% (Martin and Grossmann, 2013). To develop the coproducts from the microalgae-to-biofuel system, it has more market flexibility than traditional energy markets (Batan et al., 2016), and the production of high value-added chemicals can reinforce the robustness and resilience against unknown disturbances from the markets (Cheali et al., 2016).

Microalgae are not only attractive alternative to traditional forms of biomass for biofuel, but also it has potential to utilize carbon dioxide from industrial flue gas. A comparative life cycle analysis (LCA) of microalgae cultivation and harvesting options for open raceway ponds (ORPs) was conducted, where wastewater or industrial flue gas contributed to biofuel cost reduction (Zaimes and Khanna, 2013). A case study shows a comparative energy life-cycle analyses of microalgal biomass production in ORPs and photobioreactors (PBRs) where PBRs is not economically feasible due to the lower net energy ratio (NER) for biomass production (Jorquera et al., 2010). To explore the environmental impacts of producing biodiesel from algae, the heterotrophic cultivation, the heterotrophic and hybrid pathways have the potential to produce algal biodiesel with reduced global warming potential (GWP) and an improved NER relative to the phototrophic pathway and conventional diesel (Orfield et al., 2015). A comparison of the environmental impact of oil production from microalgae and terrestrial oilseed crops by using LCA methodology was addressed (Jez et al., 2017). They showed that microalgae oil has the greatest impact due to the electricity consumption. To explore the economic and environmental issues of producing biofuel from microalgae, a case study of an integrated biofuel system using the nutrient recycling pathways of anaerobic digestion and hydrothermal liquefaction process was presented (Bello et al., 2017). The results showed that the nutrient recycling technology can reduce the cost and GHG emissions of biofuel production system. For developing the life cycle optimization framework in biodiesel production processes, the key tenets of LCA are translated into mathematical constraints and integrated within optimization models. The results showed that the environmental impact was sensitive to the price of fertilizers and the net present value (NPV) was significantly influenced by the price of biodiesel (Gong and You, 2017).

2. Materials and methods

2.1. Microalgae-to-biofuels chains

The integration of microalgae-to-biofuels chains for producing two biofuels, diesel, and ethanol, simultaneously are developed and simulated in Aspen Plus® environment. Fig. 1 shows that (i) water, sunlight, nutrients, and CO_2 are inputs of the algae cultivation where the microalgal strain, e.g. Chlorella, with about 30% oil and 10% carbohydrate contents are cultivated in the specific pond system (Singh and Gu, 2010), (ii) TAG lipid (algae oil) with 10,000 kg/h and carbohydrate with 1430 kg/h are produced simultaneously through the cultivation (yellow block) and pretreatment processes (a series of green blocks), and (iii) algae oil and carbohydrate are completely separated and fed into the biodiesel production process (a series of brown blocks) and the bioethanol production process (a series of blue blocks), respectively.