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Integrating uncertainties to the combined environmental and economic assessment of algal biorefineries: A Monte Carlo approach

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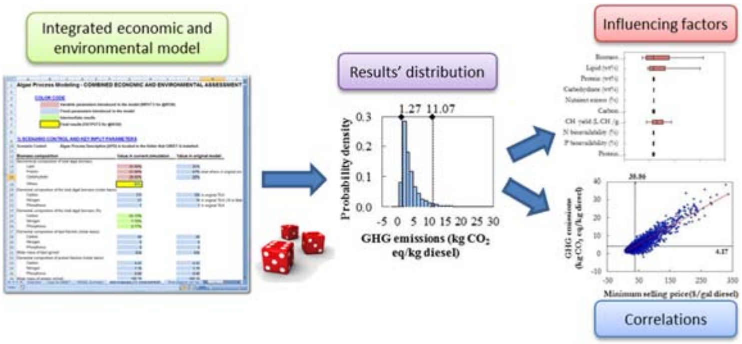
HIGHLIGHTS

- A tool for the simultaneous economic and environmental assessment of algae biorefineries was developed.
- Monte Carlo simulation was applied to propagate uncertainty throughout the model.
- High probability of favorable environmental profiles and prices of \$11–106 gal^{-1} were found.
- GHG emissions and minimum selling price had the strongest linear relationship.
- Productivity and lipid content were the main source of variation among 55 parameters.

GRAPHICAL ABSTRACT



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ABSTRACT

The economic and environmental performance of microalgal processes has been widely analyzed in recent years. However, few studies propose an integrated process-based approach to evaluate economic and environmental indicators simultaneously. Biodiesel is usually the single product and the effect of environmental benefits of co-products obtained in the process is rarely discussed. In addition, there is wide variation of the results due to inherent variability of some parameters as well as different assumptions in the models and limited knowledge about the processes. In this study, two standardized models were combined to provide an integrated simulation tool allowing the simultaneous estimation of economic and environmental indicators from a unique set of input parameters. First, a harmonized scenario was assessed to validate the joint environmental and techno-economic model. The findings were consistent with previous assessments. In a second stage, a Monte Carlo simulation was applied to evaluate the influence of variable and uncertain parameters in the model output, as well as the correlations between the different outputs. The simulation showed a high probability of achieving favorable environmental performance for the evaluated categories and a minimum selling price ranging from \$11 gal^{-1} to \$106 gal^{-1}. Greenhouse gas emissions and minimum selling price were found to have the strongest positive linear relationship, whereas eutrophication showed weak correlations with the other indicators (namely greenhouse gas emissions, cumulative energy demand and minimum selling price). Process parameters (especially

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biomass productivity and lipid content) were the main source of variation, whereas uncertainties linked to the characterization methods and economic parameters had limited effect on the results.

1. Introduction

The potential of microalgal products and particularly bioenergy is widely recognized (Collet et al., 2014; Davis et al., 2011; Wijffels and Barbosa, 2010). However, the environmental feasibility of microalgal products still requires further optimization for the reduction of energy and fertilizer consumption, as well as to the development of eco-efficient technologies for algae processing (Collet et al., 2014). Moreover, there is debate about the economic viability of large-scale algae production in the short-term (Davis et al., 2011; Richardson et al., 2012).

Life cycle assessment (LCA) is the most widespread tool addressing the environmental aspects of microalgal processes. The production of bioenergy, especially in the form of biodiesel, has been the most common focus among the large number of LCA studies (Brentner et al., 2011; Campbell et al., 2011; Clarens et al., 2010; Collet et al., 2014; Draaisma et al., 2013; Montazeri et al., 2016; Sills et al., 2013; Woertz et al., 2014; Zaimes and Khanna, 2013). Most studies evaluate impact categories related to greenhouse gas emissions (GHG) and energy consumption (Brentner et al., 2011; Clarens et al., 2010; Collet et al., 2015; Draaisma et al., 2013; Sills et al., 2013; Woertz et al., 2014; Zaimes and Khanna, 2013). Energy balance can be analyzed in terms of cumulative energy demand (CED, i.e. total primary energy consumed or generated throughout the process) or energy return on (energy) investment (ERO(E)I, i.e. ratio between the total energy produced and the energy consumed in the process), also referred to as net energy ratio (Collet et al., 2015; Montazeri et al., 2016). Other common LCA indicators include the eutrophication potential of the process, as well as land occupation and water demand (Collet et al., 2015).

Recent works highlight the multi-functional nature of microalgal processes and the importance of co-product exploitation coupled to biofuel production in a biorefinery, which may allow significant environmental benefits (Collet et al., 2015, Montazeri et al., 2016). Montazeri et al. (2016) suggest that the optimal environmental performance of biorefinery schemes is not necessarily associated with operating conditions that maximize lipid productivity (linked to the maximum biodiesel production), but with a balanced distribution of lipid and non-lipid fractions.

Techno-economic assessments of microalgal biorefineries are another essential element for the feasible implementation at large scale (Sun et al., 2011). Techno-economic models constitute key tools for the strategic planning and decision making process that help in the evaluation of project value (Borowitzka, 2013) and the decision about how and when to invest in commercial scale-up. Several studies on the economics of microalgal processes have been published in the last 30 years (Benemann and Oswald, 1996; Davis et al., 2011, 2014a, 2014b; Gong and You, 2014; Huntley and Redalje, 2007; Norsker et al., 2011; Richardson et al., 2012; Sun et al., 2011).

One of the first and more detailed economic evaluations was the analysis by Benemann and Oswald (1996). This study provided a comprehensive estimate of capital and operating costs (per barrel, bbl, of oil produced) of the most common open pond designs and auxiliary elements (including downstream processing) that were available at the time. To be actionable, the accurate evaluation of current technological advances requires an exhaustive update to include novel reactor configurations and sensitivity analyses (Richardson et al., 2012).

More recent studies compare the economics of open ponds and other production systems including tubular and flat-panel PBRs (Davis et al., 2011, 2014b; Norsker et al., 2011), as well as hybrid configurations that combine the use of open and closed reactors (Huntley and Redalje, 2007). As in the report by Benemann and Oswald (1996), the results are expressed in economic units per barrel (Huntley and Redalje, 2007; Lundquist et al., 2010) or gallon (Richardson et al., 2012; Sun et al., 2011) of microalgal oil produced, before conversion into biodiesel or renewable diesel. The term "biodiesel" refers to the mixture of mono-alkyl esters of long-chain fatty acids obtained by chemical reaction (transesterification) between crude oil (rich in triglycerides, TAG) and alcohol in the presence of a catalyst, with glycerol as co-product whereas "renewable diesel" is the mixture of straight-chain and branched alkanes and aromatic compounds produced by hydroprocessing with no alcohol required (Tu et al., 2017).

The values reported for both biodiesel and renewable diesel range between \$0.9–43 gal^{-1}, which correspond to \$28–1300 bbl^{-1} (Sun et al., 2011). Some exceptions such as Norsker et al. (2011) evaluate the cost referred to biomass production, finding values between 4 and 6 $€\cdot kg^{-1}$ biomass for the base scenarios that may decrease to 0.7 $€\cdot kg^{-1}$ biomass after optimization. Davis et al. (2011, 2014b) include the conversion of algal oil to renewable diesel in order to estimate the final minimum selling price of the product. The values obtained by Davis et al. (2011) range between \$9.8–20.5 gal^{-1} biodiesel, whereas Davis et al. (2014b) reported minimum prices from \$5 gal^{-1} up to \$22 gal^{-1}. Lundquist et al. (2010) also analyze scenarios of biogas production. For these scenarios, the production costs are expressed in \$ per kWh of electrical power produced and range between \$0.17–0.89 kWh^{-1}.

Despite the efforts to measure environmental and economic behavior of microalgal systems, few examples combine both aspects in an integrated analysis (Davis et al., 2014b; Gong and You, 2014). The integrated evaluation, using identical input parameters for the environmental and economic models, is needed to ensure the design of processes that fulfill the requirements with respect to both criteria.

Moreover, most available studies addressing either economic or environmental aspects consider one set of process and economic conditions at a time, according to a deterministic approach (Richardson et al., 2012; Sills et al., 2013). The outcomes consist of single-point results with minimal uncertainty that poorly reflect the inherent variability of the parameters and the incompleteness of process models. Due to the wide range of alternatives for each production stage as well as the numerous assumptions for growth and operational parameters considered by the authors, the results from available economic and environmental assessments show a high variability (Collet et al., 2015; Sills et al., 2013; Sun et al., 2011; Tu et al., 2017). The lack of commercial facilities and the confidential nature of existing industry information lead to data scarcity, which results in large uncertainties in model parameters and predictions (Sills et al., 2013; Tu et al., 2017).

To overcome this drawback, some authors conduct a sensitivity analysis for selected representative parameters (Clarens et al., 2010; Davis et al., 2011; Liu et al., 2013). Sensitivity and uncertainty analysis include a broad group of methodologies that have the purpose of evaluating the effect of possible variations in model inputs on the model response (Campolongo et al., 2011; Pianosi et al., 2016). In the case of algal LCAs, most of these analyses evaluate the changes associated with each variable separately rather than showing the combined effect of simultaneous changes in the entire set of parameters. In addition, they usually establish a limited number of point values (e.g. effect of ±10% change in one input parameter) instead of considering the probability distributions for all the evaluated variables (Richardson et al., 2012; Sills et al., 2013). Gong and You (2014) present one of the first studies on the integration of both economic and environmental criteria that takes into account the effect of multiple parameters simultaneously using a multi-objective optimization approach. The combined study