Algal Research 35 (2018) 547–560

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

# Techno-economic and environmental assessment of conceptually designed *in situ* lipid extraction process from microalgae

Hassan Nezammahalleh[a,*], Thomas A. Adams II[b], Faezeh Ghanati[a], Mohsen Nosrati[c], Seyed Abbas Shojaosadati[c]

[a] Department of Plant Biology, Faculty of Biological Science, Tarbiat Modares University, Tehran, Iran
[b] Department of Chemical Engineering, McMaster University, Ontario, Canada
[c] Biotechnology Group, Faculty of Chemical Engineering, Tarbiat Modares University, Tehran, Iran

ARTICLE INFO

*Keywords:*
Algae
Conceptual design
*In situ* lipid extraction
Techno-economic and life cycle assessment

ABSTRACT

An *in situ* lipid extraction process from two microalgae strains, *Chlorella vulgaris* and *Botryococcous braunii*, was conceptually designed and simulated in Aspen Plus. The techno-economic and a "pond-to-pump" life cycle carbon emission analysis were then conducted in an optimization framework consisting of two decision variables, volumetric fraction (VF) and lipid percentages (LP) of the organic phase in the extraction column. The VF significantly affected the lipid extraction efficiency and consequently both minimum lipid selling price (MLSP) and carbon emissions, while the LP was only significant at low extraction yields. The MLSP from *B. braunii* was about \$2.34 $L^{-1}$, while the cost of lipid production from *C. vulgaris* was not economically viable. A sensitivity analysis was then conducted to assess the impact of perturbations in key process and financial parameters on the MLSP and emissions from *B. braunii*. The potential efficiency of wastewater as a source of nutrients for algal cultivation was considered as well. The greatest sensitivity was attributed to lipid content and algal productivity so that a 30% deviation from the base values changed the MLSP and emissions about 44% and 70%, respectively. The results suggested the potential use of wastewater nutrients as a way to reduce both the MLSP and emissions to respectively about \$1.8 $L^{-1}$ and 4.2 kg $CO_2$ $kg^{-1}$.

## 1. Introduction

Extreme biodiversity and ability to convert waste streams into a wide-range of valuable bio-products made microalgae as a significant resource in industrial and ecological world [1,2]. Different microalgae strains are currently produced at commercial scale for aquaculture, cosmetic, pharmaceutical, and food industries [1]. In recent years, microalgae have come into the spotlight of biofuel research. It was mainly because of their 25 times higher oil yield and compatibility to grow in any climatic condition than oil crops [3]. Microalgal lipid is not only promising precursor of next generation biofuels [3], but also a valuable source of high-value commodities such as antioxidants and poly-unsaturated fatty acids [1]. In order to commercialize these bio-products, several technologies were developed for microalgae cultivation and subsequent processing [3].

One of the conventional technologies in bio-oil production is the algae cultivation in open raceway ponds followed by solvent extraction of the lipids. Using 20% wet cake of *Chlorella vulgaris* cultivated in a low-nitrogen medium, Lardon et al. [4] found a positive energy balance of 105 MJ $kg^{-1}$. However, they mentioned that it is necessary to improve the lipid productivity of the cultivation system and energetic performance of the extraction process before any measure for the algal bio-oil commercialization. The economic viability and environmental sustainability of lipid production process from *C. vulgaris* was investigated by Rogers et al. [5]. They emphasized that several cost barriers and resource challenges in algae cultivation and harvesting need to be addressed prior to successful commercialization of the lipids. The algae cultivation and harvesting accounts for the highest capital and operating expenses (> 30%) [6]. To improve the lipid productivity and overcome the resource challenges, Richardson et al. [7] economically investigated *Nannochloropsis* sp. mass cultivation in photo-bioreactors and open raceway ponds and their contribution to minimum lipid selling price (MLSP). Mass cultivation in bioreactors was accompanied by higher lipid productivity and lower risk of biomass loss, altogether resulted in 30% lower selling price of crude oil (\$20.3 ± 6.6 $L^{-1}$) than that of the open ponds. Nonetheless, the open cultivation system is applied for nearly 95% of worldwide algal mass production due to ease of scale-up and low capital cost [8]. To reach

* Corresponding author.
*E-mail address:* h.nezammahalleh@modares.ac.ir (H. Nezammahalleh).

https://doi.org/10.1016/j.algal.2018.09.025
Received 8 April 2018; Received in revised form 12 September 2018; Accepted 26 September 2018

**Nomenclatures and abbreviations**

| | |
|---|---|
| AOC | annual operating cost |
| DW | dry weight |
| FCI | fixed capital investment |
| HTL | hydrothermal liquefaction |
| LCA | life cycle assessment |
| LP | lipid percentage |
| MACRS | modified accelerated cost recovery system |
| ρ | density |
| $V$ | volume |
| $k_C$ | mass transfer coefficient |
| $a$ | interfacial area |
| $t$ | time |
| $\eta$ | Murphree stage efficiency |
| $\mu$ | viscosity |
| $\sigma$ | surface tension |
| $P$ | power consumption |
| $d_p$ | droplet size |
| MLSP | minimum lipid selling price |
| O&M | operating and maintenance |
| SI | supplementary information |
| TAG | triacylglycerides |
| TCI | total capital investment |
| TPEC | total purchased equipment cost |
| VF | volumetric fraction |
| $D$ | diffusion coefficient |
| $d_i/T$ | impeller to column diameter |
| $\phi$ | holdup |
| $\phi_F$ | volumetric fraction |

*Subscripts*

| | |
|---|---|
| D | dispersed |
| C | continuous |
| L | lipid |
| S | solvent |
| T | total |

microalgal bio-oil, some other technologies including hydrothermal liquefaction (HTL), OpenAlgae, and Valicor have been tried [9]. A comprehensive techno-economic and environmental examination of these technologies has shown that HTL can provide an optimistic minimum bio-oil selling price of $\$2\,L^{-1}$ and energy return on investment of about 5. This estimation was based on microalgae cultivation in open raceway ponds under Hawaii climatic conditions with the required electricity supplied by a wind energy generating system [9]. This stand-alone facility can be used for algal bio-oil production at a competitive price of $\$1.32\,L^{-1}$ with beneficial environmental impacts, only if the areal productivity increased to $47\,g\,m^{-2}\,d^{-1}$ [10].

For the success of algal bio-oil industry, the previous works emphasize on the improvement of both biomass production yield and lipid productivity on the upstream side and the extraction efficiency on the downstream side. These parameters greatly affect the economic and environmental performance of the process [5,11,12]. To address these challenges, *in situ* lipid extraction from microalgae was proposed by several researchers [13–16]. This bio-oil production pathway circumvents the costly step of cell harvesting by simultaneous lipid formation and extraction. The non-destructive lipid extraction by biocompatible solvents promotes both algal growth and the rate of lipid synthesis as well [17,18]. For example, *in situ* lipid extraction from *Nannochloropsis* sp. by hexadecane led to 10% increase of biological activity [18]. The non-destructive lipid extraction from *C. vulgaris* ISC33 increased the algal growth rate up to 90% [17]. However, the previous works did not consider the full process system and only studied the *in situ* extraction step itself at small experimental scales.

Given these positive attributes, a conceptual process for *in situ* extraction of triacylglycerides (TAG) from *C. vulgaris* and hydrocarbons from *Botryococcus braunii* was developed in the present research. The simulation was done in Aspen Plus using experimental lab-scale results and theoretical extraction data. In contrast to previous studies using fixed values of lipid extraction efficiency [11], it was calculated by a rigorous thermodynamic model at distinct operational conditions. To reach an optimal design, techno-economic and environmental performance of the process were considered at different values of two decision variables: the volumetric fraction (VF) and the lipid percentage (LP) of the organic phase in the extraction column. The process performance was studied using two metrics of MLSP and a "pond-to-pump" life cycle analysis of carbon equivalent emissions.

## 2. Methodology

### 2.1. Process design assumptions

Two microalgae *C. vulgaris* and *B. braunii* were respectively used as the model organisms for annual production of $10^3$ t TAG and $10^4$ t hydrocarbons by an *in situ* lipid extraction process. These lipid production rates are the same order of magnitude of annual lipid production in other economic assessment studies [5,19,20]. *Botryococcus braunii* has the highest efficiency of *in situ* lipid extraction process [17] and *C. vulgaris* is a suitable strain for outdoor cultivation in open ponds. The lipid contents of these two species were taken to be 30% of their dry weight (DW) [14,17]. The lipid composition of *C. vulgaris* was modeled with a mixture of five neutral simple TAGs based on the algal oil characterization, Table S1 of the supplementary information (SI) [21,22]. Polar lipid types were not considered as the hydrophobic solvents of *n*-heptane and *n*-decane were respectively used in the extraction process from *C. vulgaris* and *B. braunii*. The hydrocarbons of *B. braunii* were modeled with squalene because of high similarity in chemical structure with botryococcene (Fig. S1 of the SI) and also because of the availability of information on this compound in peer-reviewed literature [14,15]. The chemicals used for the extraction process were decided based on previous research works [17,23] and their physicochemical properties were presented in Table 1.

### 2.2. In situ lipid extraction process

The *in situ* lipid extraction process from two commercial microalgae species was schematically shown in Fig. 1. At steady state conditions, the solvent was pumped (by pump 4) into an extraction column and mixed with the aqueous algal phase. The two phases are agitated for a few minutes to provide suitable conditions for *in situ* lipid extraction. The organic phase including solvent and lipid was sent to the storage tank. Two streams of equal quantities were drained from the tank. One stream was transported to the extraction column for the next round of extraction. The second one was heated to a high temperature, throttled to a negative pressure, and then entered the flash drum, where it was easily separated into two streams of solvent and lipid. The solvent stream was then cooled in a condenser (shell and tube heat exchanger) and then pumped (by pump 5) to atmospheric pressure. The solvent was then returned back to the storage tank at ambient conditions.

The process was simulated in Aspen Plus v8.8 (Fig. S3) which has been widely used for similar studies on current and emerging chemicals and biochemical processing technologies. The operating conditions of