Chemie
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Short Communication

Techno-Economic Assessment of a Microalgae Biorefinery

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DOI: 10.1002/cite.202200007

A preliminary techno-economic assessment of a microalgae biorefinery plant is reported, with pulsed electric field treatment (PEF) hydrothermal liquefaction as core technology. The results indicate that standalone production of microalgae biofuel would lead to an annual loss of 2.615 M€. PEF treatment could improve this scenario by bringing the microalgae biofuel to a competitive level ($0.78\,€\,kg^{-1}$). Assuming that microalgae biofuel would be sold at the price of crude oil ($0.44\,€\,kg^{-1}$), the minimum price of the amino-acid based product should be $7.56\,€\,L^{-1}$ for positive capital returns.

Keywords: Hydrothermal liquefaction, Microalgae biorefinery, Pulsed electric field, Techno-economic assessment

Received: January 20, 2022; *revised:* September 04, 2022; *accepted:* October 26, 2022

1 Introduction

Hydrothermal liquefaction (HTL) is considered a promising thermochemical method for producing microalgae biofuel. However, microalgae biofuel via HTL is challenged by the financial viability of scaling the various associated production steps. Standalone production of microalgae biofuel has been considered unviable by many techno-economic and life cycle assessments in recent years [1]. A higher value product, such as lipid, protein, is expected along with biofuel production from microalgae. Biorefinery of microalgae refers to a value chain with the purpose of obtaining biofuels, energy, and high-value products by means of biomass transformation and process equipment. Therefore, the investigation of the added value chain within a microalgae biorefinery concept has been receiving great interest.

As examined in reported experimental work conducted by our group [2], the pulsed electric field treatment (PEF) assisted valuables extraction is intended to improve the economics of the process. PEF introduces a high-intensity electric pulse field, where algae cell membrane could lose its barrier function and becomes permeable, therefore the extraction of valuables is enhanced. HTL of the residues after PEF-assisted amino acids extraction is found to be a promising way to combine PEF and HTL technology since it enabled higher biocrude yields of better quality. However, the extent of economic benefits provided by the utilization of PEF is not yet clear. Besides, more experimentation-based techno-economic assessments are required to evaluate the economic feasibility of microalgae biofuel.

In this work, a techno-economic assessment of a microalgae biorefinery via PEF-HTL technique is demonstrated using an existing microalgae biorefinery model [3] (a pilot plant with an output of 0.5 MW in the form of biocrude) and reported experimental data [2, 4, 5].

2 Experiment

2.1 Process Description and Experimental Background

The flowchart of a potential plant is shown in Fig. 1. The model system, location, and main characteristics of the plant are taken from a previous study [3]. In brief, the plant is designed to be operated for 7500 h a year and a service life of 20 years. A flat panel airlift (FPA) technology (Subitech) is used for algae cultivation using saltwater. The water streams consist of water recovered from harvesting and aqueous phase as well as fresh seawater. A stepwise combination of sedimentation and centrifugation (Evodos 25 spiral plate technology) is designed for concentrating the algae slurry to $150\,g\,kg^{-1}$(dry mass). Approx. 818 t of microalgae biomass are required annually. The fractionation step is based on the technology developed by the University of Almería [6]. This process includes pretreatment for cell disruption, enzymatic hydrolysis (using the commercially available enzymes Alcalse and Flavourzyme) and final separation by centrifugation. Microalgae *Scenedasmus almeriensis* (*S. almeriensis*) has been selected for this study because it

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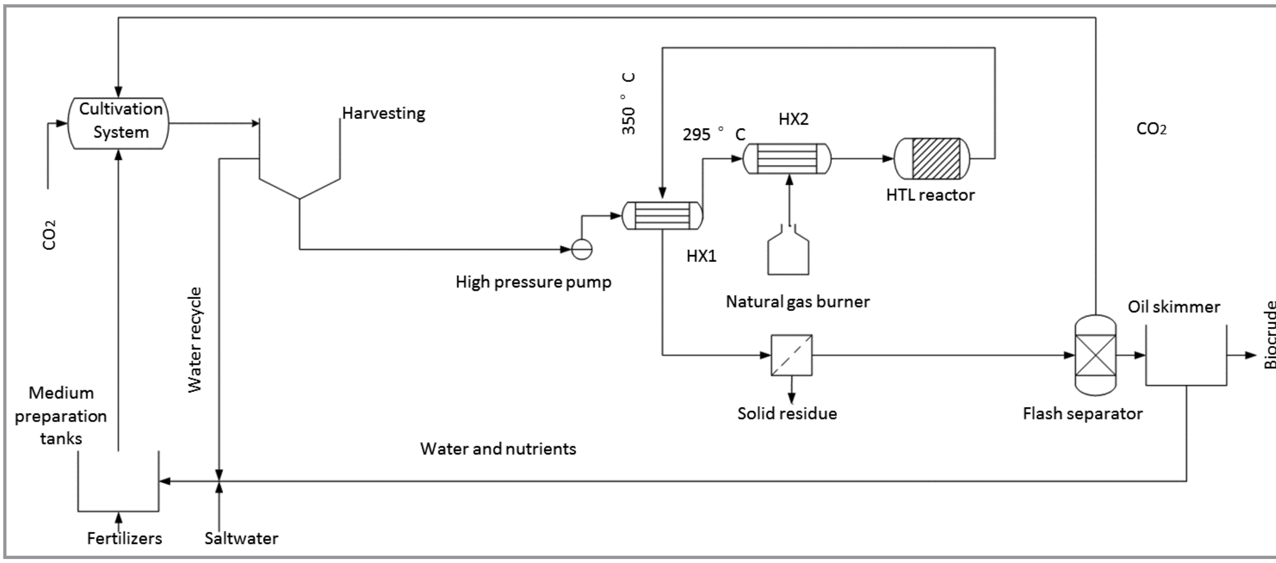

Figure 1. Flowchart of the microalgae biorefinery plant.

is a suitable and available strain in southern Spain where the plant was designed. More importantly, the biocrude from residues of PEF-assisted amino acid extraction is considered the most promising route as stated in [2]. It is intended to convert the microalgae in a continuously operated tubular reactor with a residence time of 15 min at 350 °C and 24 MPa, which is in the same range of the continuous HTL study described in [4]. The enzymatic hydrolysis of proteins and amino acid extraction is performed at 50 °C for 180 min. The extraction yields and HTL product yields of the process are based on our previous study [2]. Besides, the overestimation by the usage of DCM as separation solvent is considered ($\text{Yield}_{\text{non-DCM}} \approx 0.818\times\text{Yield}_{\text{DCM}}$) based on [4]. Moreover, a lower biocrude yield is expected in a continuous mode (65 % to 96 % of the batch-biocrude yield [7]), and, therefore, an average of 82 % of the batch biocrude yield is used for transferring the data from batch to continuous operation mode in this study ($\text{Yield}_{\text{continuous}} \approx 0.82\times\text{Yield}_{\text{batch}}$). However, it should be noted that the difference between microalgae strains in these studies could also have an impact on their processing parameters. A flash separation unit is used to split up the gas-aqueous-biocrude mixture. An oil skimmer is used to separate the biocrude from the aqueous phase.

The biocrude is assumed to be sold at price of 0.44 € kg^{-1}, as this corresponds to the crude oil price in December 2021, which would be expected to compete with biocrude. As is the case in similar products already available on the market, the biofertilizer (made of 60 wt % amino acids) is intended to be sold between 7.35 € L^{-1} (Aminosol-PS, Lebosol Dünger GmbH, derived from meat residues, therefore considered the lowest benchmark) and 10 € L^{-1} (Algafert, Biorizon biotech, Spain). The local electricity price is assumed to be about 0.065 € kWh^{-1}.

2.2 Cost Estimations

The pumpability and harvesting behavior of microalgae *S. almeriensis* are considered to be similar to that of microalgae *Nannochloropsis gaditana* used in the previous study [3]. The fixed costs and variable costs are assumed to be the same as in the previous work, as presented in Tab. 1 and 2 in € a^{-1}. The annual cost is the sum of the fixed costs and variable costs, which is about 2.75 M€ a^{-1}. It is noteworthy that the cultivation of *S. almeriensis* would require more Mg and Ca species than *N. gaditana*, however, the cost of the fertilizer amounts to less than 5 % of the total cost, which can be considered a minor factor.

Table 1. Fixed costs (FC).

Item	Cost [€ a^{-1}]	% of FC
Depreciation		
Major equipment	795 630	36.8
Piping	159 126	7.4
Instrumentation	119 344	5.5
Total	1 074 100	49.7
Engineering	322 230	14.9
Labor	675 000	31.3
Insurance	6445	0.3
Land	1945	0.1
Contingency	79 563	3.7
Total FC	2 159 294	

Table 2. Variable costs (VC).

Item	Cost [€ a^{-1}]	% of VC
Process materials		
Fertilizers	137 162	23.0
Natural gas	29 228	4.9
Electricity	397 313	66.7
Total	563 703	94.7
Maintenance and repair	31 825	5.3
Total VC	595 528	

The cost for PEF treatment is assumed to depend on three major factors: PEF equipment cost, labor cost and electricity cost, as shown in Tab. 3. The electricity efficiency of PEF treatment is about 75 %, and 40 % of the operating time is assumed to be supervised by a person with an average labor cost of 30 € h^{-1}.

Table 3. PEF treatment costs (PC).

Item	Cost [€ a^{-1}]	% of PC
Depreciation		
PEF equipment	10 000	8.5
Labour	90 000	75
Electricity	19 696	16.5
Total PEF	119 696	

The cost for the fractionation step is assumed to be 1 € L^{-1} of amino acids concentrate according to the data from the University of Almería. However, this is among the best-kept secrets of biofertilizer companies. A cost calculation on the laboratory level gives 58.34 M€ a^{-1} when scaling up to the scope of this study, thus the topic requires significant further consideration.

The economic key figures such as income, cost, return, and minimum fuel selling price (MFSP, the price for offsetting the production costs) are calculated using following equations:

$$\begin{aligned} Income = {} & yearly\ productivity\ of\ biocrude \times \\ & unit\ price\ of\ biocrude + \\ & yearly\ productivity\ of\ high\ value\ product \times \\ & unit\ price\ of\ high\ value\ product \end{aligned} \tag{1}$$

$$\begin{aligned} Cost = {} & Fixed\ costs + Variable\ costs + PEF\ costs + \\ & Fractionation\ costs \end{aligned} \tag{2}$$

$$Return = Income - Cost \tag{3}$$

$$MFSP = \frac{\left(\begin{array}{l} Fixed\ costs + Variable\ costs + PEF\ costs + \\ Fractionation\ costs - \\ \left(\begin{array}{l} yearly\ productivity\ of\ high\ value\ product \times \\ unit\ price\ of\ high\ value\ product \end{array} \right) \end{array} \right)}{(yearly\ productivity\ of\ biocrude)} \tag{4}$$

2.3 Value chain scenarios

In order to study the economic improvement by single fractionation and PEF assisted fractionation, three scenarios have been assessed, as presented in Fig. 2: In scenario 1, being the base case, microalgae biomass is directly converted to biocrude via HTL as the core technology, and biocrude is the single product; In scenario 2, microalgae first undergo a fractionation procedure for the extraction of amino acid concentrates, and then the residual biomass is converted to biocrude via HTL; In scenario 3, which is based on scenario 2, PEF treatment is introduced for assisting the extraction of amino acid concentrate.

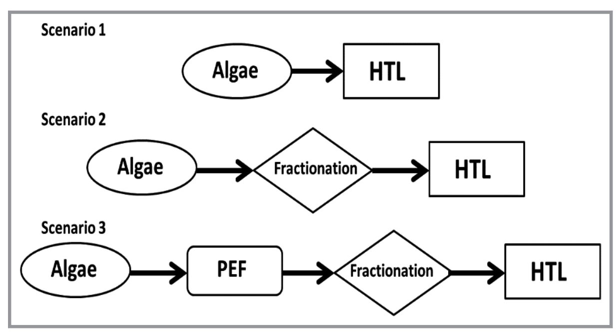

Figure 2. Three scenarios investigated in this work.

3 Result and Discussion

3.1 Mass Flow of the Scenarios

Fig. 3 shows the mass flow through the proposed plant in each scenario. After harvesting and concentration, approx. 727.25 kg h^{-1} microalgae slurry (15 wt %) is intended to be transferred to the production steps. In scenario 1, approx. 30.73 kg h^{-1} of biocrude oil can be produced (calculation based on the results from [2]). In scenario 2, the biocrude productivity is reduced to 16.82 kg h^{-1}, since only about 50 wt % of the microalgae slurry undergoes the HTL step. Meanwhile, the other 50 wt % of the microalgae slurry generate 24.54 kg h^{-1} of amino acid concentrate. It is noteworthy that the extract also contains components other than the amino acid concentrate (not shown in the chart). However,

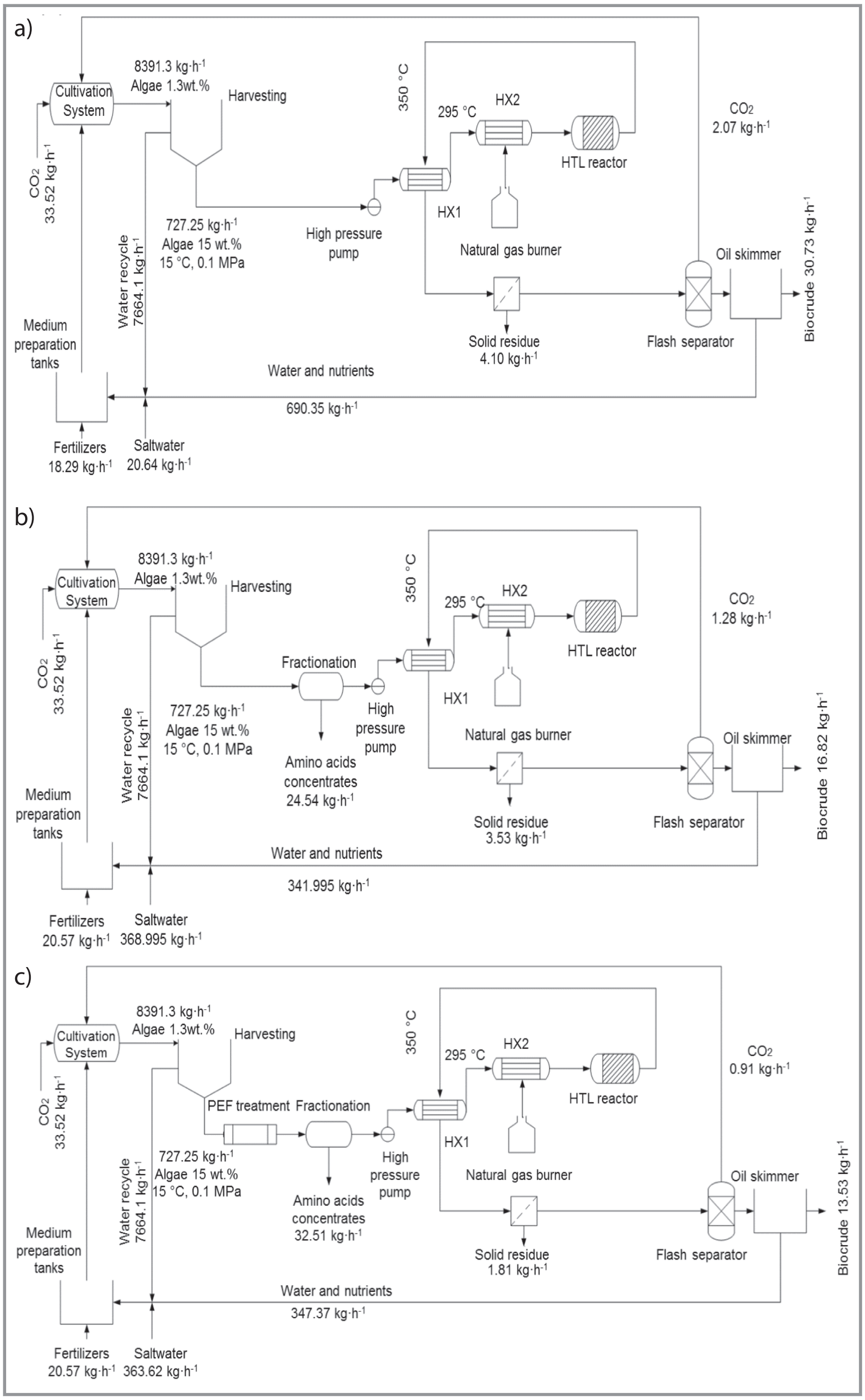

Figure 3. Mass flow of proposed microalgae biorefinery plant: a) scenario 1, b) scenario 2, c) scenario 3.

they are not considered in terms of value addition in this study. In scenario 3, 32.5 $kg\,h^{-1}$ of amino acid concentrate is intended to be produced with the help of PEF treatment, leading to a reduced production of 13.53 $kg\,h^{-1}$ of biocrude.

It is noteworthy that the required amount of fertilizer is higher in scenario 2 and 3. This is due to the lower HTL fraction. However, since most of the nutrients were recovered along with the water in the harvesting step, the increase of the fertilizer is less than 2 $kg\,h^{-1}$, which is negligible in this study (no more than 3 % of the variable cost (0.6 % of the total cost)).

3.2 Economics of the Scenarios

As shown in Tab. 4, the data of scenario 1 indicates that if the plant is designed only for microalgae biofuel production, this will lead to a net loss of 2.65 M€ a^{-1}. The MFSP of 11.95 € kg^{-1} is much higher than the fossil crude oil price (0.44 € L^{-1}), rendering microalgae biofuels uncompetitive. This price is even higher than the previously estimated price of 4.6–6.5 € kg^{-1} [3]. The main reasons for such a high value are the low HTL biocrude yield of microalgae *S. almeriensis* itself and the modifications of an expected lower biocrude yield in continuous HTL. This provides a more realistic estimation of the capital return. Nevertheless, when high value product is generated (scenario 2a), the MFSP is reduced by over 50 %. This encourages further studies on valuables extraction prior to HTL conversion. As for scenario 3a, due to the implementation of PEF, more amino acid concentrate is produced, and overall economic returns are improved. The MFSP of 1.29 € kg^{-1} brings microalgae biofuel to a competitive level as compared to fossil crude oil. When the biofertilizer is sold at 10 € L^{-1}, positive net revenues are obtained in both scenarios. It should be noted that the market price for high-value product plays a sensitive role in economic considerations. When biocrude is sold at the current price of crude oil (0.44 € L^{-1}), the biofertilizer price must be at least 7.56 € L^{-1} for a positive economic return.

Table 4. Economic key figures for three scenarios and MSFP. ('a' denotes cases where biofertilizer is sold at 7.35 € L^{-1}, 'b' denotes cases where biofertilizer is sold at 10 € L^{-1}).

Scenario	Income [M€ a^{-1}]	Cost [M€ a^{-1}]	Return [M€ a^{-1}]	MFSP [€ kg^{-1}]
1	0.101	2.75	–2.65	11.95
2a	2.31	2.93	–0.62	5.42
2b	3.12	2.93	0.19	–
3a	3.03	3.11	–0.08	1.29
3b	4.11	3.11	1	–

As shown in Fig. 4, with the data presented under the proposed scale, the PEF treatment and further fractionation are believed to play a significant role in promoting the economics of the whole process.

4 Conclusions

A techno-economic assessment of a microalgae biorefinery plant was conducted. The economic benefit of implementing PEF treatment and fractionation has been confirmed: under the given scale, the production of microalgae biofuel alone is still far from commercial viability, leading to an annual loss of 2.65 M€. It can be concluded that a fractionation step to extract high-value products unlocks significant overall capital cost reductions. Considering the lowest benchmark price of the value added amino-acid based product, PEF treatment could improve this effect by bringing the by-produced microalgae biofuel to a competitive level (1.29 € kg^{-1}) compared to the current cost of fossil crude oil (0.44 € kg^{-1}). The market price for high-value product plays an essential role in the final cost calculation. Given that microalgae biofuel should be sold at the price of crude oil, the minimum biofertilizer price for a positive capital return is 7.56 € L^{-1}.

Open access funding enabled and organized by Projekt DEAL.

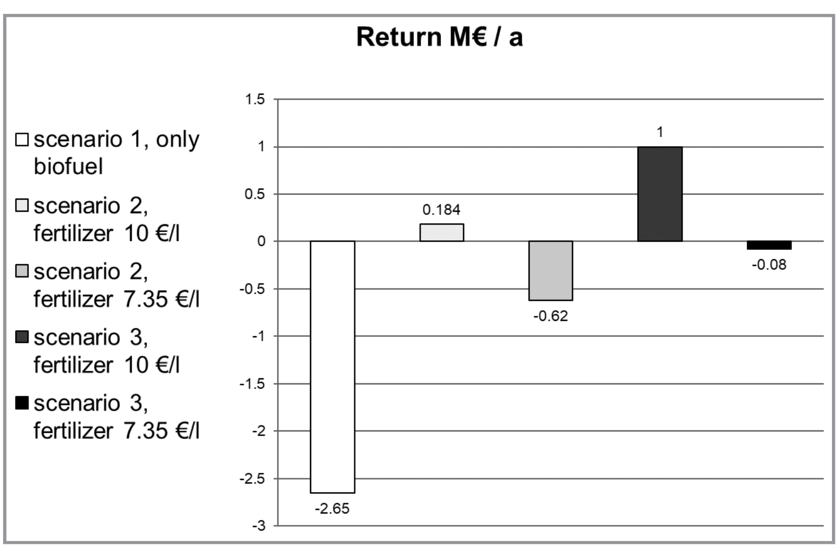

Figure 4. Return of capital in different scenarios.

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DOI: 10.1002/cite.202200007

Techno-Economic Assessment of a Microalgae Biorefinery

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Short Communication: Pulsed electric field treatment has been suggested for the extraction of high-value amino acids, and hydrothermal liquefaction of residual biomass could produce better quality biocrude with higher yield. However, the extent to which such a combined process could improve the economic prospects of the microalgae biofuel remains unclear. In this work, a techno-economic assessment is conducted to answer this question.