Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 325–332
www.elsevier.com/locate/egyr

7th International Conference on Energy and Environment Research, ICEER 2020, 14–18 September, ISEP, Porto, Portugal

Economic analysis of microalgae biodiesel production in a small-scale facility

M. Branco-Vieira[a,b,*], T.M. Mata[a], A.A. Martins[a], M.A.V. Freitas[b], N.S. Caetano[a,c]

[a] *LEPABE-Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto (FEUP), R. Dr. Roberto Frias S/N, 4200-465 Porto, Portugal*

[b] *PPE, Energy Planning Program, Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE), Federal University of Rio de Janeiro. Avenida Horácio de Macedo, 2030, Cidade Universitária, 21.941-914, Rio de Janeiro, Brazil*

[c] *CIETI, Department of Chemical Engineering, School of Engineering (ISEP), Polytechnic of Porto (P.Porto), R. Dr. Antonio Bernardino de Almeida 431, 4249-015 Porto, Portugal*

Received 30 October 2020; accepted 15 November 2020

Abstract

Industrial production and commercialization of biodiesel from microalgae have become a good alternative to conventional feedstock. Microalgae show high growth rate and carbon sequestration and can be easily cultivate in fresh and/or marine water, using non-arable soil. This study aims to analyze the technical and economic feasibility of biodiesel production from *Phaeodactylum tricornutum*, using an algae biomass production scaled-up scenario, considering local reality prices and available technologies. The model assumes 80,000 m^3 of microalgae cultivation, in a set of bubble column photobioreactors installed on 15.247 ha of land, reaching a total of 1,811 tons of microalgae biomass and 171,705 L of biodiesel per year. The production cost estimated for microalgae biomass is 2.01 € kg^{-1} and for biodiesel is 0.33 € L^{-1}. The ROI calculated for the project is 10% with a 10 years' payback time and an EBITDA of 588,139 € $year^{-1}$. Despite the project's viability in the medium term, the cost of producing microalgae biodiesel remains high when compared to fossil fuels. Thus, unless greater technological maturity is achieved to make the process more economical, it will not be viable in the short term.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

Keywords: Bubble column photobioreactor; Microalgae biodiesel; *Phaeodactylum tricornutum*; Techno-economic analysis

1. Introduction

Microalgae include a wide variety of photosynthetic microorganisms capable of fixing CO_2 from the atmosphere to produce biomass more efficiently and rapidly than terrestrial plants [1]. They are considered to be a promising

* Corresponding author at: LEPABE-Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto (FEUP), R. Dr. Roberto Frias S/N, 4200-465 Porto, Portugal.
E-mail address: monique.branco@fe.up.pt (M. Branco-Vieira).

https://doi.org/10.1016/j.egyr.2020.11.156

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

feedstock for applications in different industrial segments, such as food, feed, nutraceuticals, pharmaceuticals and biofuels [2].

When compared with traditional crops, microalgae provide a plethora of advantages for biofuel production [3]: high growth and productivity, potential for high lipid or carbohydrate contents, ability to grow on wastewater, saline or seawater. In addition, microalgae can be successfully cultivated symbiotically with bacteria to improve cells growth and biomass productivity [4]. Moreover, it has been demonstrated experimentally that numerous microalgae species produce more than 50% of their biomass as lipid, mostly triglycerides, the raw material for biodiesel production [5,6]. Furthermore, renewable fuels can be more environmental-friendly than fossil fuels and can be produced locally, contributing to energy independence [7]. Nevertheless, in order to produce biofuels from microalgae, it is important to have significant biomass production capacity. The microalgae strain and the cultivation method also have a significant effect on the types of lipids and the fatty acid profile [8]. For instance, for the production of biodiesel, the easiest and widely used method for inducing the lipid accumulation on the microalgae cells is the application of culture stresses, such as nitrogen deprivation, after a first growth period under optimal conditions [9].

Nowadays, there are many harvesting methods available. Centrifugation is one of the most popular and efficient methods for biomass harvesting, and it has been demonstrated that the association with previous flocculation step leads to an increase of dewatering efficiency [10]. Lipids are then extracted from biomass, commonly by supercritical CO_2 or using a co-solvent method, after which they can be converted to biodiesel [11].

Despite the potential of these organisms, there are some hurdles and challenges to overcome in order to establish strategies to expand the production and commercialization of these biofuels [12]. For example, there are tradeoffs in terms of growth-related characteristics, biomass yield, ability to compete for nutrients versus lipid content [13]. Nutrient supply and water recycling after biomass dewatering, are also essential for a sustainable microalgae biofuel production system [14].

Hence, this work focuses on analyzing the potential of microalgae biodiesel production and commercialization, considering a scaled-up scenario based on data obtained from real operation of a pilot-scale *Phaeodactylum tricornutum* cultivation, besides investigating its competitiveness for replacing conventional diesel production.

2. Microalgal biodiesel production processes

The proposed industrial facility is located in the city of Concepción, Chile, where microalgae are cultivated in closed modular photobioreactors (PBR) of bubble column shape. After the microalgae cultivation period, the culture medium is pumped into a reservoir tank that feeds a centrifuge, thus harvesting the biomass to be used in the downstream processes. After centrifugation, the residual water from the culture medium is filtered and returned back to the seawater tank to be reused in another culture batch. The lipid content of microalgae is extracted by supercritical carbon dioxide (SC–CO_2) method and biodiesel is produced via an alkali-catalyzed transesterification process.

2.1. Upstream processes

In this study, the upstream processes include the cultivation and harvesting of microalgae, considering the continuous operation throughout the year. The production model under consideration was developed based on experimental data obtained from a real pilot-plant located in Concepción, Chile, as described by Branco-Vieira et al. [15]. It considers a scaled-up scenario of microalgae cultivation in 100,000 modules of bubble column PBR, installed on 15.247 ha of land, totalizing a cultivation volume of 80,000 m^3, using natural seawater and a Chilean *P. tricornutum* strain, as described by Branco-Vieira et al. [16,17]. The annual production of *P. tricornutum* biomass obtained by the applied model is 1,811 tons of dried microalgae biomass, with a total lipids content of 9.08% [17,18]. The industrial plant requires low quality (LQ) and high quality (HQ) labor, corresponding to technicians and graduates, respectively, which is required for the daily operations in the industrial plant or extra labor needed for PBR cleaning or maintenance (e.g. replacement of broken reactors or maintenance of the clogged pipes and leaking reactors, etc.); in this case just LQ is required. For the calculation of the workers' hours, it was considered separately microalgae cultivation and biomass production. Therefore, 4 crashes in the production of biomass were considered throughout the year, for PBR cleaning and maintenance. Each crash considered 14 days of duration, divided as

Table 1. Capital investment, unit cost of supplies and rentals for microalgae biomass production.

Capital investment	Value [€]	Life Span [years]	Source
Reactor construction	119,731	10	Calculated
Circulation pump	10,000	8	[19]
Heating & cooling equipment	55,000	10	[19]
Process control	18,473	15	[19]
Infrastructure for cultivation	65,619	15	Calculated
Centrifuge	310,015	10	[19]
Infrastructure for harvesting	16,564	15	[19]
Total	595,402	–	–
Unit cost of supplies	Value		
Water [€ m^{-3}]	0.593	–	[20]
Electricity [€ kWh^{-1}]	0.121	–	[21]
Labor LQ [€ h^{-1}]	8.880	–	[22]
Labor HQ [€ h^{-1}]	20.650	–	[22]
Fertilizer (N) [€ kg^{-1}]	0.123	–	[23]
Fertilizer (P) [€ kg^{-1}]	0.617	–	[23]
Wastewater [€ m^{-3}]	0.773		[20]
Land rental [€ ha yr^{-1}]	7,104	–	[24]

Table 2. Capital investment and unit costs of supplies for biodiesel production.

Capital investment	Value [€]	Life span [years]	Source
Dryer	5,000	20	[19]
Ball mill	10,000	15	[19]
SC–CO_2 extractor	120,000	20	[19]
Refining	14,432	20	[19]
Transesterification equipment	22,520	20	[19]
Process control	15,695	5	[19]
Infrastructure	30,000	20	[19]
Total	217,648		–
Unit cost of supplies	Value		
Chemicals [€ kg^{-1}]	0.200	–	[25]
Methanol [€ kg^{-1}]	0.282	–	[25]
Carbon dioxide [€ kg^{-1}]	0.142	–	[25]

follows: 7 days of microalgae cultivation and harvesting downtime, including PBR cleaning and maintenance; and another 7 days for starting another microalgae culture batch; totaling 56 days·year^{-1} of crash.

Table 1 shows the capital investment, the unit cost of supplies and land rental for microalgae production (cultivation and biomass harvesting).

2.2. Downstream processes

After harvesting, microalgae biomass is addressed to biodiesel production, which is performed according to the method proposed by Spruijt et al. [19], modified accordingly in this study. The downstream processes for biodiesel production consider five process steps: (1) biomass drying; (2) disruption of cell walls by milling process; (3) SC–CO_2 lipid extraction; (4) lipids refining; and (5) transesterification process for biodiesel production. Table 2 shows the capital investment and the unit cost of supplies for biodiesel production.

2.3. Economic analysis of biodiesel production

The economic analysis of microalgae biodiesel production is based on the estimation of capital investment, operating costs and earnings or sales. It considers that in addition to the sale of biodiesel, the two by-products of the process (residual microalgae biomass and glycerol) are also sold. This way it is evaluated the impact of the by-products economic valorization on the final cost of biodiesel production. The conversion of values used in the economic analysis was done considering €1 equivalent to CLP 724 and US$ 1.22 at the exchange rates of 2018-01-19.

To obtain a perspective of the economic viability of the proposed project, and to make it possible for decision-makers to plan for improvements on the actual approach, it was calculated as financial indicators the earnings before interest, taxes, depreciation and amortization (EBITDA), return on investment (ROI) and payback time.

3. Results and discussion

3.1. Biomass production

First, it was estimated the operating and capital costs for producing 1,811 tons·year^{-1} of dried microalgae biomass. These are 1,595,323 € year^{-1} of total cost of supplies and 1,933,212 € year^{-1} of capital costs. To these costs, it was added the rental of the land, where the production plant is implemented, obtaining a total of 3,636,840 € year^{-1} that is the cost of biomass production (Table 3).

Table 3. Operating and capital costs for producing microalgae biomass.

Supplies cost	Value [€ year^{-1}]
Water	123,154
Electricity	390,938
Labor LQ	704,818
Labor HQ	202,259
Fertilizer (N)	16,160
Fertilizer (P)	5,451
Wastewater	152,543
Total	1,595,323
Capital costs	Value [€ year^{-1}]
Depreciation	804,991
Interest	622,808
Maintenance	505,412
Total	1,933,212
Rentals	Value [€ year^{-1}]
Land	108,305
Total	3,636,840

Considering that biomass is sold immediately after production, without any prior lipid extraction, at a selling price of 35 € kg^{-1} of dry biomass, it is estimated a ROI of 648%, a payback time of 0.2 year, and a production cost of microalgae biomass of 2.01 € kg^{-1} (Fig. 1a). These results indicate that microalgae biomass production is economically viable in the short term.

Results also show that the cost items that most contribute to the final cost of biomass production are the capital costs, followed by labor and electricity (Fig. 1a). Some studies have shown that fertilizers have the biggest weight in the final cost of producing microalgae biomass [26]. However, in the present study fertilizers contribute less than 1% on the final production cost, similarly to the results obtained by Acién et al. [27] and Tredici et al. [28].

3.2. Biodiesel production

For biodiesel production, it is estimated a total operating cost of 4,262,857 € year^{-1} and a total capital cost of 516,107 € year^{-1} (Table 4).

Total earnings were calculated considering the selling prices of 0.75 € L^{-1} for biodiesel, 2.85 € kg^{-1} for dry protein-rich residual biomass and 0.10 € kg^{-1} for glycerol. Results of the economic analysis for microalgae biodiesel production show that it is profitable under the current conditions (Table 5).

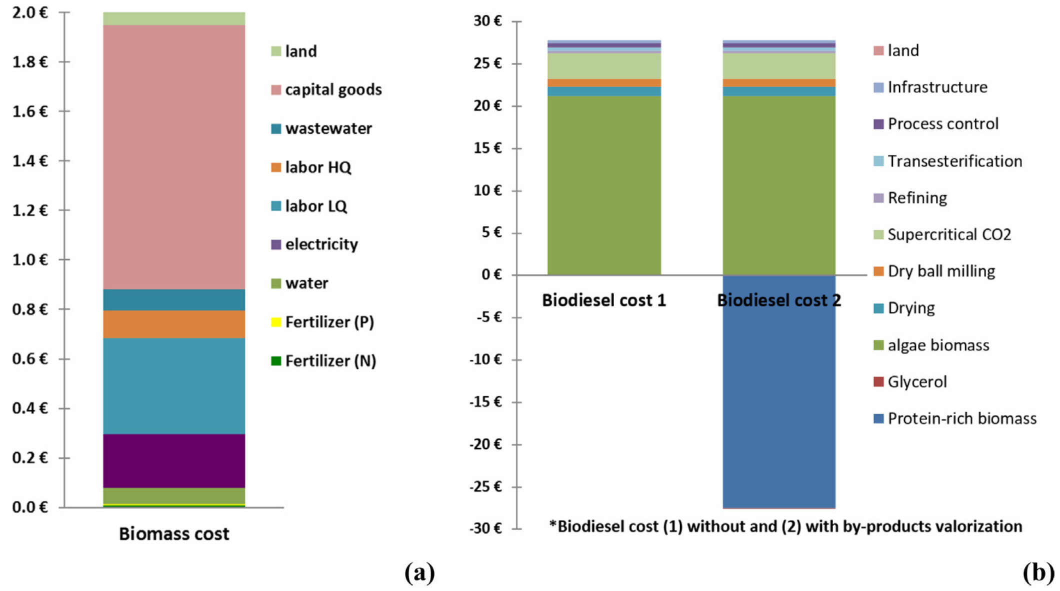

Fig. 1. Total production costs of (a) *P. tricornutum* biomass and (b) of biodiesel, showing each components considered in the cost calculation and their contribution to the final cost.

Table 4. Annual operating and capital costs for biodiesel production.

Supplies cost	Value [€ year^{-1}]
Algae biomass	3,636,840
Water	3
Electricity	173,246
Chemicals	121
MeOH	1,173
Carbon dioxide	161,313
Wastewater	5
Labor LQ	262,112
Labor HQ	28,045
Total	4,262,857
Capital costs	Value [€ year^{-1}]
Depreciation	273,048
Interest	149,026
Maintenance	94,033
Total	516,107

It was estimated a final cost of 0.33 € L^{-1} for biodiesel production, considering the economic valorization of residual biomass and glycerol. Under these conditions, it was calculated an EBITDA of 588,139 € year^{-1}, a ROI of 10% and payback time of 10 years (Fig. 1b).

It is important to highlight that the by-products economic valorization plays an important role in the process financial performance. Otherwise, if the economic valorization of by-products was not considered, the final cost of biodiesel production would be 27.83 € L^{-1} (Fig. 1b). This value is similar to the one found by Ahmad Ansari et al. [29].

Furthermore, by analyzing the contribution of each sub-process to the final cost of biodiesel, it can be seen that the cost of producing algae biomass is the main responsible for the final cost of biodiesel (similar to what Mohammady et al. [30] had found), followed by SC–CO_2 extraction, biomass drying and dry ball milling for cell disruption (Fig. 1b).

Table 5. Economic analysis of the project for the scaling-up scenario to biodiesel production.

Financial parameters	Value
Total earnings [€ $year^{-1}$]	4,850,995
Total operating costs [€ $year^{-1}$]	4,262,857
EBITDA[a] [€ $year^{-1}$]	588,139
Depreciation, interest, maintenance [€ $year^{-1}$]	516,107
Net result [€ $year^{-1}$]	72,031
ROI[a] [%]	10
Payback time [year]	10

[a]EBITDA = Earnings before interest, taxes, depreciation and amortization; ROI = return on investment

The technologies considered in this study are high energy intensive, in particular for biomass drying and lipids extraction, increasing the electricity consumption, and the biodiesel production cost. Improvements should target to use less energy intensive technologies or off-grid electricity sources, such as solar or wind energy microgeneration to enhance the profitability of microalgae-based biodiesel production. Besides, from an environmental point of view, the methodologies and technologies considered in this analysis represent better alternatives than those commonly used at the "business-as-usual" scenario for biodiesel production, possibly contributing to mitigate the environmental burden. On the other hand, the valorization of high-value compounds from residual microalgae biomass, under the biorefinery strategy, should considerably decrease the final cost of microalgae biofuels, contributing to make this approach feasible in an early future.

4. Conclusions

The production of biodiesel from microalgae was analyzed in this study. The final production cost of biodiesel was estimated as 0.33 € L^{-1} and of biomass 2.01 € kg^{-1}, in a 15.247 ha facility size, with capacity for producing about 1,811 tons of dry microalgae biomass and 171,705 L of biodiesel. This study results indicate that the production of microalgae biodiesel is economically viable on the medium term of 10 years if one considers the economic valorization of residual biomass and glycerol by-products. Moreover, to increase the profitability of the investment, it is important to consider the location of the production plant, the microalgae biomass and lipid productivities achieved under specific conditions. Additionally, it is essential to consider the local reality, prioritize use of local resources, low energy-intensive technologies or renewable energies at the plant facility, to decrease the final cost of biodiesel production. Furthermore, it is significant to consider a biorefinery strategy for valorizing the residual biomass into high-value compounds and to maximize the use of resources leading to a different product-market portfolio.

CRediT authorship contribution statement

M. Branco-Vieira: Investigation, Formal analysis, Validation, Writing - original draft. **T.M. Mata:** Data curation, Writing - review & editing, Project administration, funding acquisition. **A.A. Martins:** Data curation, Writing - review & editing. **M.A.V. Freitas:** Writing - review & editing, Supervision, Project administration, funding acquisition. **N.S. Caetano:** Writing - review & editing, Supervision, Project administration, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by Base Funding – UIDB/00511/2020 of Laboratory for Process Engineering, Environment, Biotechnology and Energy – LEPABE – funded by National funds through the FCT/MCTES (PIDDAC), Portugal; Base Funding – UIDB/04730/2020 of Center for Innovation in Engineering and Industrial

Technology, CIETI – funded by national funds through the FCT/MCTES (PIDDAC); project IF/01093/2014/CP1249/CT0003; project EXTRATOTECA - POCI-01-0247-FEDER-033784, funded by FEDER funds through COMPETE2020 – Programa Operacional Competitividade e Internacionalização (POCI) and by national funds (PIDDAC) through FCT/MCTES, Portugal; António Martins thank FCT (Fundação para a Ciência e Tecnologia), Portugal for funding through program DL 57/2016 – Norma transitória. Monique Branco-Vieira also thanks the grants: PFRH Petrobrás (Brazil) and European Commission (through Erasmus Mundus Program) postgraduate research scholarship and "Convenio de Desempeño Ciencia, Tecnología e Innovación para la Bioeconomía", from the Chilean government, for their support throughout the experimental work. The authors acknowledge Cristian Agurto and Sergio San Martín for supporting the experimental data collection at the pilot-plant in Concepción, Chile, during the Research Visiting period of Branco-Vieira in GIBMAR (Biotechnology Centre of the University of Concepción).

References

[1] Oliveira GM, Caetano N, Mata TM, Martins AA. Biofixation of CO_2 emissions from natural gas combined cycle power plant. Energy Rep 2020;140–6. http://dx.doi.org/10.1016/j.egyr.2019.08.032.
[2] Morais Junior WG, Gorgich M, Corrêa PS, Martins AA, Mata TM, Caetano NS. Microalgae for biotechnological applications: cultivation, harvesting and biomass processing. Aquaculture 2020;528:735562. http://dx.doi.org/10.1016/j.aquaculture.2020.735562.
[3] Mata TM, Martins AA, Caetano NS. Microalgae for biodiesel production and other applications: A review. Renew Sustain Energy Rev 2010;14:217–32. http://dx.doi.org/10.1016/j.rser.2009.07.020.
[4] Contreras-Angulo J, Mata T, Cuellar-Bermudez S, Caetano N, Chandra R, Garcia-Perez J, Muylaert K, Parra-Saldivar R. Symbiotic co-culture of *Scenedesmus* sp. and *Azospirillum brasilense* on n-deficient media with biomass production for biofuels. Sustainability 2019;11(707). http://dx.doi.org/10.3390/su11030707.
[5] Mata TM, Martins AA, Sikdar SK, Costa CAV, Caetano NS. Sustainability considerations about microalgae for biodiesel production. In: Advanced biofuels and bioproducts. New York, NY: Springer New York; 2013, p. 745–57. http://dx.doi.org/10.1007/978-1-4614-3348-4_31.
[6] Mata TM, Martins AA, Caetano NS. Microalgae processing for biodiesel production. In: Luque R, Melero JA, editors. Advances in biodiesel production: Processes and technologies. Woodhead publishing series in energy, Woodhead Publishing; 2012, p. 204–31. http://dx.doi.org/10.1016/B978-0-85709-117-8.50009-5.
[7] Martins AA, Mata TM, Oliveira O, Oliveira S, Mendes AM, Caetano NS. Sustainability evaluation of biodiesel from *Arthrospira platensis* and *Chlorella vulgaris* under mixotrophic conditions and salinity stress. Chem. Eng. Trans. 2016;49. http://dx.doi.org/10.3303/CET1649096.
[8] Caetano N, Melo AR, Gorgich M, Branco-Vieira M, Martins AA, Mata TM. Influence of cultivation conditions on the bioenergy potential and bio-compounds of *Chlorella vulgaris*. Energy Rep 2019. http://dx.doi.org/10.1016/J.EGYR.2019.08.076.
[9] Mata TM, Mendes AM, Caetano NS, Martins AA. Sustainability and economic evaluation of microalgae grown in brewery wastewater. Bioresour Technol 2014;168:151–8. http://dx.doi.org/10.1016/j.biortech.2014.04.091.
[10] Caetano NS, Martins AA, Gorgich M, Gutiérrez DM, Ribeiro TJ, Mata TM. Flocculation of *Arthrospira maxima* for improved harvesting. Energy Rep 2020;6:423–8. http://dx.doi.org/10.1016/j.egyr.2019.08.083.
[11] Gorgich M, Mata TM, Martins AA, Branco-Vieira M, Caetano NS. Comparison of different lipid extraction procedures applied to three microalgal species. Energy Rep 2020;6:477–82. http://dx.doi.org/10.1016/j.egyr.2019.09.011.
[12] Faried M, Samer M, Abdelsalam E, Yousef RS, Attia YA, Ali AS. Biodiesel production from microalgae: Processes, technologies and recent advancements. Renew Sustain Energy Rev 2017;79:893–913. http://dx.doi.org/10.1016/J.RSER.2017.05.199.
[13] Chew KW, Yap JY, Show PL, Suan NH, Juan JC, Ling TC, Lee DJ, Chang JS. Microalgae biorefinery: High value products perspectives. Bioresour Technol 2017;229:53–62. http://dx.doi.org/10.1016/j.biortech.2017.01.006.
[14] Martins AA, Marques F, Cameira M, Santos E, Badenes S, Costa L, Vieira VV, Caetano NS, Mata TM. Water footprint of microalgae cultivation in photobioreactor. Energy Procedia 2018;153:426–31. http://dx.doi.org/10.1016/J.EGYPRO.2018.10.031.
[15] Branco-Vieira M, San Martin S, Agurto C, Santos M, Freitas M, Mata T, Martins A, Caetano N. Potential of *Phaeodactylum tricornutum* for biodiesel production under natural conditions in Chile. Energies 2018;11(54). http://dx.doi.org/10.3390/en11010054.
[16] Branco-Vieira M, Costa D, Mata TM, Martins AA, Freitas MAV, Caetano NS. A life cycle inventory of microalgae-based biofuels production in an industrial plant concept. Energy Rep 2020;6:397–402. http://dx.doi.org/10.1016/j.egyr.2019.08.079.
[17] Branco-Vieira M, San Martin S, Agurto C, Freitas MAV, Martins AM, Mata TM, Caetano NS. Biotechnological potential of *Phaeodactylum tricornutum* for biorefinery processes. Fuel 2020;268. http://dx.doi.org/10.1016/j.fuel.2020.117357.
[18] Branco-Vieira M, Costa DMB, Mata TM, Martins AA, Freitas MAV, Caetano NS. Environmental assessment of industrial production of microalgal biodiesel in central-south Chile. J Clean Prod 2020;266:121756. http://dx.doi.org/10.1016/j.jclepro.2020.121756.
[19] Spruijt J, Schipperus R, Kootstra M, de Visser CLM, Parker B. AlgaEconomics: bio-economic production models of micro-algae and downstream processing to produce bio energy carriers. Swansea. 2015.
[20] SISS. Superintendencia de servicios sanitarios [WWW Document]. 2018, URL http://www.siss.cl. [Accessed 12 January 18].
[21] CGE. Compañía General de Electricidad S.A [WWW Document]. 2018, URL http://www.cgedistribucion.cl. [Accessed 23 January 18].
[22] MINEDUC. Subsecretaría de Educación Superior. Mifuturo.cl [WWW Document]. 2018, URL http://www.mifuturo.cl. [Accessed 20 January 18].

[23] Pentair. [WWW Document]. 2018, URL https://pentairaes.com/kent-f-2-algal-formula.html. [Accessed 22 January 18].
[24] MinVU. Tablas de costo unitario por metro cuadrados de construcción [WWW Document]. Minist. Vivienda y Urban. 2018, URL http://www.minvu.cl/opensite_20080311104413.aspx. [Accessed 15 February 18].
[25] Haas MJ, Mcaloon AJ, Yee WC, Foglia TA. A process model to estimate biodiesel production costs. Bioresour. Technol. 2005;97(4):671–8. http://dx.doi.org/10.1016/j.biortech.2005.03.039.
[26] Gonçalves A, Alvim-Ferraz M, Martins F, Simões M, Pires J. Integration of microalgae-based bioenergy production into a petrochemical complex: techno-economic assessment. Energies 2016;9(224). http://dx.doi.org/10.3390/en9040224.
[27] Acién FG, Fernández JM, Magán JJ, Molina E. Production cost of a real microalgae production plant and strategies to reduce it. Biotechnol Adv 2012;30:1344–53. http://dx.doi.org/10.1016/j.biotechadv.2012.02.005.
[28] Tredici MR, Rodolfi L, Biondi N, Bassi N, Sampietro G. Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP®) plant. Algal Res 2016;19:253–63. http://dx.doi.org/10.1016/j.algal.2016.09.005.
[29] Ahmad Ansari F, Nasr M, Guldhe A, Kumar Gupta S, Rawat I, Bux F. Techno-economic feasibility of algal aquaculture via fish and biodiesel production pathways: A commercial-scale application. Sci Total Environ 2020;704:135259. http://dx.doi.org/10.1016/j.scitotenv.2019.135259.
[30] Mohammady NGE, El-Khatib KM, El-Galad MI, Abo El-Enin SA, Attia NK, El-Araby R, El Diwani G, Manning SR. Preliminary study on the economic assessment of culturing *Nannochloropsis* sp. in Egypt for the production of biodiesel and high-value biochemicals. Biomass Convers Biorefinery 2020. http://dx.doi.org/10.1007/s13399-020-00878-9.