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A life cycle inventory of microalgae-based biofuels production in an industrial plant concept

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Abstract

Microalgae have been reported as a promising alternative for biofuels production. However, the use of microalgae for biofuels is still a challenge due to the intense energy use and the generation of a significant amount of biomass residues in the process. In order to analyze the environmental impacts of different technological processes for the production of biodiesel from microalgae, several studies have been published making use of the Life Cycle Assessment (LCA) methodology, which allows the recognition of the process bottlenecks and supports the identification of alternatives for a more efficient use of the feedstock. Therefore, in this study, a Life Cycle Inventory (LCI) is compiled, based on real pilot-scale process data, which was scaled-up to a microalgae biomass industrial plant for biofuel production. Values of energy, nutrients, water, and materials consumption are used to create an inventory of inputs and outputs for biomass cultivation and biodiesel production, in order to acquire data to conduct a complete LCA modeling in future studies. According to this model, to produce 1 kg of biodiesel it is necessary about 12 kg of dried algae biomass. This study supports the decision-making process in biofuel production to promote the development of sustainable pilot and large-scale algae-based industry, through the identification of critical factors.

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Keywords: Biofuels; Life Cycle Assessment (LCA); Life Cycle Inventory (LCI); Microalgae; *Phaeodactylum tricornutum*

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1. Introduction

Many microalgae strains are lipid-rich species, showing high growth rates and land use efficiency, when compared with traditional crops [1]. Therefore, microalgae have become a good alternative feedstock for biofuels production [2]. Among microalgae, this study focus on *Phaeodactylum tricornutum*, a marine diatom that can also grow in freshwater [3]. The *P. tricornutum* is one of the most thoroughly studied diatom species, highly productive and environmentally adaptable that can be used for biodiesel production but also has other applications through a biorefinery process [4]. For microalgae cultivation, either open or closed bioreactors can be used [5]. However, there are expressive differences among these production systems, mostly related to energy and water use [6].

Since a number of factors must be considered to choose the best alternative for producing microalgae-based products, the use of Life Cycle Assessment (LCA) is promising since it consists of a harmonized tool that supports the systematic assessment of environmental impacts, considering its entire life cycle [7]. LCA has been extensively applied to the assessment of biofuels [8], but a variety of theoretical assumptions is considered, making it difficult to compare results and different realities [9]. Besides, most studies in the existing scientific literature make use of secondary data and design predictive scenarios to support their assessment [10], which leads to unrealistic microalgae-based biofuels LCA studies [11]. Such studies often disregard the economic reality of each location, as well as the availability of infrastructure and the considerable differences that exist in microalgae growth rates, mainly due to the climatic conditions of each site [12].

According to the ISO 14040:2006 [13], the LCA is typically divided into four phases: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation. For the compilation of the Life Cycle Inventory (LCI), data on the relevant system inputs and outputs should be collected and/or calculated, using real process data as much as possible to obtain more reliable results and conclusions. This phase is often regarded as the most time consuming and critical in the context of a LCA.

In this study, primary data from the *P. tricornutum* cultivation were gathered from a pilot-scale bubble-column photobioreactor (PBR), located in the city of Concepción, Chile. These data were used to compile a LCI, which presents the necessary energy, nutrients, water, and materials inputs to produce a microalgae-based biofuel in an industrial concept, as well as the outputs related to the production process, such as wastewater, carbon dioxide (CO_2) emissions, and biomass residues.

2. Materials and methods

The scenario used to perform the LCI is based on an industrial microalgae plant facility at the city of Concepción, Chile. The facility encompasses an area of 2.5 ha, using the microalga *P. tricornutum*, with dry biomass production of 0.96 kg m^3 per batch of 14 days, cultivated in 10,000 modules of PBR, totalizing 8,000 m^3 of microalgae culture, operating 24 h/day. The industrial scenario consists of scaling-up the process, using the methodology described by Spruijt et al. [14], based on experimental data obtained on site from one module of PBR, using the same strain of this study. The scaled-up process considered all climate conditions for microalgae growth and economic factors of the location during one-year of operation.

The microalgae cultivation process is shown in Fig. 1 and consists of (1) pumping seawater to the reservoir, (2) mixing seawater with the nutrients required for the *P. tricornutum* growth, (3) feeding the PBR with the culture medium. After microalgae cultivation, (4) microalgae culture is harvested through centrifugation. The remaining wastewater from the culture medium, after biomass centrifugation, is (5) filtered and returns to the seawater tank to be reused in another culture batch. Then, the biomass recovered (containing 15% of dry matter) is used for lipid extraction (6) and biodiesel production via transesterification process (7). The inventory for biodiesel production from microalgae was built using an industrial process concept. Based on this, the system boundary for biodiesel production, on a cradle-to-gate perspective, is defined in Fig. 2.

The functional unit is defined as 1 kg of biodiesel to allow comparability to the production process of other biofuels. The developed LCI considers all processes in the foreground system, in which the primary data corresponds to all input and output flows that were obtained on a pilot-scale, which were considered to the industrial scaled-up scenario. Secondary data for the background system in the complete LCA considers the Ecoinvent database as the main data source [15]. The LCI analysis was carried out considering one year of industrial plant operation and 30 years of industrial lifespan. The LCI data and assessment model will be hereafter compiled using the SimaPro version 8.4 software of PRé Consultants [16].

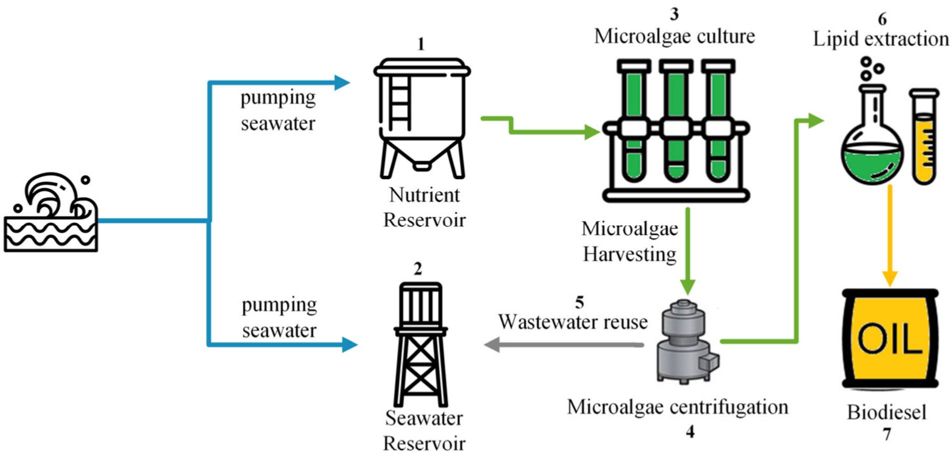

Fig. 1. Industrial microalgae cultivation and biodiesel production.

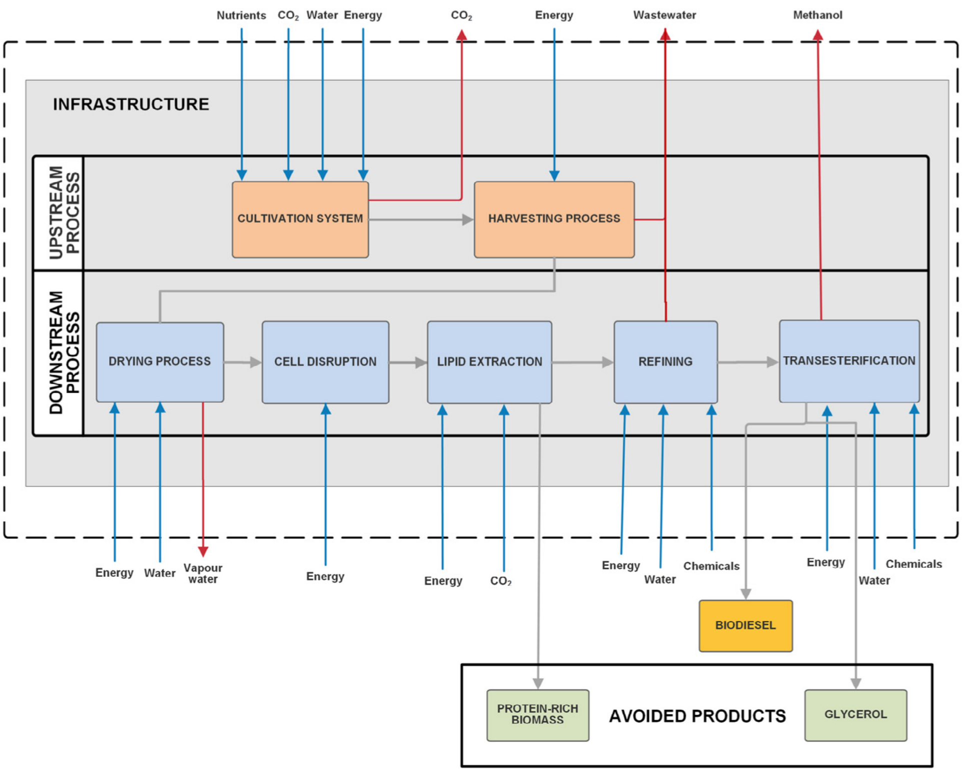

Fig. 2. The system boundary of microalgae-based biodiesel production indicated by the dashed lines; blue arrows indicate process inputs, red arrows indicate process outputs, and gray lines indicate product and co-products of the process. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

The data obtained for the upstream process are reported in Table 1, which characterizes the microalgae cultivation and biomass-harvesting steps. Table 2 shows the inventory data for the downstream processes, i.e., the biodiesel production. The values of inputs and outputs are reported to the functional unit of 1 kg of biodiesel from microalgae.

Table 1. Inventory data for upstream processes per functional unit of 1 kg of biodiesel, and considering one year of operation.

Feedstock	Inputs	Value	Unit.kg^{-1}	Outputs	Value	Unit.kg^{-1}
Cultivation						
	$ZnCl_2$	2.62E−07	kg	–	–	–
	$CoCl_2.6H_2O$	2.50E−07	kg	–	–	–
	$(NH_4)_6Mo_7O_{24}.4H_2O$	1.12E−07	kg	–	–	–
	$CuSO_4.5H_2O$	2.50E−07	kg	–	–	–
	B12 Vitamin	1.25E−08	kg	–	–	–
	B1 Vitamin	1.25E−08	kg	–	–	–
	H Vitamin (Biotin)	2.50E−08	kg	–	–	–
Chemicals	$FeCl_3.6H_2O$	1.62E−02	kg	–	–	–
	$MnCl_2.2H_2O$	4.50E−03	kg	–	–	–
	H_3BO_3	0.42	kg	–	–	–
	EDTA	0.56	kg	–	–	–
	$NaH_2PO_4.2H_2O$	0.25	kg	–	–	–
	$NaNO_3$	1.25	kg	–	–	–
	Na_2SiO_3	0.21	kg	–	–	–
	CO_2	−24.06	kg	–	–	–
Energy	Electricity for mixing	1.07	kWh	–	–	–
Water	Freshwater	585.31	m^3	–	–	–
	Seawater	13.07	m^3	Water reuse	−11.77	m^3
Biomass	–	–	–	Culture	12.50	m^3
Harvesting						
	–	–	–	Wastewater	1.31	m^3
Water	–	–	–	Phosphorus-lost	0.22	kg
	–	–	–	Nitrogen-lost	0.51	kg
Energy	Electricity for pumping	20.25	kWh	–	–	–
Biomass	Culture	12.50	m^3	Biomass paste	79.97	kg

All data were obtained from experimental results and scaled-up for a projected industrial scenario, considering one year of operation.

Regarding the process inputs, results show that biomass cultivation requires a large quantity of nitrogen, as algae nutrient, and freshwater for cooling the production system during summer. Biomass cultivation is the most water intensive process of the system. However, the impacts of water use in this phase were minimized by the 90% water reuse rate, which substantially reduces the water footprint [17]. Instead, the consumption of CO_2 for algae growth decreases considerably the carbon footprint of the process, contributing to mitigate the global warming potential of the process [18]. Otherwise, the most energy-intensive step in the production of biodiesel from microalgae is biomass drying, followed by cell disruption using a ball milling technology and pumping of the biomass culture to be harvesting through centrifugation.

For process outputs, the flows consist of CO_2 emissions, water vapor, wastewater, methanol, besides proteins, and glycerol as co-products of the process. The produced wastewater is characterized based on its macronutrients concentrations. Other possible constituents of the wastewater were not contemplated due to their very low concentrations.

According to this model, a total of 181 tons of algae biomass and 15 tons of biodiesel can be produced a year. Consequently, to produce 1 kg of biodiesel it is necessary about 12 kg of dried algae biomass. Proteins and glycerol are co-products of the process and will be allocated as avoided products on the LCA modeling, in order to increase the environmental performance of the whole process and increase the economic feasible of the value chain. Each 1 kg of biodiesel generates about 10-fold more of protein-rich residual biomass and 10% of glycerol. The protein-rich biomass can be considered for animal feed and glycerol can be used in industry for several applications. The obtained results offer a detailed characterization of the process and support further environmental assessment of the microalgae biodiesel value chain from an LCA perspective.

Table 2. Inventory data from downstream processes, considering one year of operation.

Feedstock	Inputs	Value	Unit.kg^{-1}	Value	Unit	Unit.kg^{-1}
Drying						
Water	Freshwater	67.97	m^3	Water vapor	64.97	kg
Energy	Electricity from the grid	40.79	kWh	–	–	–
Biomass	Paste biomass	79.97	kg	Dried biomass	12.00	kg
	–	–	–	Lost biomass	2.17	kg
Cell disruption						
Energy	Electricity from the grid	22.43	kWh	–	–	–
Biomass	Dried biomass	12.00	kg	Processed biomass	12.00	kg
Lipid extraction						
Energy	Electricity from the grid	7.50	kWh	–	–	–
Biomass	Processed biomass	12.00	m^3	Residual biomass	10.97	kg
Gas	CO_2	9.57	kg	–	–	–
Oil	–	–		Lipid	1.03	kg
Refining						
Chemicals	H_3PO_4	1.05E−04	kg	–	–	–
	NaOH	3.16E−04	kg	–	–	–
	$C_6H_8O_7$	6.62E−05	kg	–	–	–
Water	Wash water	4.10E−02	m^3	Wastewater	0.05	m^3
Energy	Electricity from the grid	3.17E−02	kWh	–	–	–
Oil	Lipid	1.03	kg	Refined oil	1.02	kg
Transesterification						
Chemicals	KOH	0.01	kg	–	–	–
	CH_3OH	0.22	kg	CH_3OH	0.11	kg
	–	–	–	CH_3OH recovered	0.10	kg
	H_2SO_4	8.87E−03	kg	–	–	–
Water	Wash water	0.25	m^3	–	–	–
Energy	Electricity from the grid	0.06	kWh	–	–	–
Products	Refined oil	1.02	kg	Biodiesel	1.00	kg
	–	–	–	Glycerol	0.10	kg
	–	–	–	Residual biomass	10.97	kg

4. Conclusion

This study compiled a LCI for the production of microalgae-based biodiesel, using real process data obtained from an experimental pilot-scale facility and then extrapolating it for a scaled-up scenario. Results showed that microalgae cultivation is a water intensive step, not only for the preparation of the culture medium but also for its thermoregulation. However, water consumption is minimized by the reuse of about 90% of the input water. The most energy intensive steps are the biomass drying, followed by cell disruption by ball mill and pumping of the biomass culture.

Results also show that for the production of 1 kg of biodiesel it is required about 12 kg of dried algae biomass. The remaining biomass after lipids extraction is protein rich and can be used for animal feed, improving the process viability. The results obtained consist of the first step towards a full assessment of the system through a complete LCA, making use of characterization factors in the life cycle impact assessment phase. Besides, the compiled data may also support the comparison among biodiesel from other microalgae production systems, revealing the critical steps while using this feedstock.

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