Journal of Cleaner Production 259 (2020) 120782

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Harvesting time and biomass composition affect the economics of microalgae production

Yixing Sui [a, b], Yu Jiang [c, d], Michele Moretti [a, e], Siegfried E. Vlaeminck [a, *]

[a] Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020, Antwerp, Belgium
[b] Algal Biotechnology Research Group, Faculty of Engineering and Science, University of Greenwich, Central Avenue, Chatham Maritime, Kent, ME4 4TB, UK
[c] Biobased Chemistry and Technology, Wageningen University & Research, PO Box 17, 6700 AA, Wageningen, the Netherlands
[d] Environmental Economics and Natural Resources Group, Wageningen University & Research, Hollandseweg 1, 6706 KN, Wageningen, the Netherlands
[e] Research Group of Environmental Economics, Department of Engineering Management, Prinsstraat 13, B-2000, Antwerp, Belgium

A R T I C L E I N F O

Article history:
Received 30 August 2019
Received in revised form
10 January 2020
Accepted 26 February 2020
Available online 29 February 2020

Handling editor: Kathleen Aviso

Keywords:
Novel food
Microalgae
Single-cell protein
Food market
Biobased economy

A B S T R A C T

Cost simulations provide a strong tool to render the production of microalgae economically viable. This study evaluated the unexplored effect of harvesting time and the corresponding microalgal biomass composition on the overall production cost, under both continuous light and light/dark regime using techno-economic analysis (TEA). At the same time, the TEA gives evidence that a novel product "proteinaceous salt" from *Dunaliella* microalgae production is a promising high-value product for commercialization with profitability. The optimum production scenario is to employ natural light/dark regime and harvest microalgal biomass around late exponential phase, obtaining the minimum production cost of 11 €/kg and a profitable minimum selling price (MSP) of 14.4 €/kg for the "proteinaceous salt". For further optimization of the production, increasing microalgal biomass concentration is the most effective way to reduce the total production cost and increase the profits of microalgae products.

1. Introduction

The rising global population and accompanying demands for food, feed, energy and other high-value compounds have brought up microalgae as one of the most important sources in the biobased economy (Fasaei et al., 2018). These photosynthetic microorganisms use natural sunlight and convert carbon dioxide and other nutrients into valuable biomass, which can further be used for various applications (Dassey and Theegala, 2013; Slade and Bauen, 2013). Besides, the fact that microalgae can be cultivated without using arable land and freshwater makes them a sustainable alternative to the current practices of food production, which exploit natural resources (Dassey and Theegala, 2013; Ruiz et al., 2016). Lastly, the possibility of cultivating and harvesting microalgae all-year-round also brings great commercial interests (Ruiz et al., 2016).

Nevertheless, microalgae production world-widely is still in its infancy, facing challenge of high production cost (Fasaei et al., 2018; Ruiz et al., 2016). Although large amount of efforts have been invested, exploring ways to reduce the production cost, the current price of microalgae products still remains higher comparing with conventional protein sources. According to Ruiz et al. (2016), the commercial production cost of microalgae products can be significantly reduced by increasing production scales and choosing a suitable production location. Based on these parameters, the projections indicate that only high-value compounds from microalgae used in e.g. food additive, cosmetics and biorefinery can be profitable currently, leaving bulk commodities from microalgae such as carbohydrates, lipids and protein unprofitable (Ruiz et al., 2016). More studies also investigated other parameters affecting the microalgae production cost, including harvesting and dewatering methods (Fasaei et al., 2018; Musa et al., 2019), reactor designs (Norsker et al., 2011; Ruiz et al., 2016) and lighting methods (Blanken et al., 2013). Despite the various considerations in previous studies, almost all existing techno-economic analysis (TEA) on microalgae production still share one fact in common: the harvesting time of microalgae and the microalgal biomass is either

* Corresponding author.
E-mail address: siegfried.vlaeminck@uantwerpen.be (S.E. Vlaeminck).

https://doi.org/10.1016/j.jclepro.2020.120782
0959-6526/

assumed fixed, or not mentioned at all. For instance, Ruiz et al. (2016) adopted a fixed harvesting time at biomass concentration of 0.15 g/L with a fixed biomass composition of *Nannochloropsis* sp. with 50% protein, 20% carbohydrate, 20% lipid in the TEA, Rogers et al. (2014) assumed a fixed harvesting time at biomass concentration of 0.5 g/L and fixed 25% lipid content of microalgae in the economic assumption and Tredici et al. (2016) assumed 40–50% protein content of *Tetraselmis suecica* reflecting an average biomass productivity of 15 g/m^2/d in the TEA. Whereas other studies did not even specify the biomass composition. For example, Acién et al. (2012) employed a fixed biomass concentration of 1.26 g/L in a flat panel photobioreactor and Norsker et al. (2011) used three fixed biomass concentration of 0.32 g/L, 1.7 g/L and 2.01 g/L in a raceway pond, horizontal tubular and flat panel photobioreactor, respectively, neither mentioning any biomass composition at all.

The biomass composition among different microalgal species can be remarkably different (Sudhakar et al., 2019). Even more, biomass composition of one microalgal strain can also vary significantly depending on multiple factors including the growth phases (Fidalgo et al., 1998; Sui and Vlaeminck, 2019), nutrient levels (Sui et al., 2019a), temperature (Zhu et al., 1997) and light intensities (Sui et al., 2019a). For example, the protein content can typically present an increase-decrease pattern throughout the growth phases, depending on the microalgal species and specific cultivating conditions, reaching the highest protein content around the exponential phase (Piorreck and Pohl, 1984; Sui et al., 2019b; Sui and Vlaeminck, 2019). Although higher microalgal protein content might be very appealing, very little biomass can be accumulated during the exponential phase. Whereas the stationary phase indicates the most microalgal biomass accumulation, this biomass can be poor in protein. As a result, choosing different harvesting times, thus different microalgal growth phases can significantly affect the biomass composition and final production of microalgae and the targeted microalgal compounds e.g. protein or lipid. Ultimately, these factors can influence the overall production cost to large extent.

This study uses a TEA method to analyze the variations of microalgae production cost introduced by harvesting time with different biomass composition from different growth phases, with special focus on the protein content. Furthermore, the results from the TEA are complemented with a market analysis, where the economic profitability of a novel high-value product "proteinaceous salt" is proposed and discussed.

2. Scenario description

All biological parameters for the definition of the scenarios were collected from previous experimental studies (Sui et al., 2019b; Sui and Vlaeminck, 2019). In these studies, the authors evaluated the effects of different growth phases and light regimes on *Dunaliella salina* growth and protein accumulation. Based on real experimental data and assumptions obtained from literature studies, this study adopts *Dunaliella salina* cultivation in open raceway ponds which occupies 1 ha (ha) of area in Belgian or Dutch climate conditions (Table 1). The microalgal biomass production chain is divided into three major steps: medium preparation, cultivation and harvest (Fig. 1). The production regime is batch-harvest, which means after every harvest of entire production volume, a new batch cultivation starts. In total sixteen different scenarios were analyzed in this study, including eight different harvest points at day 4, 7, 10, 13, 16, 19, 24 and 28 from the exponential growth phase until the stationary growth phase for both continuous light regime (L) and light/dark regime (LD). Each harvest point corresponds to a different biomass and protein productivity.

The lifetime of the scenario project is 22 years, including two years of construction period and empowerment, twenty years of production period. To elevate and enhance the value of microalgal biomass, a novel product "proteinaceous salt" was conceived in this study. Instead of microalgal biomass alone, this novel product combines both the values of microalgal protein and their biomass, as well as the salt accumulation properties of halophilic *Dunaliella salina*. Since such novel salt production does not exist on the market, the ideal purpose of "proteinaceous salt" is to complement conventional table salt by supplying major nutritional advantages of proteins in human salt consumption.

3. Techno-economic analysis (TEA)

The TEA method used in this study consists of three steps:

1) Production assessment: during this step, both techno- and economic-analyses evaluate the total production cost, total production and individual production cost of the three main products: biomass organics, biomass protein and "proteinaceous salt", from all sixteen production scenarios. However, these three products are not coexisting. The "proteinaceous salt" contains biomass organics and protein.

The production cost is divided into capital expenditure (CAPEX) and operational expenditure (OPEX). The total CAPEX of the project is determined by multiplying the total annual CAPEX ($CAPEX_a$) with the project lifetime (T) (Equation (1), Table 4). The total annual CAPEX involves the depreciation of the fixed capital investment, property tax, insurance and purchase tax (Equation (2), Table 4). The fixed capital investment (CI) includes direct cost (DC), indirect cost (IC) and other cost (OC), which are all based on multiplying Lang factors to the major equipment expenditure (MEE) (Equation (3), Table 4). The MEE covers all major equipment in need for the entire production chain from medium preparation to harvest (Table 3).

$$Total\ CAPEX = CAPEX_a \times T \qquad \text{Equation 1}$$

$$CAPEX_a = \frac{CI}{T} + Property\ tax + Insurance + Purchase\ tax \qquad \text{Equation 2}$$

$$CI = DC + IC + OC \qquad \text{Equation 3}$$

The total OPEX of the project is determined by multiplying the annual OPEX ($OPEX_a$) with the project lifetime (T) (Equation (4), Table 6). The annual OPEX involves major utility expenditure (MUE), labor cost and others (maintenance, overheads, contingency etc.) (Equation (5), Table 6). The MUE covers all major utilities in need for the entire production chain from medium preparation to harvest (Table 5). Detailed cost assumptions can be found in Table 2.

$$Total\ OPEX = OPEX_a \times T \qquad \text{Equation 4}$$

$$CAPEX_a = MUE + Labor + Maintenance + Operating\ supplies + General\ overhead + Contingency \qquad \text{Equation 5}$$

The total production cost is the sum of total CAPEX and OPEX, and by dividing the total microalgal biomass or protein production, the biomass production cost and protein production cost can be determined. To assess the proteinaceous salt production cost, it is assumed that after the harvest without washing the biomass, 30% salt from the medium will still remain together with the biomass.

Table 1
Basic assumptions and scenario specific parameters defining the production scenario.

Case study	Value	Unit	Reference
Basic assumptions			
Location	BE/NL	n.a.	n.a.
Production period	256	Day	(Thomassen et al., 2016)
Land area	1	Ha	Norsker et al. (2011)
Raceway pond area	0.9	Ha	Norsker et al. (2011)
Raceway pond volume	1800	m^3	Norsker et al. (2011)
Scenario specific parameters[a]			
Cultivation period	16	day	Sui et al. (2019)
Number of batches	16	n.a.	n.a.
Biomass concentration	0.58	Kg/m^3	Sui et al. (2019)
Protein concentration	0.35	Kg/m^3	Sui et al. (2019)
Annual production volume	28,357	m^3	n.a.
Daily equivalent volume	111	m^3	n.a.
Annual biomass production	16	Ton	n.a.
Annual protein production	10	Ton	n.a.
Annual proteinaceous salt production	23	Ton	n.a.
Price of main consumables			
Electricity price	0.116	€/Kwh	(European Union, 2017)
CO_2 price	0.184	€/kg	Norsker et al. (2011)
Nutrient price	0.44	€/kg dried biomass	Norsker et al. (2011)
Salt price	68.53	€/ton	(Thomassen et al., 2016)

n.a. not applicable.
[a] Scenarios specific parameters are using biomass specifics from light/dark regime harvested at day 16.

The "proteinaceous salt" is considered to contain 30% salt and 70% biomass organics, hence its production is simply 30% more than the microalgal biomass production. Based on the outcome, the scenario with the lowest production cost of all three products is considered the base scenario used in all later analyses.

2) Economic assessment: the economic feasibility of all sixteen production scenarios are determined using criteria parameters net present value (NPV) and minimum selling price (MSP).

Based on the TEA performed, a market analysis was also performed to evaluate the profitability of the proposed project. The analysis calculates the minimum selling price (MSP) in each of the sixteen scenarios in order to reach first positive net present value (NPV) after the project lifetime. The construction period of the project was considered two years, thus no revenues can be generated in those years. It is assumed that 70% of the total project CAPEX is on the loan with an interest rate of 2%. A positive NPV value indicates a good option for investment. The equation to calculate NPV is as follows:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} \qquad \text{Equation 6}$$

where T is the project lifetime (22 years including 2 years construction), t is the year of the cash flow, R_t is the net cash flow in year t and i is the discount rate. The cash flow comprises cash inflow and cash outflow (negative). Cash inflow includes revenues of the product sales. Cash outflows includes total CAPEX, total OPEX, re-investment of equipment and loan interest.

3) Sensitivity assessment: this step investigates the impact of varying input parameters on the final output parameters of the TEA results, including changes in total production cost, NPV and MSP.

Based on the significances of contribution to the total production cost, three parameters were considered in the sensitivity analysis: spray dryer price, CO_2 usage and labor cost. One additional

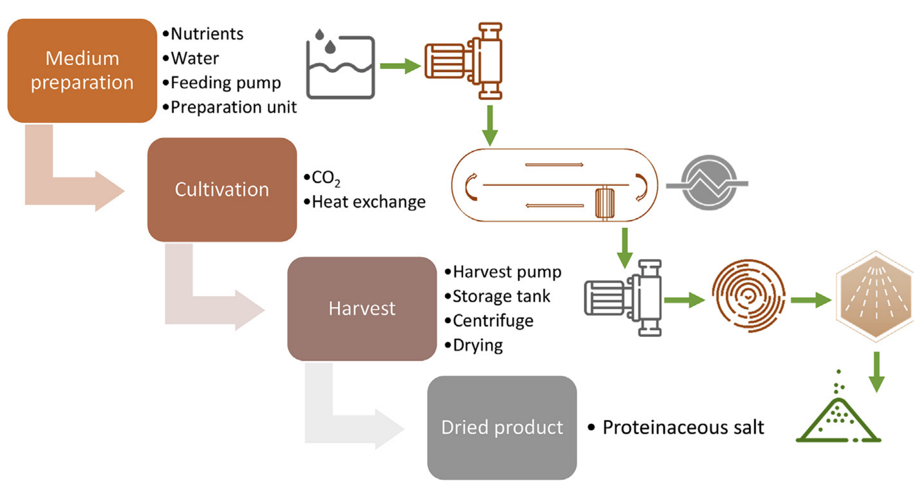

Fig. 1. General process of microalgae production.

Table 2
Basic price assumptions from LD16.

	Value	Unit	Reference
Medium preparation			
Medium preparation unit[a]	40,767	€	Norsker et al. (2011)
Medium feed pump[b]	2165	€	Ruiz et al. (2016)
Medium preparation unit	6.6	kWh/d	Acién et al. (2012)
Medium feed pump[c]	1	kWh/m^3	Norsker et al. (2011)
Cultivation			
Photobioreactors, PVC liner	7.9	$€/m^2$	Norsker et al. (2011)
Paddle wheel	883	€/pond	Norsker et al. (2011)
CO_2 supply unit[d]	6542	€/unit	Acién et al. (2012)
Heat exchange	133,830	€/unit	Tredici et al. (2016)
Mixing power by paddle wheel	5	kW/ha/d	Norsker et al. (2011)
CO_2 usage[e]	9.15	kg/kg DW	Slade and Bauen (2013)
Heat exchange power	6323	€	Tredici et al. (2016)
Harvest and dehydration			
Harvest pump[f]	2165	€	Ruiz et al. (2016)
Harvest storage tank[g]	40,767	€	Norsker et al. (2011)
Decanter centrifuge[h]	67,151	€	Ruiz et al. (2016)
Spray drying unit	113,422	€/unit	Ruiz et al. (2016)
Harvest	1.1	kWh/m^3	Norsker et al. (2011)
Spray drying	1	kWh/kg Feed	Fasaei et al. (2018)

All prices presented are corrected to year 2018 using consumer prices index.
[a] Capacity 60 m^3, number of units required: 1.8.
[b] Capacity: 2 m^3/h, number of units required: 4.6, assuming working 12h daily.
[c] Assuming the same with harvest energy consumption.
[d] Capacity: 4 kgCO_2/h, working 12h daily, amount of CO_2 required obtained from biomass concentration and CO_2 requirement per biomass dry weight (DW).
[e] Reported range from 1.83 to 9.15 kg/kg DW, high range is used in this model.
[f] Same with medium feed pump.
[g] Same with medium preparation unit.
[h] Capacity: 16.3 m^2/h, unit required: 0.6, assume working 12h daily.

Table 3
Major equipment expenditure (MEE).

	Value (€)
Medium preparation	
Medium preparation unit	40,767
Medium feed pump	2165
Cultivation	
Raceway, PVC liner	7894
Paddle wheel	7950
CO_2 supply unit	6542
Heat exchange	133,830
Harvest and dehydration	
Harvest pump	2165
Harvest storage tank	40,767
Decanter centrifuge	67,151
Spray drying unit	113,422
Total MEE	**422,654**

parameter, microalgal biomass concentration, was also included in the sensitivity analysis because it affects both cash outflows e.g. CAPEX and OPEX, and cash inflows i.e. revenues. The magnitude of variation for these parameters is set at ±10%. Besides, five more scenarios with practical implications were also included in the sensitivity analysis: increased CO_2 usage efficiency from 20% to 50% in raceway pond; free CO_2 source from flue gas; varied biomass concentration to 1 g/L and 0.3 g/L in raceway pond; cheaper labor cost if placing the project in countries with lower cost per unit of labor, such as Poland. These factors were tested without considering their associated cost input/output and biological effects, e.g. improved facilities and technologies to enhance CO_2 usage efficiency or biomass concentration, pipeline work and composition of flue gas, relocation to countries with cheaper labor.

4. Results and discussion

Four different aspects of the TEA, including production assessment, economic assessment, cost distribution and sensitivity analysis are included in this section.

4.1. Production assessment: variations of total production, total production cost and product production cost

As seen in Fig. 2A and B, different harvesting time not only substantially affect the total production of biomass organics, microalgal protein and proteinaceous salt, but also the total production cost and the corresponding CAPEX and OPEX distribution. Although the total production of all three products are much higher when cultivated under continuous light (L) than light/dark regime (LD), the associated cost, both CAPEX and especially OPEX, are also considerably more. From both light regimes, the total production of biomass organics and proteinaceous salt both showed peaks around day 16, while the production of microalgal protein started to drop earlier (Fig. 2A and B). The main cause is from the changing biomass protein content in *D. salina* at different growth phases (Sui et al., 2019b). As reported, the biomass protein content of *D. salina* presents an increase-decrease pattern with the highest protein content of around 80% achieved in the exponential growth phase and falls by up to 50% towards the stationary phase (Sui et al., 2019b).

Microalgal protein result in the highest production cost, while proteinaceous salt showed the lowest production cost under both light regimes (Fig. 2C and D). Comparing the two light regimes, continuous light leads to much higher production cost for all biomass organics, microalgal protein and proteinaceous salt (Fig. 2C). Nonetheless, under both light regimes, the production cost of each product gives a similar decrease-increase pattern (Fig. 2C and D). This pattern reveals the importance of choosing the optimum harvest point, in the interest of achieving the minimum production cost. The early harvest point around the exponential phase (around day 4) of microalgal growth gives difficulties for harvesting diluted microalgal culture, resulting in higher

Table 4
Total capital expenditure (CAPEX) of LD16.

		Factor	Value	Unit
Direct investment cost (DC)	Major equipment expenditure (MEE)	1	422,654	€
	Installation costs	0.2 MEE	84,531	€
	Instrumentation and control	0.15 MEE	63,398	€
	Piping	0.2 MEE	84,531	€
	Electrical	0.1 MEE	42,265	€
	Buildings	0.23 MEE	97,210	€
	Yard improvements	0.12 MEE	50,718	€
	Service facilities	0.2 MEE	84,531	€
	Land	0.06 MEE	25,359	€
Indirect investment cost (IC)	Engineering and supervision	0.3 DC	126,796	€
	Construction expenses	0.05 DC	47,760	€
Other investment cost (OC)	Contractor's fee	0.03	28,656	€
	Contingency	0.08 (DC + IC)	92,673	€
Total fixed capital investment (DC + IC + OC)			**1,251,083**	€
CAPEX	Lifetime		20	year
	Discount rate		10	%
	Depreciation		61,286	€/year
	Property tax	0.01 depreciation	613	€/year
	Insurance	0.006 depreciation	368	€/year
	Purchase tax	0.016 (MEE - Contingency)	18,535	€/year
	Total annual CAPEX		80,801	€/year
Total CAPEX			**1,616,026**	€

Table 5
Major utility expenditure (MUE) of LD16.

	Value (€/year)
Medium preparation	
Medium preparation unit	196
Medium feed pump	3289
Nutrient	7174
Salt	479
Cultivation	
Mixing power by paddle wheel	148
CO_2 usage	27,451
Heat exchange power	6323
Harvest and dehydration	
Harvest	3618
Spray drying	12,609
Total MUE	**61,289**

Table 6
Total operational expenditure (OPEX) of LD16.

	Factor	Value	Unit
Materials and utilities	1 MUE	61,289	€/year
Maintenance	0.04 MEE	16,906	€/year
Operating supplies	0.004 MUE	245	€/year
General plant overheads	0.55 (labor + maintenance)	39,033	€/year
Contingency	0.05 MUE	3064	€/year
Labor	3 FTE[a]	54,063	€/year
Total annual OPEX		174,601	€/year
Total OPEX cost		**3,492,017**	€

[a] Full time equivalent (FTE) is based on the minimum labor cost in the Netherlands (Ruiz et al., 2016).

production cost and low amount of harvested biomass. The late harvest point in the stationary phase (around day 28) in fact reduces the total production cost. However, the longer cultivation period largely hinders the total microalgae production, which elevates the production cost as well. To harvest around late exponential phase (around day 16) seems to be the optimum, with sufficient amount of biomass in the culture and relatively short cultivation time, securing the lowest production cost. At this point, microalgal biomass also possesses the high amount of proteins in the cell, strengthening its nutritional value.

From both light regimes, the lowest production costs of biomass organics and proteinaceous salt were 16 €/kg and 11 €/kg, obtained from light/dark regime on day 16 and day 19. The lowest microalgal protein production costs were 25 €/kg from day 13 and 26 €/kg from day 16 under light/dark regime. Therefore, day 16 from light/dark regime (LD16) is considered to be the optimum scenario for microalgae production and harvest, having the lowest production cost of all microalgae products. Tables 2–6 report the detailed CAPEX and OPEX from LD16. This scenario is also used as base scenario in the following analyses of e.g. CAPEX and OPEX distribution, NPV calculation and sensitivity. The biomass production cost in this study is similar with other reported values of comparable cultivation conditions. Norsker et al. (2011) has reported a biomass production cost of 18 €/kg based on 1 ha raceway cultivation in the Netherlands. However, when the production scale is increased to 100 ha, the production cost can be significantly reduced to only 5 €/kg. Besides the scale, different photobioreactor (PBR) designs such as horizontal and vertical tubular PBR, flat panel PBR can also reduce the production cost by more than 40% (Norsker et al., 2011). Regarding locations, even applying the same 1 ha raceway pond, warmer and cheaper locations such as Canary Islands, Turkey, Curacao, Saudi Arabia and southern Spain can contribute to more than 50% reduction of the biomass production cost (Ruiz et al., 2016). As mentioned, many parameters can influence the microalgae production to different extend, it is therefore crucial to understand how all major causes can affect the production strategies differently. The results from this study can certainly complement the existing knowledge, providing more detailed information to help promoting microalgae production more economically.

4.2. Economic assessment: feasibility of "proteinaceous salt" as a novel microalgae product

In Fig. 3B, when using a selling price of 1.1 €/kg as microalgal protein (Ruiz et al., 2016), it is evidently that this project will not profit at all (negative NPV) after the lifetime of twenty years, from neither light regimes. This result confirms that selling microalgae as bulk commodities as protein is still too costly, therefore new insights for the market are required to commercialize novel microalgae products (Fasaei et al., 2018; Ruiz et al., 2016). One way

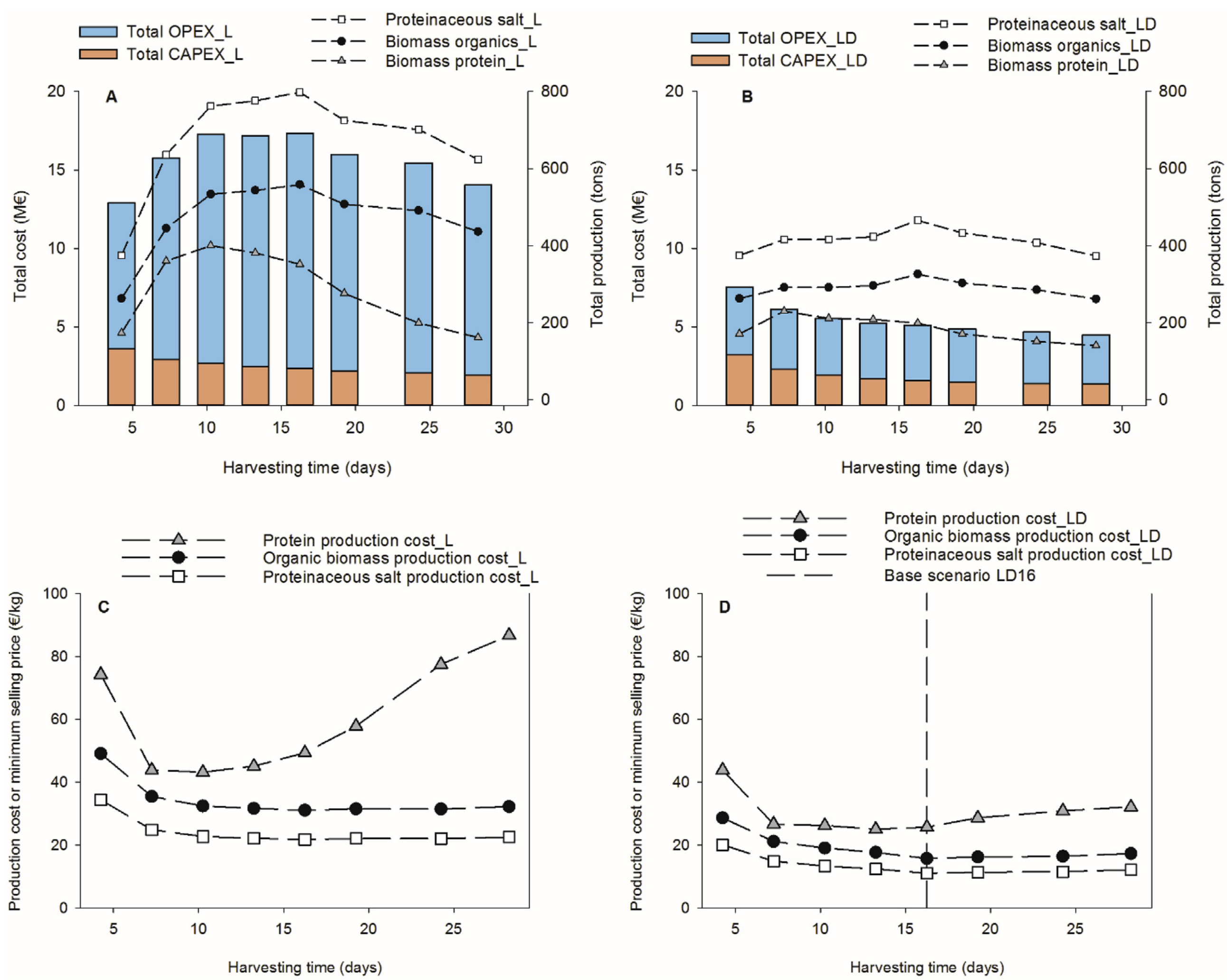

Fig. 2. Impact of harvesting time on: total production cost and total production from A) continuous light (L) and B) light/dark regime (LD); production costs of different products of the project from C) continuous light and D) light/dark regime.

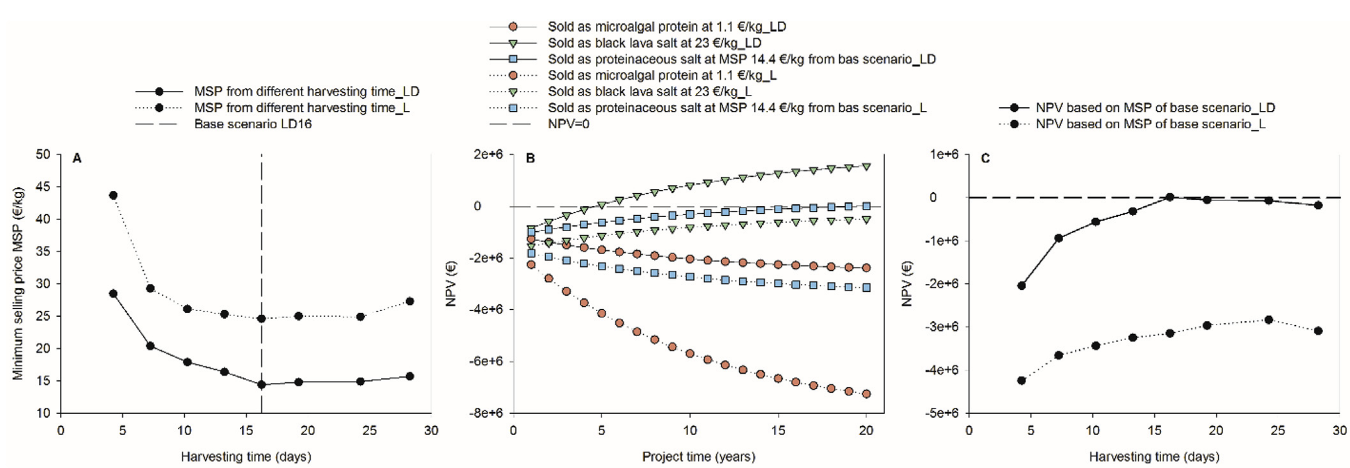

Fig. 3. A) Impact of harvesting time on minimum selling price (MSP), B) impact of selling price on the net present value (NPV) of the project and C) impact of harvesting time on NPV of the project, from continuous light (L) and light/dark regime (LD).

is to explore possible high-value compounds (e.g. pigments) from microalgal cells, however it requires more delicate biorefinery steps. Another way is to explore the novel usage of microalgal biomass, hence potentially boosting their relevant market price. For instance, black lava salt has been on the market used in cooking for its enhanced flavor and detoxifying effect from blended activated charcoal, with a selling price of around 23 €/kg. Using this selling price, the NPV of the project in this study can substantially increase,

Table 7
Sodium content of different commercially available salt products.

	Sodium content (%)	Reference
Table salt		
Rock salt	97.8	Sui and Vlaeminck (2019)
Sea salt	99.2	Sui and Vlaeminck (2019)
Seasoned salt		
Garlic salt	35	Website[a]
Celery salt	32	Website[a]
Onion salt	35	Website[a]
Saloni salt	73–77	Website[b]
Proteinaceous salt	29	(Sui and Vlaeminck, 2019)[c]

[a] https://www.mccormick.com/.
[b] https://www.indiamart.com/proddetail/saloni-vegetable-salt-1852114855.html.
[c] 30% salt remaining with 97.8% sodium content in the salt.

achieving a positive NPV in five years from light/dark regime (Fig. 3B). This result confirms that as long as a novel product with unique nutritional functionalities can fit in a niche market, its economic profitability can achieve positive, benefiting from a higher selling price. Consequently, to elevate the project profitability in this study, a novel microalgae product "proteinaceous salt" is proposed for commercialization. Fig. 3A displays the minimum selling price (MSP) of "proteinaceous salt" from all sixteen scenarios under both light regimes. The pattern of the MSP in each light regime is similar with the production costs, giving a decrease-increase form following the harvesting time (Fig. 3A). Continuous light again showed drawbacks resulting in general higher prices compared with light/dark regime (Fig. 3A). The MSP of 14.4 €/kg from day 16 under light/dark regime shows the lowest MSP of all scenarios, agreeing with the base scenario chosen above based on the lowest production cost (Fig. 3A). As seen in Fig. 3B and C, apart from using the price of black lava salt, the MSP of 14.4 €/kg is the only case where a positive NPV is achieved after the project time, indicating its great economic potential for commercialization. Comparing with all other fifteen scenarios, Fig. 3C also indicates that only the base scenario of harvesting microalgal biomass at day 16 from light/dark regime can actually contribute to a profitable project, giving the only positive NPV.

Besides the economic feasibility, the proposed "proteinaceous salt" also provides some unique nutritional qualities, thus fits in a slightly different market than some conventional microalgae products. Taking *Chlorella* for example, it is currently sold and used as food ingredient in other conventional foods such as pastas, snacks, candies, beverages, or as food supplements in the form of powder, tablets, capsules and liquids (Kay, 1991). The average selling price of *Chlorella* is 25 €/kg in Europe, which can go as high as 267 €/kg (Frost and Sullivan, 2015; Muys et al., 2019). Fitting in the niche market of nutritional and functional food with lasting customers makes *Chlorella* production still profitable by its relatively high selling price (Frost and Sullivan, 2015). *Dunaliella* biomass on one hand is adopting similar market strategy, offering β-carotene rich biomass as an ingredient of dietary supplements and functional foods (Spolaore et al., 2006). Beyond this, the "proteinaceous salt" can also be marketed more into a day-to-day scheme, sharing with conventional table salt, sea salt and other higher valued salts on the kitchen table (Table 7). More importantly, the lower sodium content in "proteinaceous salt" is comparable with other common types of seasoned salt, potentially contributing to health benefits related for instance to high blood pressure (Table 7). Two main advantages can be achieved with this product. Firstly, *Dunaliella* microalgae requires large amount of salt (e.g. from natural sea water) in their medium for cultivation due to the halophilic characteristic, hence washing off the salt to obtain clean biomass will largely increase production cost. Without such washing step, the harvested *Dunaliella* biomass will contain both edible salt and nutritional biomass, saving production cost while presenting a novel nutritional salt product. Secondly, "proteinaceous salt" does not only provide the salt requirement, but also part of protein requirement for human. Assuming an average adult with 70 kg body weight needs 46.2 g protein and consumes 8–12 g salt per day (EFSA, 2015; European Commission, 2012), consuming "proteinaceous salt" can provide 25–37% of the daily protein requirement for human, which certainly reveals top nutritional advantages of the product. Additionally, *Dunaliella* strains are known to tolerate iodine in the culture medium and tend to accumulate small amount of iodine in the biomass (Van Bergeijk et al., 2016). Consequently, when needed, iodine addition to the culture medium is foreseen to increase the amount of iodine in "proteinaceous salt". Based on the results from this study, "proteinaceous salt" can have a promising future on the market, complementing, expanding or even creating a new niche market for nutritional daily foods.

4.3. Cost distribution: artificial light comes with cost

Harvesting time day 16 from both continuous light (L) and light/dark regime (LD) was used as an example to look into detailed cost distribution. In Fig. 4, the major equipment expenditure (MEE) and major utility expenditure (MUE) are broken into the three main production steps. The most costly step is further divided into all elements composing that step. From all the results above regarding the total CAPEX and OPEX of the project, production cost of biomass organics, microalgal protein and proteinaceous salt, MSPs and NPVs of different scenarios, it is obvious that continuous light brings much more cost to the project, yields higher potential selling price of the product, thus results in no profitability comparing with using natural light/dark cycles. Using continuous light, the cultivation step is responsible for more than 57% of the total MEE costs, and the investment for the lighting infrastructure contributes to more than 54% of the MEE costs in cultivation step (Fig. 4A). The cultivation step also covers 93% of the total MUE costs, with more than 90% of these costs coming from the energy usage for artificial lighting (Fig. 4B). The breakdown of MEE and MUE gives evidence that artificial lighting comes with great cost, directly elevating the production cost of microalgal biomass. Even though various efforts have been made to improve PBR designs for a more cost-effective lighting strategy, both capital and operational cost of artificial lighting has still been reported as a major issue (Chen et al., 2011). Moreover, using artificial lighting can result in a negative energy balance, meaning the ratio of incorporated energy from energy input into the microalgal biomass can be largely reduced (Blanken et al., 2013). As a consequence, from an economic perspective, natural light/dark cycle is the preferred option for outdoor microalgae production.

When the same practice of breaking down MEE and MUE costs is done in the light/dark regime, the harvesting process become the major contribution to the overall MEE costs, taking up 53% of the total MEE costs (Fig. 4C). The cost of spray drying unit composes 51% of the total cost of the harvest step (Fig. 4C). The significance of harvesting and dewatering steps has also been shown in various studies, with a 20–30% cost contribution to microalgae production for biofuels and other purposes (Fasaei et al., 2018; Musa et al., 2019). Regarding MUE, the most significant cost comes from the cultivation step (around 55%) with CO_2 usage covering 81% of the total cost in this step (Fig. 4D).

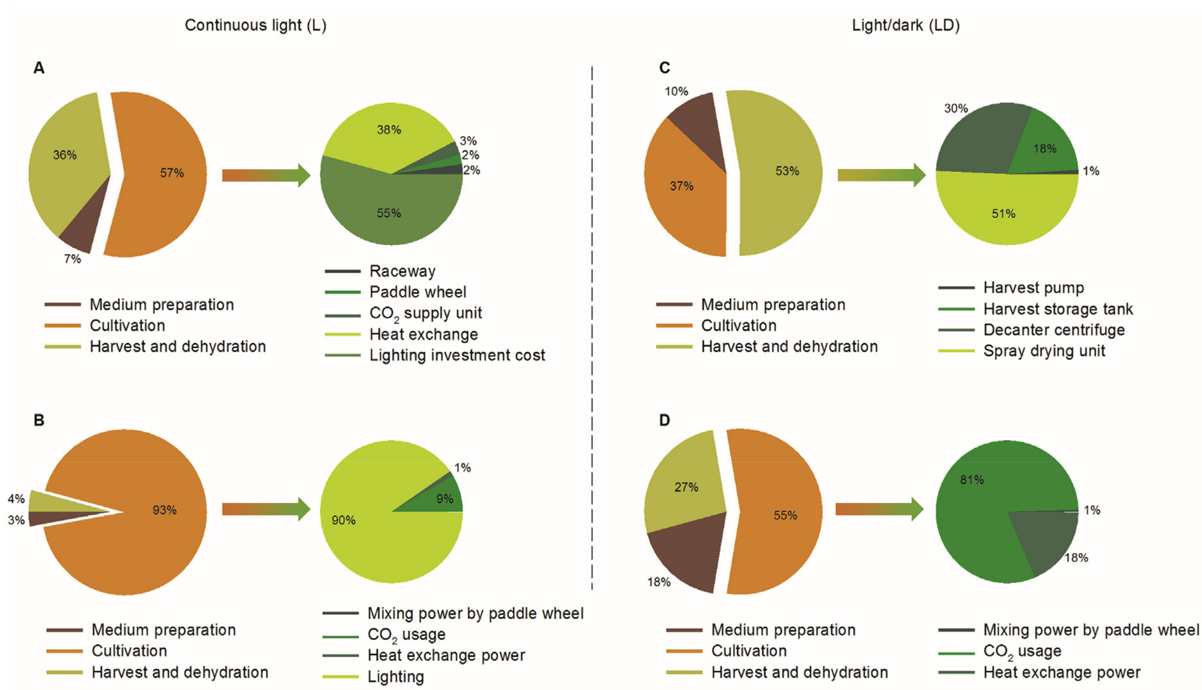

Fig. 4. Cost distribution (in percentage) of major equipment expenditure (MEE) and major utility expenditure (MUE) from both continuous light (L) and light/dark regime (LD): A) MEE distribution of L; B) MUE distribution of L; C) MEE distribution of LD and D) MUE distribution of LD.

4.4. Sensitivity analysis: key parameters have major impact

As seen in Fig. 5A and B, the ±10% variations for each of the analyzed parameter in the bas scenario do not bring large changes in the total production cost (less than 4%) and NPV (less than 1900%). If the CO_2 usage efficiency can be increased from 20% to 50% in the raceway pond, 7% of the total production cost can be saved while increasing the NPV by 1153% (Fig. 5A and B). Moreover, if flue gas containing CO_2 can be adopted in the production, the production cost can be reduced by 12%, while increasing the NPV by 1922% (Fig. 5A and B). Regarding the labor cost, when cheaper labor can be employed, a substantially 24% drop of total production cost can be reached, meanwhile improving the NPV by 3993% (Fig. 5A and B). For most parameters, an increase in total production cost translates into a decrease in the NPV, reflecting a symmetric pattern in Fig. 5A and B. Nonetheless, microalgal biomass concentration results in an asymmetric pattern, increasing or decreasing total production cost and the NPV simultaneously (Fig. 5A and B). Since biomass concentration is determining several CAPEX and OPEX related costs, such as higher biomass concentration requires more CO_2 thus bigger capacity of CO_2 supply unit, adopting a biomass concentration of 1 g/L or 0.3 g/L in the base scenario instead of 0.58 g/L directly determines an increase of 15% or a decrease of 10% total production cost, respectively (Fig. 5A). However, microalgal biomass is also the only source of revenue generated in this project, thereby the less biomass is produced, the less revenues are generated. As seen in Fig. 5B, the decreased biomass concentration results in a 8922% lower NPV. Conversely, the NPV increase by increasing biomass concentration achieved the best of all considered parameters, with 13788%. This subsequently results in a 36%

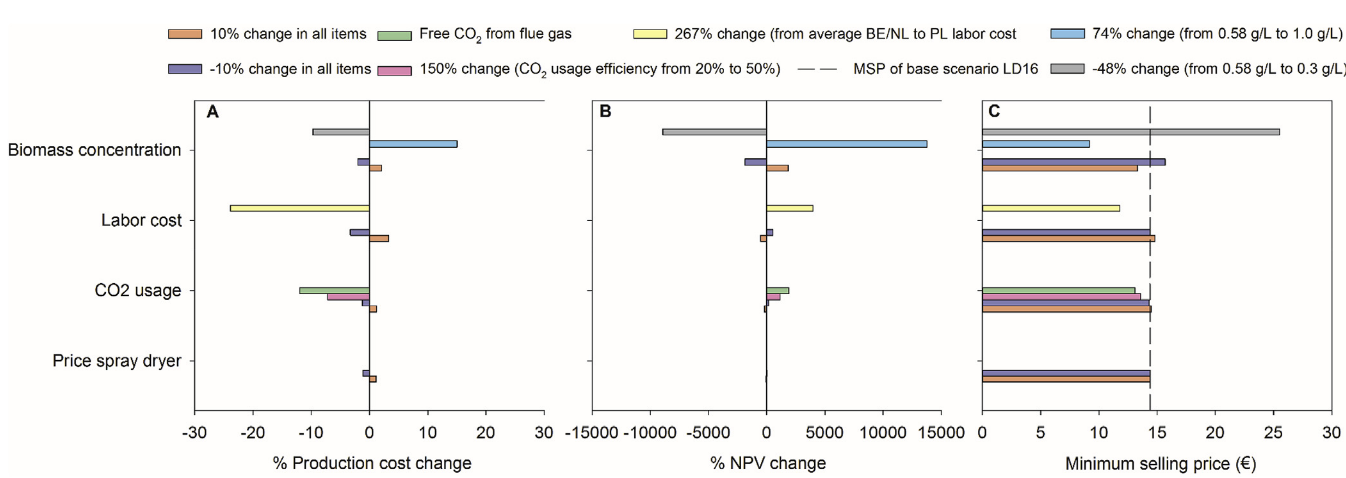

Fig. 5. Sensitivity analysis of base scenario: A) changes in production cost, B) changes in the NPV and C) resulted MSP.

reduction of the MSP, from 14.4 €/kg to 9.2 €/kg, largely increasing the profitability of the project (Fig. 5C). Therefore, biomass concentration should be considered primary target for enhanced profitability, rather than any other type of CAPEX or OPEX reduction.

Although the results from the sensitivity analysis have very clear indications, in practice, it still requires thorough considerations and calculations regarding the associated influences of each parameter on the total cost, NPV and biological effects on microalgae production. For instance, it is unlikely to increase the CO_2 usage efficiency without investing in more sophisticated equipment and facilities, hence increasing the total production cost (Li et al., 2013). Nevertheless, increased CO_2 usage efficiency will enhance biomass production at the same time, which brings revenues in return (Li et al., 2013). With respect to using flue gas, it also does not just eliminate the cost of CO_2 without bringing extra cost. It is known that transportation of gas is costly, flue gas with unknown impurities which are corrosive can further increase the cost input for pipeline designs (Raheem et al., 2018; Spiller et al., 2020). Although the effect of using flue gas can have various impact on microalgal growth, it is quite possible that the composition of flue gas can also assist microalgal growth, bringing more revenues (Raheem et al., 2018).

4.5. New possibilities for cost-effective microalgae production with enhanced nutritional value

The results from this study may open doors to more possibilities in optimizing the economics of microalgae production. Two important factors must be considered for further optimizations. Firstly, the harvesting time and the corresponding biomass composition is crucial in determining the value of microalgal biomass with specified characteristics. For example, when aiming at biofuel and bioenergy production, carbohydrate and lipid levels of microalgae surely affect the final yield, thus influencing the production economics. Therefore, it is recommended to conduct an economic assessment including actual variations of carbohydrate and lipid composition to establish the optimal production scenario. Secondly, novel microalgae products with high-value compounds must be identified for better profitability. For instance, to gain extra advantages of novel salt products from *Dunaliella* microalgae, it is essential to include carotenoids and amino acids contents into the economic assessment. For such purpose, a semi-continuous cultivation system can also be opted for, e.g. enhanced carotenoids production (Del Campo et al., 2007). However, for every economic assessment, the actual variations of microalgal composition obtained from experimental work will likely yield the most credible economic assessment.

5. Conclusions

This study addressed the importance of harvesting time and the corresponding microalgal biomass composition in determining the overall production cost, employing both continuous light and light/dark regime. Subsequently, the economic feasibility of a novel microalgae product "proteinaceous salt" was determined. From this study, it is obvious that using artificial light is not economically feasible due to its high cost. The TEA analyses indicate that harvesting time on day 16 (around late exponential phase) from light/dark regime is optimal. This optimum results in protein-rich microalgal biomass with the lowest "proteinaceous salt" production cost at 11 €/kg. Furthermore, this novel product can bring economic profitability in the project with a MSP of 14.4 €/kg, thus presenting great potential for commercialization. To further optimize the economics of microalgae production, it can be suggested that increasing biomass concentration should be the primary focus for future research, as shown by the sensitivity analysis. Moreover, the outcomes of this study provide insights to improve the environmental performance of microalgae production. To eliminate biomass washing, to recycle the medium and to adopt CO_2 from flue gas are indeed potential technological solutions which can contribute to enhance the environmental sustainability of microalgae production while increasing its economic feasibility.

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.

CRediT authorship contribution statement

Yixing Sui: Conceptualization, Methodology, Data curation, Investigation, Writing - original draft, Visualization, Funding acquisition. **Yu Jiang:** Methodology, Validation, Writing - review & editing. **Michele Moretti:** Conceptualization, Methodology, Validation, Writing - review & editing.

Acknowledgements

This work was supported by the China Scholarship Council (File No. 201507650015) and the MIP i-Cleantech Flanders (Milieuinnovatieplatform; Environment innovation platform) project Microbial Nutrients on Demand (MicroNOD).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120782.

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