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A techno-economic assessment of an algal-based biorefinery

Gwenny Thomassen[a,b,*], Urko Egiguren Vila[a], Miet Van Dael[a,b], Bert Lemmens[a], Steven Van Passel[b,c]

[a] Unit Separation and Conversion Technologies, VITO, Boeretang 200, 2400 Mol, Belgium
[b] Centre for Environmental Sciences, Hasselt University, Martelarenlaan 42, 3500 Hasselt, Belgium
[c] Department of Engineering Management; University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium

ABSTRACT

Economic and technological assessments have identified difficulties with the commercialization of bulk products from microalgae, like biofuels. To overcome these problems, a multi-product algal-based biorefinery has been proposed. This paper performs a techno-economic assessment of such a biorefinery. Four production pathways, ranging from a base case with commercial technologies to an improved case with innovative technologies, are analyzed. All region-specific parameters were adapted to Belgian conditions. Three scenarios result in techno-economically viable production plants. The most profitable scenario is the scenario which uses a specialized membrane for medium recycling and an open pond algae cultivation. Although the inclusion of a photobioreactor decreases the culture medium costs, the higher investment costs result in lower economic profits. The carotenoid content and price are identified as critical parameters. Furthermore, the economies of scale assumption for the photobioreactor is critical for the feasibility of this cultivation technology. The techno-economic assessment is an important methodology to guide and evaluate further improvements in research and shorten the time-to-market for innovative technologies in this field.

KEYWORDS

Carotenoids, integrated assessment, *Dunaliella salina*, food additives, *Haematococcus pluvialis*, microalgae

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[*] Corresponding author. Tel.: +32 11 26 87 50; +32 14 33 57 86

E-mail address: gwenny.thomassen@uhasselt.be; guinevere.thomassen@vito.be

1. INTRODUCTION

Can microalgae live up to their reputation as the ‘green gold’? To answer this question, a thorough assessment of a microalgae-based business case is required. Such an assessment is the main objective of the current study. A large and widely varying group of microorganisms is congregated under the name ‘microalgae’. Their main common characteristics are the capability of carrying out photosynthesis with chlorophyll *a* as the primary photosynthetic pigment and the lack of typical plant structures such as roots, stems and leaves (Lee 2008). Despite these common properties, microalgae vary in the biochemical components they possess and in the corresponding concentrations. This variety enables a large spectrum of potential applications (Spolaore et al. 2006). The total amount of algae species has been estimated at approximately 72,500 (Guiry 2012). However, only a few species are used for commercial applications (Raja et al. 2008). The first successful applications were the production of *Chlorella* and *Spirulina* as healthy food additives. Subsequently, the cultivation of *Dunaliella salina* for the production of β-carotene was commercialized (Borowitzka 2013). β-carotene is a carotenoid which can be used for food, feed and health applications due to its strong antioxidant properties (Spolaore et al. 2006). The second carotenoid which was commercialized was astaxanthin, which was primarily produced from a *Haematococcus pluvialis* feedstock (Lorenz and Cysewski 2000). Possible applications of astaxanthin are for example the use as a colorant for the aquaculture industry or for the production of nutraceuticals (Borowitzka 2013). In the last decades, research has focused as well on the use of microalgae as a feedstock for the production of biofuels. As microalgae could provide a sustainable alternative for fossil fuels, this application has been the main responsible for the ‘green gold’ reputation (Waltz 2009). Multiple studies have evaluated the economic potential of such microalgae-based biofuels. Their results indicate that multiple hurdles, such as for example the large production cost, still jeopardize their economic viability (Chisti 2013).

A biorefinery concept, in which multiple products (i.e. materials and fuels) are produced, was therefore suggested as a solution to the economic problems of algal-based biofuels (Zhu 2015). To evaluate if such an algal-based biorefinery could improve the economic viability, a thorough economic assessment is needed. Such an economic assessment will evaluate the economic viability of this concept and provide guidelines for further research. This should not only cover the economic aspect, but fully integrate the technological process as well. A preliminary economic assessment of a biorefinery concept was performed by Abdo et al. (2016), focusing on the production of biofuels, cake and glycerol. Another study by Rogers et al. (2014) assessed a biorefinery which produced crude oil and a feed supplement. Beal et al. (2015) combined a techno-economic assessment and a life cycle assessment of ten different biofuel scenarios on a scale of 100 ha. Besides biofuel, other products such as biocrude, ethanol and animal feed where produced as well. Consistent with most of the assessments in literature, these studies all focus on biofuel as the primary product. However, according to the cascading principle (emphasized by the European Parliament (2013)), priority should be given to high-value products. Pacheco et al. (2015) performed an assessment of an algal-based biorefinery producing high-value pigments and hydrogen. Although their study included an extensive environmental assessment, the economic dimension was only briefly discussed by a short overview of product prices and the energy costs. Another study, which did not primarily focus on bioenergy products, was performed by Chauton et al. (2015). They concluded that the production of omega-3 fatty acids from microalgae for aquaculture could become economically feasible in the near future. However, this study only valorized one product stream and was therefore not considered as a biorefinery assessment.

This paper will elaborate an early assessment of the overall feasibility of an algal-based biorefinery concept. Instead of developing a new scenario with applications, which have not been valorized yet, this paper starts from a conventional scenario, resembling current microalgae production of *Dunaliella salina* for the valorization of β-carotene. Although this process has been commercialized, no techno-economic assessment studies were found in literature. This study extends this production process by valorizing an additional product, fertilizer, and therefore assesses the technological feasibility and economic viability of a biorefinery case focused on the production of high-value products. Starting from this conventional scenario, three other scenarios were assessed as well, including more innovative technologies. This enables a comparison and the determination of the specific advantages and disadvantages of these new technologies. The commercialization of a biorefinery as assessed in this study, may catalyze the market introduction of microalgae-based biofuels, by stimulating research on more cost-effective technologies for microalgae production.

2. METHODOLOGY

Most of the techno-economic studies in the literature do not follow a clear framework or guidelines. However, a transparent assessment methodology enables the harmonization of different studies and the comparison of different algal-based biorefinery concepts. Therefore, this assessment follows a framework methodology which has already been successfully implemented in earlier techno-economic studies, for example by Kuppens et al. (2015) and Van Dael et al. (2014b). This techno-economic assessment (TEA) framework consists of four steps (Van Dael et al. 2014a):

1) Market study. During this first step, the market perspectives and external factors influencing the commercialization of a product are examined.
2) The process flow diagram and mass and energy balance. This step forms the technological 'backbone' of the assessment. An Excel-based spreadsheet model was constructed and used throughout the entire techno-economic assessment.
3) The economic assessment. The economic feasibility is determined based on the integrated technological process by calculating economic investment criteria like the net present value (NPV).
4) The sensitivity assessment. This step examines the impact of a variation of the input parameters on the economic output parameters. The sensitivity assessment identifies the critical parameters by assuming a triangular distribution for all input parameters. This distribution varies the input parameters with a positive and negative change of maximum 10%. The Crystal Ball extension was used to perform Monte Carlo simulations (10,000 trials). The crucial parameters should be investigated in more detail in later iterations of the TEA, which justifies the chosen distribution and range (Van Dael et al. 2013).

The assumptions, calculations and process data used to develop the technological process flow diagram and mass and energy balance can be found in Table 1 in Online Resource 1. Table 2 of Online Resource 1 contains all information on the cost of the equipment, the lifetime of the equipment, the operational costs, the revenues, and the financial assumptions such as loan interests and taxes. All references and information sources are provided as well. This data was mainly based on literature and calculations and was discussed with experts in the field.

3. CASE STUDY

This paper evaluates four different scenarios. The first scenario is the basic scenario which consists of conventional technologies. In the second scenario, the intermediate scenario, a membrane is added to enable medium recycle. The third scenario is a more advanced scenario, in which a photobioreactor (PBR) is used for the cultivation stage instead of an open pond. These three scenarios are based on the cultivation of *Dunaliella salina* as a feedstock for the biorefinery. In the fourth scenario a different microalgae-based biorefinery concept is analyzed. *Haematococcus pluvialis* is cultivated in a process similar to the advanced scenario, in order to compare this scenario with an alternative case.

The four scenarios each produce 170 tonnes of dry weight (DW) biomass per year to enable a comparison of the different scenarios. As the microalgal biomass is an intermediate product, this choice enables a comparison of both cultivation and downstream processes. Each scenario assumes optimal growth conditions as found in the literature. All scenarios produce two products: a high value carotenoid and a fertilizer, consisting of the residual biomass. The algal-based biorefinery is operated for 256 days per year. The other days cannot be used for cultivation due to inappropriate climate conditions and maintenance requirements.

All the scenarios use two stages for cultivation. The first stage maximizes biomass production. During the second stage, stress conditions are induced to maximize carotenoid production. Most studies in the literature use a linear or exponential growth assumption. However, this would assume that the microalgae would grow infinitely. Xu and Boeing (2014) have therefore discussed a logistic growth model. This study uses the sigmoidal growth curve as defined in equation 1:

$$N(t) = \frac{K}{1 + (\frac{K}{N_0} - 1) \times e^{-rt}} \qquad (1)$$

In this equation, K is the maximum biomass concentration, N(t) is the biomass concentration at time t, r is the maximum specific growth rate and N_0 is the initial biomass concentration. The growth parameters and corresponding growth curves are displayed in Online Resource 2.

Algae cultivation depends on region-specific parameters, such as temperature, evaporation, precipitation and solar irradiation. As the current study uses Belgian conditions as a reference, this was incorporated in the cultivation parameters.

3.1 Basic scenario

The first scenario cultivates *Dunaliella salina* as a feedstock to produce β-carotene and fertilizer. *Dunaliella salina* was one of the first microalgae used for commercial applications (Spolaore et al. 2006). The process flow diagram and mass and energy balance of this first scenario are illustrated in Figure 1.

3.1.1 First stage cultivation

The start-up of the production plant required inoculum for the initial concentration. This inoculum was produced on site. The amount of initial inoculum depends on the cultivation volume and the initial biomass concentration.

The cultivation stage was based on the pilot culture study of Tafreshi and Shariati (2006). They cultivated three strains of *Dunaliella salina* for β-carotene production in open paddlewheel ponds. As the average yearly temperature in Iran (19°C) is much higher compared to Belgium (11°C), additional heating was required (Jones et al. 2012; Osborn and Jones 2014). The ponds were heated to 20°C. Supplementary heating by radiation and solar energy was assumed to increase this temperature to 25°C. Temperature losses of 30% per day were included and compensated for by additional heating. As the precipitation rate in Belgium is higher than the evaporation rate, no additional water compensation due to evaporation was included. Another important region-specific parameter is the solar irradiation (Norsker et al. 2011). The solar irradiation is relatively low in Belgium: 1,040 kWh m^{-2} compared to 2,100 kWh m^{-2} in Iran (SolarGIS). Therefore, a correction factor for the growth function was included based on the ratio of solar irradiation of Belgium and the country where the cultivation study was performed.

The initial concentration of biomass in the first cultivation stage was set at 0.06 g l^{-1} (Prieto et al. 2011). This corresponds to a concentration of 38 g DW m^{-2} after the first stage. A specific growth rate of 0.12 day^{-1} was used, incorporating the correction factor for the Belgian climate. According to the study of Tafreshi and Shariati (2006), the growth rate of *Dunaliella salina* starts to decline after approximately 16 days. This period was therefore used as the cultivation time. The biomass production corresponds to a linear biomass productivity of 1.8 g m^{-2} day^{-1} or 0.012 g l^{-1} day^{-1}. An overview of microalgae biomass productivities was reported by Brennan and Owende (2010) and Mata et al. (2010). The value calculated in this study corresponds to the lower range of productivities. As most microalgae cultivation experiments are performed in warmer climate conditions, this biomass productivity was considered as a valid estimate, given Belgian climate conditions.

The following nutrients were supplied during the first cultivation stage: NaCl (2 M), KNO_3 (5 mM), $MgSO_4$ (2 mM), KH_2PO_4 (0.1 mM) and $FeCl_3.6H_20$ (0.01 mM) (Tafreshi and Shariati 2006). Instead of the use of $NaHCO_3$ as only carbon source, this study added CO_2 as well. The use of CO_2 as an input for microalgae cultivation has been frequently discussed, for example by Wang et al. (2008). It has also been included in multiple techno-economic studies on microalgae cultivation for biofuels, such as in Pokoo-Aikins et al. (2009). The $NaHCO_3$ and CO_2 consumption was therefore based on the study of García-González et al. (2003). On

Figure 1, the $NaHCO_3$ consumption is part of the total nutrient consumption. The CO_2 supply is given separately. Freshwater was used in the cultivation stage to ensure that the quality of the end products is safeguarded. For the same reason, CO_2 was supplied from a commercial source. The energy consumption of the CO_2 supply originated from the injection of CO_2 and the mixing. An automatic preparation unit was included to prepare the cultivation medium.

The cultivation ponds for this first stage covered an area of 24 hectares and had a depth of 15 cm (Tafreshi and Shariati 2006). This corresponded to a pond volume of 35,549 m^3. After the first cultivation stage, a certain amount of biomass remained in the first pond. This amount equaled the initial inoculum amount. Therefore, no additional inoculum production was required.

3.1.2 Second stage cultivation

In the second stage of cultivation, stress conditions were induced based on a limitation of nitrogen and a higher NaCl concentration (2.5 M) (Tafreshi and Shariati 2006). KNO_3 was supplied in a minor concentration (1 mM). The other nutrients were added in the same concentrations as in the first stage. Based on the results of Prieto et al. (2011) who examined the β-carotene content relative to the solar irradiation, a DW β-carotene concentration of 9.78% was assumed. The maximum specific growth rate was assumed to be two thirds of its first stage value. This equaled a biomass productivity of 1.08 g m^{-2} day^{-1} and 0.009 g l^{-1} day^{-1}. The ponds for the second stage had a depth of 12 cm and covered a total area of 22 hectares (Tafreshi and Shariati 2006). The required pond volume in this second stage equaled 26,895 m^3.

3.1.3 Harvesting

A centrifuge was used to harvest the microalgae. During this step, the biomass concentration was increased from 0.37 g DW l^{-1} to 120 g DW l^{-1} (Shelef et al. 1984). The centrifuge was assumed to have a biomass recovery rate of 97% and an energy consumption of 1.4 kWh m^{-3} culture medium (Milledge and Heaven 2011). The wastewater resulting from the centrifuge was not treated on the production plant itself, but was sent to a wastewater treatment plant.

3.1.4 Washing

Due to the high salinity level during cultivation, a high amount of salt remained in the biomass flow after centrifugation (0.12 kg l^{-1}). A washing step was therefore required. New water is added with a ratio of 30 to the total volume to ensure a salt concentration in the end products under 3%. After the water addition, the biomass flow was centrifuged until a biomass concentration of 120 g DW l^{-1} was restored.

3.1.5 Drying

A drying step increased the solid concentration of the biomass flow to 934 g l^{-1}. The technological specifications for the drying step were based on the study of Leach et al. (1998). To calculate the total energy consumption of this spray dryer, a factor of 2.9 was used to account for the heat exchanger energy transition efficiency. This calculation was based on the course “Sproeidrogen” by Technotrans BV in 2001. The total energy consumption equaled 5.1 MJ per kg of removed water. *Dunaliella salina* lacks a rigid cell wall (Oren 2005). The cells were therefore disrupted during spray drying and centrifugation and no additional cell disruption was required.

3.1.6 Extraction

The lipid fraction of the microalgae was extracted by the use of hexane. This process was based on the study of Cerón et al. (2008), where lutein was extracted from microalgae biomass. Six extraction steps were included, using a ratio of 1:1 of hexane to sample volume. The extraction efficiency of β-carotene was assumed to be 95% and the extraction time was 60 minutes per step (Hu et al. 2008). The bead mill and alkaline treatment used by Cerón et al. (2008) were assumed not to be necessary, due to the fragile cell wall of *Dunaliella salina* which breaks during the drying and centrifuge step and due to the relatively high carotenoid content (Oren 2005). The energy consumption was assumed to be the same as for the paddle wheel mixing in the open ponds, 3.72 W m^{-3}.

3.1.7 Filtration

The filtration step separated the liquid fraction, which contained the lipids dissolved in the hexane, from the solid fraction, which contained the residual biomass. No energy consumption was required in this step.

3.1.8 Evaporation

The solid fraction went to an evaporation step to recycle the hexane. The remaining fraction was sold as fertilizer. To calculate the energy consumption, a correction factor for the heat transfer efficiency was included. This factor was equal to the correction factor used in the drying step.

3.1.9 Vacuum distillation

The liquid fraction from the filtration step contained the carotenoids and the hexane. This hexane was distilled in a vacuum distillation to obtain a relatively pure stream of carotenoids. The calculation of the energy consumption used the same heat transfer efficiency factor as the drying and evaporation step. The carotenoids had a residual fraction of 1 mg of hexane per kg carotenoid, corresponding to the legal limit of hexane as a solvent for food or feed (European Commission 2009). To obtain this high distillation efficiency, the vacuum distillation was performed in three steps.

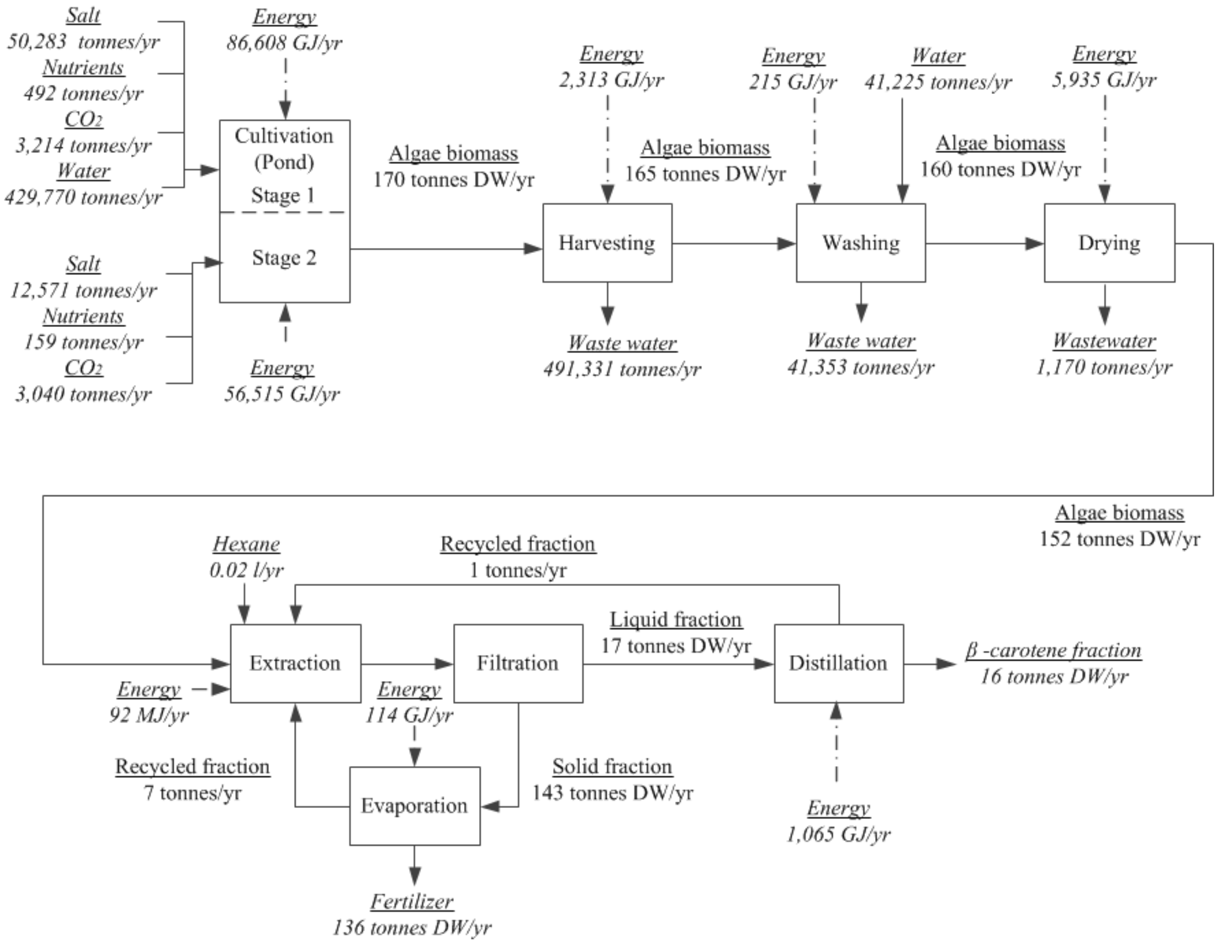

Figure 1. Basic scenario

3.2 Intermediate scenario

The second scenario cultivated the same species of microalgae. Therefore, the same cultivation parameters, such as nutrient and salt concentration were used. To harvest the microalgae, a filtration step was added using the integrated permeate channel membrane (IPC). This backwashable membrane was developed at VITO and consists of three dimensional fabric spacers which form a membrane envelope. De Baerdemaeker et al. (2013) compared the performance of this backwashable submerged membrane to other membranes Technological specifications can therefore be found in their benchmark study. The IPC membrane concentrated the biomass to a concentration of 10 g l^{-1}. The membrane filtered out bacteria and contaminations and enabled the recycling of water and salt. The amount of salt and water which needed to be supplied during the first cultivation stage was therefore lower compared to the basic scenario. The recycling ratio was limited by the difference in salt concentrations between the two cultivation stages. The residual water left the process to a wastewater treatment plant. After this membrane filtration, the downstream processes remained the same as in the basic scenario. The process flow diagram for this intermediate scenario is illustrated in Figure 2.

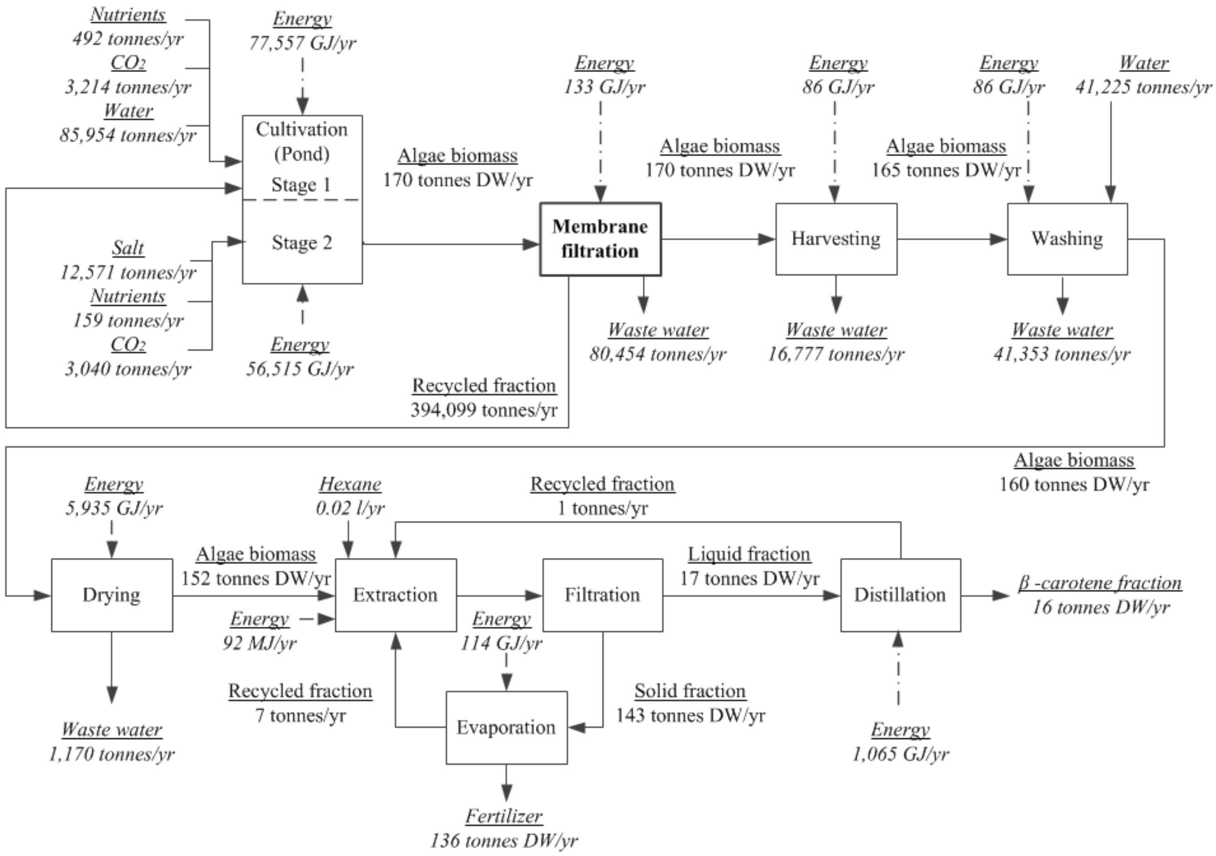

Figure 2. Intermediate scenario

3.3 Advanced scenario

The third scenario used a PBR to cultivate *Dunaliella salina.* This PBR enables a higher biomass productivity and facilitates a more strict control of cultivation conditions (Prieto et al. 2011). Less area is needed for the cultivation compared to open ponds. However, a PBR is more expensive and less durable than an open pond (Mata et al. 2010).

The two-stage system from the previous scenarios was preserved in this scenario. The growth curve was based on the study of Prieto et al. (2011). An initial biomass concentration of 0.23 g l^{-1} and a maximum biomass concentration of 2 g l^{-1} were assumed. As the study of Prieto et al. (2011) was performed in Cadiz, the difference in solar irradiation with Belgium is smaller. According to the growth curve of Prieto et al. (2011), biomass productivity leaves the exponential stage after the fifth day of cultivation. This period was therefore adopted as the cultivation period. A maximum specific growth rate of 0.25 day^{-1} was assumed, incorporating the correction factor for the Belgian climate. This corresponds with a biomass accumulation of 0.80 g l^{-1} day^{-1}, which was approximately the biomass productivity from the study of García-González et al. (2005). This productivity was again in the low range of the productivities mentioned in the literature (Brennan and Owende 2010). The nutrients were added in the same volumes as for the open ponds. The CO_2 was added in the same rate per m². As a smaller surface was required, this resulted in a lower CO_2 consumption. This lower CO_2 supply was motivated by the lower amount of CO_2 that escapes into the atmosphere. The reactor volume was 5,098 m³ in this first stage, which equals 14% of the pond volume in the previous scenarios.

The β-carotene accumulation in the second stage remained constant compared to the open pond cultivation. The energy consumption was assumed to be the same as for the first stage of this scenario. The reactor volume was 3,232 m³. The other processes included in this scenario were the same as used in the intermediate scenario. The process design of this advanced scenario is illustrated in Figure 3.

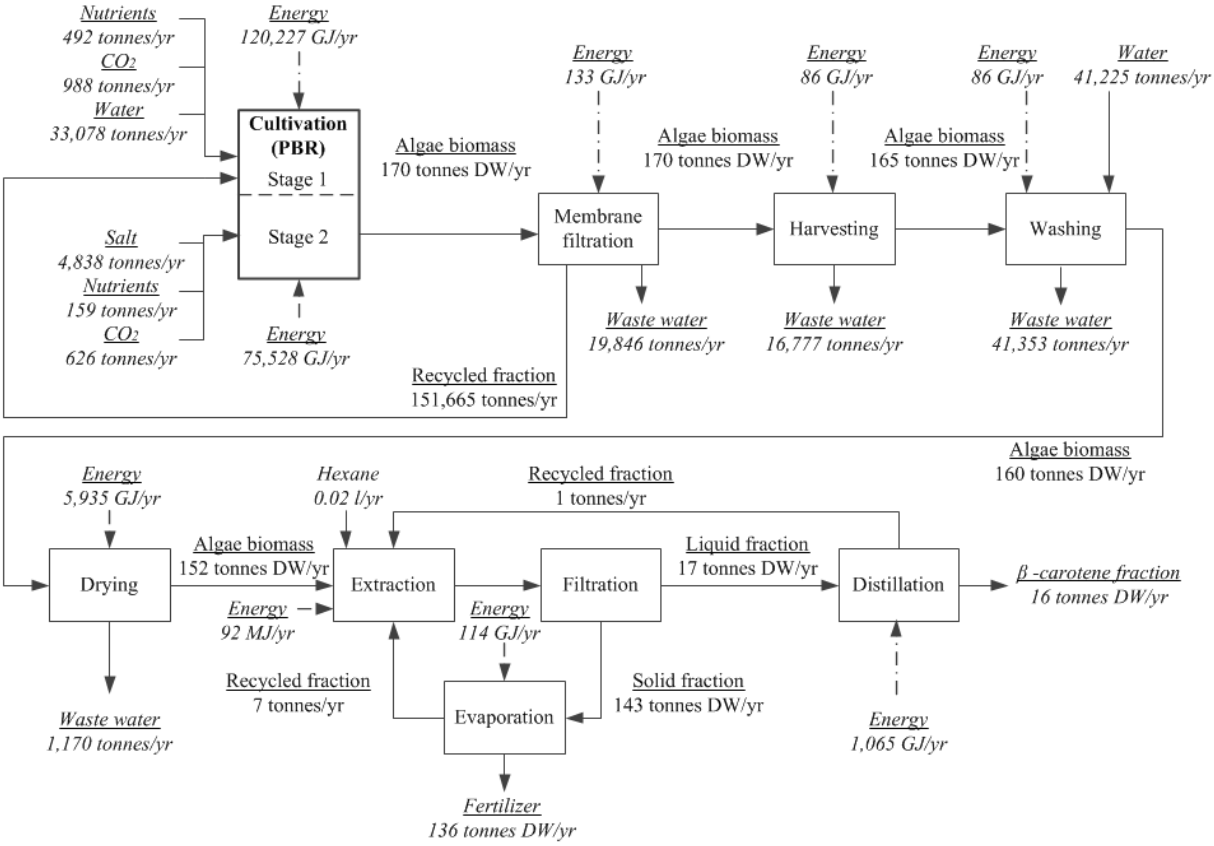

Figure 3. Advanced scenario

3.4 Alternative scenario

The fourth scenario uses an alternative microalgae, *Haematococcus pluvialis,* to produce astaxanthin and fertilizer. The production of astaxanthin from this microalga has already been commercialized. Therefore, it is an interesting case for comparison with the previous scenarios. As there is a large variety in characteristics between the different microalgae species, this comparison gives an idea of the variation in technological and economic feasibility. *Haematococcus pluvialis* is a freshwater alga, which produces haematocysts to accumulate astaxanthin in stress conditions (Del Campo et al. 2007). Therefore, it does not require any addition of salt. This microalga is very sensitive to extreme conditions, which marks the PBR as the most suitable cultivation method (Del Campo et al. 2007). The maximum biomass concentration was assumed to be 4.1 g DW l^{-1} based on the studies of Wang et al. (2013) and Aflalo et al. (2007). The maximum specific growth rate was assumed to be 0.14 day^{-1}, based on Olaizola (2000) and the correction factor. According to Wang et al. (2013), the optimal biomass concentration for astaxanthin accumulation is 0.8 g DW l^{-1}. To reach this concentration at the end of the first cultivation stage, the initial biomass concentration was assumed to be 0.45 g DW l^{-1}. This resulted in a productivity of 0.073 g l^{-1} day^{-1}, which is slightly higher than the productivity measured by Olaizola (2000) (0.036-0.052 g l^{-1} day^{-1}), but much lower than the biomass productivities found by García-Malea Lopez et al. (2006) (0.41 g l^{-1} day^{-1}) and Aflalo et al. (2007) (0.37 g l^{-1} day^{-1} – 0.8 g l^{-1} day^{-1}). The optimal growth temperature for *Haematococcus pluvialis* is 27 °C (Evens et al. 2007). As the total biomass production remained the same as in the previous scenario, the same amount of nutrients was added. The reactor volume in this first cultivation stage was 6,440 m³, which is 26 % higher compared to the advanced scenario.

The second stage of cultivation had a specific growth rate of 0.09 day^{-1}. Astaxanthin accumulated to 2.9% of total dry weight, according to the results of Olaizola (2000). A reactor volume of 2,874 m³ was used.

As the recycling ratio of the IPC membrane in this scenario is not restricted by the salt concentration, a maximum recycling ratio of 97% was assumed. *Haematococcus pluvialis* is less fragile than *Dunaliella salina.* The cell walls are therefore not broken during the drying and centrifugation step which necessitates a disruption step (Mendes-Pinto et al. 2001). As no salt was added to the cultivation step, no washing step was required. The other downstream processes remained the same as in the previous scenarios. Figure 4 illustrates the process design of this alternative scenario.

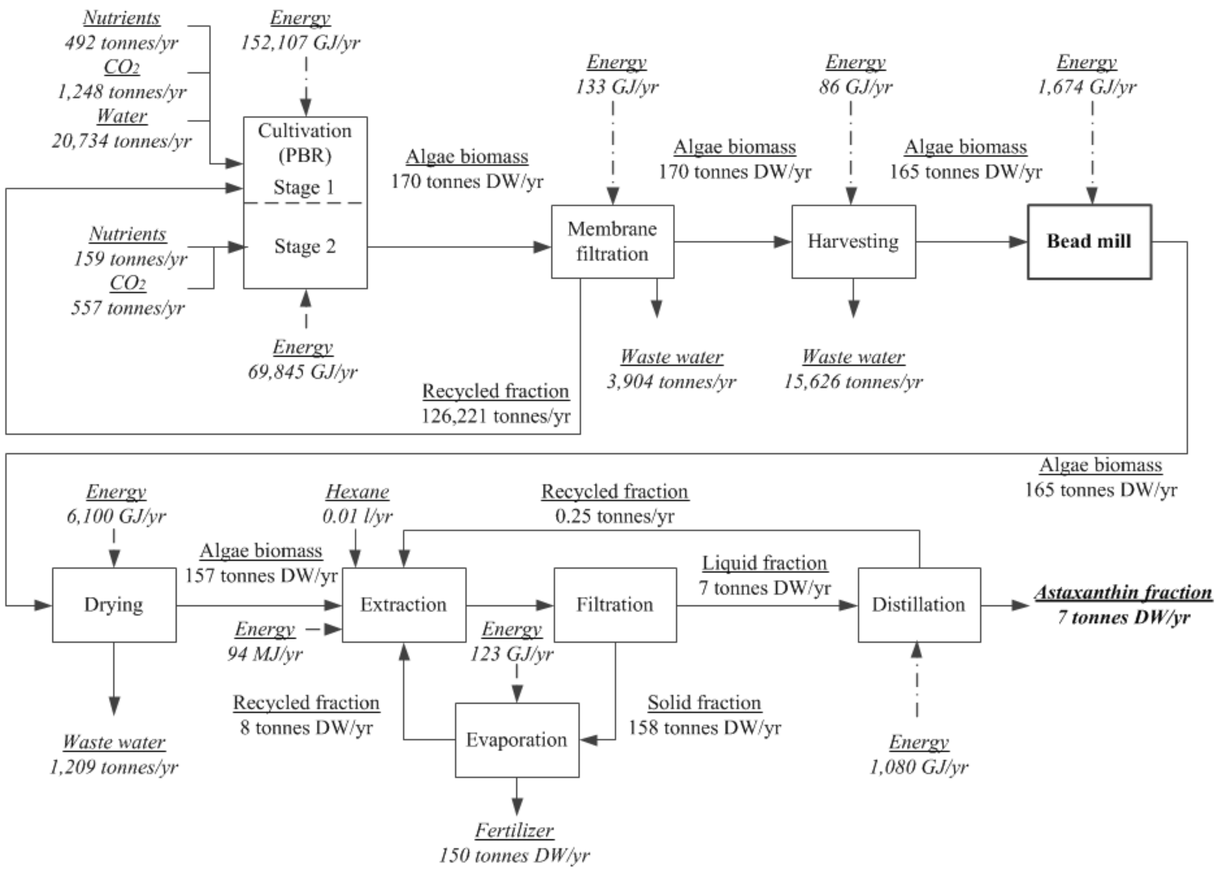

Figure 4. Alternative scenario

3.5 Economic assumptions

The investment costs for the open pond cultivation included high-density polyethylene (HDPE) liners, landscaping, paddlewheels and mixers. The PBR installation consisted of a reactor and an air blower. Both cultivation installations also included an inoculum production system, a medium preparation unit, a CO_2 supply unit and a heat exchanger unit, including a circulation pump. For the scenarios cultivating *Dunaliella salina*, a titanium heat exchanger was required as the high salt concentration could induce corrosion. For *Haematococcus pluvialis* cultivation, a cheaper heat exchanger of incoloy was used. Downstream investment costs included the IPC membrane, centrifuges, spray dryer, bead mill, filter, evaporator and distillator. For the evaporator, the same investment cost as for the distillator was used. For the extraction and washing stage, a tank and mixer were included. For these equipment costs, additional direct and indirect costs were added according to Peters et al. (2004). These additional costs were also added for the IPC membrane. For the equipment costs which originated from literature the relative direct and indirect cost of the study itself were used. The other installation costs were based on vendor prices, where the direct and indirect costs were assumed to already be included. For the entire installation a site preparation cost of 10% of total investment cost was added. The pumping requirements on the production site were based on the estimate of Rogers et al. (2014), who analyzed a similar production process.

Operational costs included the costs for the personnel, electricity and heating, water, nutrients, salt, CO_2 and hexane. As the wastewater is not treated on the plant itself, the disposal costs are included. These costs are based on the average prices for the region of Flanders in Belgium.

For region-specific costs, such as taxes, the specific rates for Belgium were used. The evaluation period was 10 years. For the installations with a shorter lifetime than the evaluation period, reinvestment was taken into account. To incorporate the effect of time on the economic parameters, the CEPCI index was used where necessary. The reference year was set at 2014. No cost data older than 2010 were used in the model. Scale effects were included based on the prices of the equipment on different scales. If only one price estimate was given, the scale effect was based on the typical exponents given by Peters et al. (2004). For equipment where no typical exponent was available, the six tenth rule was used. However, if the scale difference was more than a factor ten, an exponential scale factor of 0.8 was used. This exception was also made for the cultivation stage. The cultivation installation will require multiple units of the same scale, which necessitates a higher scale factor (Taylor et al. 2013). Revenues originate from the sales of fertilizers, β-carotene and/or astaxanthin.

4. RESULTS

4.1 Market study

There are many market studies on the different applications of microalgae. Subhadra and Edwards (2011), for example, provide information on market prices, volumes and trends of different products such as algal meal. Discussions on the commercialization opportunities of microalgae-based carotenoids can be found in Guedes et al. (2011). A broad discussion on market opportunities for microalgae-based products in the EU was provided by Vigani et al. (2015) and the report of JRC (2014). As these studies extensively discuss the market opportunities of the different algal-based products, no additional market study was included in this TEA.

In the current study, an average β-carotene price of € 1,183 per kg is assumed (Brennan and Owende 2010). The astaxanthin price is an estimate of 2013, which was retrieved from Pacheco et al. (2015): € 5,113 per kg.

4.2 Mass and energy balance and economic assessment

4.2.1 Basic scenario

Table 1 illustrates the mass and energy balance for the four different scenarios. The basic scenario requires a large amount of water and salt to obtain optimal cultivation conditions. This subsequently results in a large amount of wastewater. The 1,700 tonnes of DW biomass which are produced during the entire project lifetime (10 years), are converted into 141 tonnes β-carotene and 1,476 tonnes of fertilizer. The largest energy requirement is the heating during cultivation.

Table 2 illustrates the main economic results for the four scenarios. Investment costs are the lowest for the basic scenario. The main investment costs are the costs for the open ponds, land, the dryer and the centrifuges. The main operational costs are the salt and water consumption and the personnel costs. The first scenario has a positive NPV and can therefore be considered economically viable.

Table 1. Mass and energy balance of the four scenarios

	Unit	Basic	Intermediate	Advanced	Alternative
Input					
Water	m^3	4,718,608	1,357,745	747,486	213,372
Salt	Tonnes	629,552	129,867	48,974	0
Nutrients	Tonnes	6,516,095	6,516,095	6,516,095	6,516,095
CO_2	Tonnes	62,543,762	62,543,762	16,139,753	18,046,540
Hexane	Liter	955	955	955	970
Electricity	GJ	132,270	111,383	1,997,281	2,239,657
Heat	GJ	1,400,535	1,310,600	37,918	49,884
Land use	ha	69	69	18	20
Output					
Fertilizer	Tonnes	1,476	1,476	1,476	1,583
β-carotene	Tonnes	141	141	141	0
Astaxanthin	Tonnes	0	0	0	43
Wastewater	m^3	5,000,345	1,329,928	765,453	207,429

Table 2. Economic results of the four scenarios

	Basic	Intermediate	Advanced	Alternative
Investment costs (EUR)	11,358,196	11,274,929	43,215,635	46,175,710
Operational costs (EUR year^{-1})	13,239,346	7,541,169	13,198,809	13,710,227
Revenues (EUR year^{-1})	16,746,464	16,746,464	16,746,464	22,119,970
Net Present Value (EUR)	8,664,744	36,761,330	-13,805,375	8,333,770

4.2.2 Intermediate scenario

The intermediate scenario includes a membrane to recycle the water to the cultivation stage. This recycling reduces the water and salt consumption during cultivation fivefold compared to the basic scenario. Consequently, the amount of wastewater is much lower. Electricity consumption is lower for this second scenario as the centrifuge uses more energy than the IPC membrane. The heating requirement is reduced by 6%. This is due to the high temperature of the recycled water which reduces the overall heating during cultivation. The downstream processes after drying remain the same, as a constant amount of biomass is produced and the water content after the centrifuge is constant for all scenarios. The inputs to cultivation also remain constant, as no additional nutrients or CO_2 are recycled. The total production plant occupies 69 hectares.

The intermediate scenario has the highest NPV of all four scenarios. The investment costs decrease by 0.7% compared to the basic scenario. The addition of the IPC membrane increases the investment costs. However, a smaller centrifuge can be included in this scenario as less water needs to be removed. This results in small decrease in the investment costs. The operational costs are reduced by 43% compared to the basic scenario. This is explained by the recycling of medium, which lowers the salt and water requirements. Another reason is the lower energy requirement during cultivation. The most influencing operational costs are the CO_2 and salt cost. The revenues remain the same compared to the basic scenario.

4.2.3 Advanced scenario

The use of a PBR reduces the water and salt consumption during cultivation by 92% compared to the basic scenario. The energy consumption during cultivation is higher due to the large mixing requirements. The heating requirements are reduced due to the lower water volume. The nutrient consumption remains constant as the same biomass amount is produced. However, less CO_2 is required as the uptake in a PBR is more efficient. The amount of fertilizer and β-carotene produced remains constant as well. Less wastewater is produced as a lower volume of water is required in the cultivation stages due to a higher biomass concentration and productivity. The total production plant area is 18 hectares.

The advanced scenario is the only scenario which has a negative NPV. Therefore, it is not considered economically viable. The investment costs increase by 283% compared to the intermediate scenario. This can be explained by the inclusion of a PBR, which is responsible for 89% of the total equipment cost. The membrane costs are reduced as a smaller volume needs to be filtered. This scenario has higher operational costs than the intermediate scenario, due to the energy consumption during cultivation. Maintenance and personnel costs are also important components of the total operation costs. The total revenues remain the same compared to the previous scenarios.

4.2.4 Alternative scenario

The fourth scenario cultivates the freshwater algae *Haematococcus pluvialis*. Therefore, no salt is required. The cultivation stage requires more water as this algae has a lower productivity compared to the advanced scenario. The total water consumption however, will be lower as no washing step is included. The water recycling ratio is higher as well, as this ratio is limited by the amount of salt. The addition of the bead mill and the larger water volume increases the electricity consumption compared to the advanced scenario. The heating requirement is higher than in the advanced scenario due to the higher cultivation temperature. CO_2 consumption increases compared to the advanced scenario as a larger area is required. Due to the constant biomass production, the nutrient consumption remains the same. The total production plant area is 20 hectares, which is lower than for the first two scenarios but higher compared to the advanced scenario.

The alternative scenario has a positive NPV, which is lower than the NPV for the first two scenarios. The investment costs are the highest of all scenarios, due to the costs of the PBR and the lower productivity. Therefore, a larger capacity for the PBRs is required. The inclusion of a bead mill further increases the investment costs, although the PBR is still the largest contributor to the investment costs. Moreover, the operational costs are also higher than in the advanced scenario. The energy costs are higher, due to a higher cultivation volume, more heating and the bead mill electricity consumption. This compensates for the lower salt and water consumption. The amount of revenues for the alternative scenario with *Haematococcus pluvialis* is 32% higher than the advanced scenario. Although *Haematococcus pluvialis* contains a lower amount of astaxanthin than the β-carotene content of *Dunaliella salina*, the price for astaxanthin is much higher.

4.3 Sensitivity assessment

The sensitivity assessment identifies the parameters which have a large impact on the variance of the NPV. The critical parameters that contribute more than 5% to the variance of the NPV are summarized in Table 3 for all four scenarios.

The most crucial parameters for the basic scenario are the β-carotene content and price. The yield of β-carotene in the process is relatively low. However, the high price of β-carotene renders the project economically viable. The other important parameters are related to all the processes where part of this β-carotene can be removed in a waste stream. The higher the recovery of these processes, the higher the economic profitability. The intermediate scenario has the same critical parameters as the basic scenario. In the advanced scenario, the sizing factor of the PBR is of main importance. The cost of this PBR was based on the study by Acién et al. (2012), which linearly upscaled a PBR of 3 m³. Due to this small unit scale, a large amount of units are required. Moreover, the total PBR cost was the main component of the total investment cost and therefore paramount to the overall economic viability. The measure to include scale advantages of the PBR will therefore have a large impact on the overall economic profitability. In the alternative scenario, the scaling factor of the PBR is also important. However, the impact of the carotenoid content and price is larger compared to the advanced scenario.

The carotenoid price is identified as one the most critical parameters for an economic profitable process. However, this price is highly uncertain as future market trends may have a large influence. The lowest carotenoid price for which the process has a positive NPV for the different scenarios, keeping all other parameters constant, is € 1,060 per kg β-carotene (basic scenario), € 661 per kg β-carotene (intermediate scenario), € 1,379 per kg β-carotene (advanced scenario) and € 4,726 per kg astaxanthin (alternative scenario).

Table 3. Relative contribution of the critical parameters to the variance in NPV

Variable	Basic	Intermediate	Advanced	Alternative
Carotenoid content (%)	+18.4%	+17.1%	+5.3%	+7.1%
Price β-carotene/astaxanthin (EUR $tonne^{-1}$)	+17.5%	+16.7%	+5.4%	+6.9%
Extraction efficiency (%)	+10.7%	+10.1%		
Drying carotenoid recovery (%)	+10.5%	+10.8%		
Washing (centrifuge) efficiency (%)	+8.3%	+7.9%		
Centrifuge efficiency (%)	+8.3%	+7.9%		
PBR scaling factor			-51.9%	-51.1%

5. DISCUSSION

This study performs a TEA of four different algal-based biorefineries. The NPV was positive for three of the four scenarios, although all four scenarios had higher yearly revenues than yearly costs. The cultivation of *Dunaliella salina* currently occurs in open ponds. The use of PBRs instead of these ponds is not yet economically viable as was assessed in the advanced scenario. However, PBRs are commercially viable for the cultivation of *Haematococcus pluvialis* for astaxanthin.Although the current assumed production scale is not sufficient to obtain four economically viable scenarios, scale advantages exist. Each scenario can therefore be characterized by a minimum viable production scale. This minimum biomass production scale for a positive NPV in the advanced scenario is 598 tonnes DW per year. This corresponds to a land use of 63 hectares. As the other scenarios have a positive NPV, a lower scale may also be economically viable. For the basic scenario, a minimum biomass production scale of 75 tonnes DW per year is identified. The intermediate scenario, which had the largest NPV in this TEA, requires a scale of 25 tonnes DW per year. The alternative scenario needs a minimum production scale of 105 tonnes DW per year to be economically viable.

There are multiple other studies which assessed the techno-economic potential of a microalgae business case, with widely varying results. This variety is for example due to different process pathways, which convolutes the comparison (Quinn and Davis 2015). If the revenues and taxes are omitted from the calculations of the current study, a biomass production cost of € 65 per kg (basic scenario), € 40 per kg (intermediate scenario), € 82 per kg (advanced scenario) and € 86 per kg (alternative scenario) was calculated. This is higher than for example the biomass calculation costs calculated by Norsker et al. (2011), which range between € 4.15 and € 5.96 per kg. Their study focused on the production of biofuels and could therefore use a microalgae species with a higher productivity. The biorefinery which was assessed in the current study produces high-value products such as food additives, which are accumulated in specific microalgae species. This makes the production process more expensive.

Three main challenges for the implementation of an algal-based biorefinery focused on high-value products in Belgium can be identified.

The first challenge which needs to be taken into account is the relatively small market volume of the different products. According to Spolaore et al. (2006), β-carotene and astaxanthin have a market volume of respectively 1,200 tonnes per year and 300 tonnes per year. A large production scale can therefore saturate the market and drastically reduce the market price. This biorefinery case study is a partial analysis, specifically adapted to Belgian conditions. Therefore, the specific impact on regional production and changing world prices has not been included.

The second challenge is the high salt content of the waste water, which can be a hurdle for the commercial implementation of this process. In the current model we assume a tax for water disposal. However, in reality it will be difficult to obtain legal approval for this process in Belgium. Therefore an additional water treatment technology should be added to further iterations. This could increase the recycling ratio of the water and enable the recycling of salt. An appropriate technology for this application could be a membrane distillation (Eykens et al. 2016). The use of this technology for desalination is currently developed at a pilot scale and is therefore an interesting innovative technology to include in further models (Ruiz-Aguirre et al. 2014).

The third challenge is the land occupation of the entire process. Belgium is a country with a high population density, which could render a large production scale unfeasible. According to the report of ILVO, the flower region in Belgium consists of 13.24 hectares of free greenhouses (Verhoeve et al. 2015). As greenhouses have been used for microalgae cultivation in PBRs before, this could give an indication of the feasible production scale. In our model, a cultivation area of 13.24 corresponds to a total plant area of 20 hectares, which was the total plant area for the alternative scenario. The production scales as assumed in this study could therefore be a realistic case for Belgium. In our model, we assume a centralized production plant. However, in reality the cultivation plants can also be shattered with a centralized downstream processing plant. In this case, additional logistic costs should be added to the model.

The two algae species used in this TEA have a relatively low biomass productivity. As only a small amount of microalgae is currently used, the ideal microalgae for a biorefinery may yet be discovered. The selection of an appropriate microalgae species for a certain application can be facilitated by screening tools (Picardo et al. (2012).

This techno-economic assessment assesses the technological and economic feasibility of algal-based biorefineries. However, for the biobased economy, environmental aspects are also crucial. An example of an environmental impact which needs to be taken into account is the land use. Another environmental impact, which is important in the current model, is the freshwater consumption. Excessive water use may lead to water scarcity, which will also influence the water purchase costs. Process water or ground water can be a cheaper water source. However, in this case additional water treatment will be required to obtain the required water quality for food applications. These linkages between environmental impacts and economic costs are an interesting field of research, but can only be identified in a fully-fledged assessment which integrates technological, economic and environmental aspects.

6. CONCLUSION

This study has analyzed the technological and economic potential of four different algal-based biorefinery scenarios, based on two different microalgae species. Based on the results, we can conclude that algal-based biorefineries can be economically viable. However, large differences between the technological and economic parameters have been observed. The inclusion of the IPC membrane increases the economic viability of the production process, although other process parameters are more critical to the overall techno-economic viability. The use of PBRs is currently too expensive to be implemented on a commercial scale for the cultivation of *Dunaliella salina*. However, for the cultivation of *Haematococcus pluvialis*, PBRs can be used for an economically viable production process. Further process optimization can increase the techno-economic viability of these technologies. The carotenoid content and price are identified as the critical parameters for the open pond cultivation. This implies that an accurate estimate of the carotenoid accumulation is required to narrow down the error range of the analysis. Moreover, price volatilization of carotenoid prices can have a large impact on the profitability of the project. For the PBR cultivation, the scale assumption for the PBR investment is crucial. A more specific price estimate on large scale for the PBR costs is therefore required in future TEA iterations. These further iterations should also integrate an environmental assessment. Such an integrated environmental and techno-economic assessment will be able to identify the critical parameters which can both increase the economic profitability and lower the environmental impact and can therefore decrease the time-to-market for algal-based biorefineries.

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