90. An environmental techno-economic assessment of algal-based biorefineries

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ABSTRACT

Microalgae have been proposed as an important feedstock for the biobased economy. However, the economic profitability and environmental impact of microalgae-based biofuels remains an issue. A microalgae-based biorefinery, valorizing multiple products, has been stated as an interesting solution. To explore the feasibility of this concept, an assessment of both the economic feasibility and environmental impact is required. This paper extends a techno-economic assessment of an algal-based biorefinery with an integrated life cycle assessment (LCA). Four different scenarios, ranging from a basic scenario with conventional technologies to more advanced scenarios with innovative technologies, are assessed. Using this environmental techno-economic assessment, the biomass productivity was identified as a crucial parameter for both the economic and environmental feasibility. The inclusion of a membrane to enable the recycling of water and salt had a positive influence on both the economic profitability and the environmental sustainability of the project. The environmental techno-economic assessment can provide important information to optimize the economic profitability and environmental impact of new technologies and to catalyze the transition to a biobased economy.

Sustainability assessment, integrated assessment, microalgae

1. Introduction

The group of algae can be defined as plant-like organisms which contain chlorophyll α as the primary photosynthetic pigment and lack typical plant structures like stem, roots and leaves (Lee, 2008). Microalgae are the small algae which can generally not be seen with the naked eye (Lundquist et al., 2010). These microorganisms have a relatively high productivity and can accumulate multiple valuable components, such as carotenoids. They are also considered as a potential feedstock for biofuels, as they can accumulate high amounts of lipids (Mata et al., 2010). However, there are a few challenges concerning the commercialization of these applications. Firstly, the production price is still too high to enable the profitable valorization of algal-based biofuels (Cheng and Timilsina, 2011). Therefore, an algal-based biorefinery, which valorizes multiple products, has been proposed as a more promising commercialization strategy in the near term (Zhu, 2015). Secondly, the sustainability of biofuels has been questioned, for example due to the large freshwater consumption of large scale production (Chisti, 2013). A thorough sustainability assessment of algal-based biorefineries in an early stage of technology development is therefore required. Both problems are usually discussed independently, with economic assessments aiming to quantify the economic potential and life cycle assessments aiming to quantify the environmental impact. This study extends the existing techno-economic assessment (TEA) methodology as introduced by Van Dael et al. (2014) with an environmental assessment, based on the life cycle assessment (LCA) methodology, as suggested by Thomassen et al. (2016b). The case study is based on previous work of the authors (Thomassen et al., 2016a). The results will enable the identification of trade-offs or synergies between the different sustainability dimensions and the crucial parameters which should be enhanced to shorten the time-to-market for algal-based biorefineries.

2. Methods

A TEA aims to quantify the economic potential of new technologies during each stage of their technology development over the entire value chain. The mass and energy balance is integrated to enable a dynamic model, where an alteration in each technological or economic input assumption is directly translated in the results. The environmental techno-economic assessment integrates the LCA framework into the TEA methodology and consists of five steps: (1) *Market study*, (2) *Process flow diagram (PFD) and mass and energy balance*, (3) *Environmental assessment,* (4) *Economic assessment,* and (5) *Interpretation*.

This paper focusses on the environmental part of the assessment, an in-depth description of the TEA methodology can be found in the previous study by the authors (Thomassen et al., 2016a). The environmental assessment uses the ReCiPe midpoint impact indicators (hierarchist perspective): climate change (CC), ozone depletion (OD), terrestrial acidification (TA), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), freshwater eutrophication (FE), marine eutrophication (ME), ionizing radiation (IR), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MD) and fossil fuel depletion (FD) (Goedkoop et al., 2013). The environmental impacts of all inputs and outputs of the process were extracted from the Ecoinvent database version 3.2 using the Simapro software and transferred to a spreadsheet model in order to directly link the environmental impacts with the technological analysis.

3. Case study

The case study is based on an update of previous work of the authors, where four algal-based biorefinery scenarios were discussed. An extended description of the case studies can therefore be found in Thomassen et al. (2016a). The four scenarios range from a basic scenario with conventional technologies to a more advanced scenario. An alternative scenario, using a different microalgae species with a different end product is assessed as well. All scenarios produce 170 tonnes dry weight (DW) biomass per year for the production of carotenoids and fertilizer. The biomass production was used as a constant factor to enable both the comparison of the cultivation phase and the downstream processing.

The basic scenario cultivates the microalgae *Dunaliella salina* in open ponds. This cultivation consists of two stages. During the first stage, optimal growth conditions are assumed to enable maximum growth of the microalgae. During the second stage, stress conditions are induced to enable maximum accumulation of the carotenoid β-carotene. The microalgae take up CO_2 with an efficiency of 45%, and convert it into O_2 (Pires et al., 2012). The resulting CO_2 is emitted to the environment. The nitrogen fertilizer is converted by the microalgae to N_2O ($2.35\ 10^{-5}$ kg N_2O-N kg N^{-1}) and NH_3 (4 kg N_2O kg N^{-1}) (Fagerstone et al., 2011, Yuan et al., 2014). Due to nitrogen-limiting conditions, no N_2O is produced in the second stage of cultivation (Fagerstone et al., 2011). The microalgae are harvested using a centrifuge. As *Dunaliella salina* survives in very saline conditions, a washing step is required to lower the salt content of the biomass. The biomass is dried using a spray dryer. Hexane is used as a solvent to extract the β-carotene. The extraction results in a hexane emission of 2 g kg biomass^{-1} (Lardon et al., 2009). The residual biomass goes to an evaporation step where the hexane can be recycled. After this step the residual biomass is sold as fertilizer. The extract goes to a vacuum distillation where the carotenoids are purified and the hexane can be recycled.

The intermediate scenario adds a preliminary harvesting step between the cultivation step and the harvesting with centrifugation. For this step, the integrated permeate channel (IPC) membrane as developed by the Flemish Institute of Technological Research (VITO) is used to recycle the medium (De Baerdemaeker et al., 2013). The other steps of the production process remain the same as for the basic scenario. The advanced scenario uses a photobioreactor (PBR) for the cultivation step instead of open ponds. This results in a higher N_2O emission to the environment during the first stage of cultivation, $3.9\ 10^{-3}$ kg N_2O-N kg N^{-1} (Fagerstone et al., 2011). The other steps of the production process remain the same as in the intermediate scenario. The alternative scenario assesses an alternative microalgae-based biorefinery concept, based on the cultivation of *Haematococcus pluvialis* in a PBR. Unlike *Dunaliella salina, Haematococcus pluvialis* is a freshwater algae. Therefore, no washing step is required. The cell wall of *Dunaliella salina* is relatively thin and breaks during centrifugation and drying (Oren, 2005). The cell wall of *Haematococcus pluvialis* is thicker and requires a cell disruption step, using a bead mil to enable the extraction of the cellular components (Mendes-Pinto et al., 2001). The other steps in the production process remain the same as in the advanced scenario.

The environmental assessment will use the total production process of the carotenoids and the fertilizer over the entire lifetime (10 years) as a functional unit to ensure one harmonized functional unit for the economic and environmental assessment. The impacts related to the conventional production of fertilizer, which is a coproduct in the algal-based biorefineries, were considered as avoided impacts. The environmental assessment adopted a cradle-to-gate perspective where the use and the disposal phase of the carotenoids and fertilizers were not included. The biorefinery scenarios were considered for Belgian conditions. For the environmental impact of the equipment, two proxy parameters were used. For all tanks and centrifuges, the mass of stainless steel of a centrifuge, adapted to the required capacity, was used as material. The evaporator, bead mill, distillator and spray dryer used the mass of stainless steel of the spray dryer. A linear sizing factor was used to adapt the weight to the required capacity. The end of life phase assumed that 95% of the plastic and stainless steel could be recycled and the other 5% would be landfilled. The upstream environmental impact of smaller equipment such as pumps and membranes was not included in the assessment.

4. Results

The mass and energy balance of the four scenarios is illustrated in Table 1. The addition of the medium recycling step in the intermediate scenario lowers the water and salt consumption and the amount of wastewater. The electricity consumption in the advanced and alternative scenario is much higher compared to the previous scenarios as pumping and mixing in a PBR requires more energy.

Table 1: Mass and energy balance

Parameter	**Unit**	**Basic**	**Intermediate**	**Advanced**	**Alternative**
Input					
Water	m³	4,718,608	1,301,961	747,486	213,372
Salt	tonnes	629,552	129,867	48,974	0
Nutrients	tonnes	6,516	6,516	6,516	6,516
CO_2	tonnes	6,904	6,904	4,935	4,930
Hexane	kg	3,827	3,827	3,827	3,936
Electricity	GJ	128,269	107,382	1,996,831	2,239,348
Heat	GJ	1,400,535	1,310,600	37,918	49,884
HDPE	tonnes	4,507	4,507	2,305	2,578
Stainless steel	tonnes	31	31	9	10
Intermediate product					
Algae biomass	tonnes	1,700	1,700	1,700	1,700
Output					
Fertilizer	tonnes	1,476	1,476	1,476	1,583
Carotenoid	tonnes	141	141	141	43
Wastewater	m³	5,000,345	1,362,019	770,180	213,418
CO_2 emissions	tonnes	3,797	3,797	1,826	1,824
N_2O emissions	kg	15	15	2,437	2,437
NH_3 emissions	tonnes	16	16	16	16
Hexane emissions	kg	3,827	3,827	3,827	3,936
HDPE to recycling	tonnes	4,281	4,281	2,190	2,449
HDPE to landfill	tonnes	225	225	115	129
Stainless steel to recycling	tonnes	30	30	9	9
Stainless steel to landfill	tonnes	1.56	1.56	0.46	0.48

The results of the environmental impact assessment are illustrated in Table 2. The main process contributing to the environmental impact in the basic scenario is the cultivation. This process contributed more than 90% to all impact categories except for ionizing radiation (64%) and marine eutrophication (75%). In these impact categories, the energy consumption during the drying process and the wastewater treatment also had a major influence. The main contributors to the environmental impact during cultivation were the salt and heat consumption.

The environmental impact of the intermediate scenario is lower for all impact categories compared to the basic scenario. The medium recycling step results in a lower salt requirement in the intermediate scenario, which is an important contribution to the environmental impact. The cultivation process is again the main contributor for all environmental impact categories, although its contribution is lower compared to the basic scenario. In the intermediate scenario the heat and nutrient consumption were the main contributors during cultivation.

In the advanced scenario, twelve environmental impact categories are higher compared to the intermediate scenario and six impact categories are reduced. The cultivation process has a contribution of more than 90% to all environmental impact categories, except for marine eutrophication (89%). The main contributor during cultivation is the electricity consumption. The ionizing radiation and water depletion potential are higher than in the basic scenario.

In the alternative scenario, the biomass productivity was lower, which required more water, land and energy. This results in higher environmental impacts compared to the advanced scenario for categories such as climate change, ozone depletion, ionizing radiation, natural land transformation, water depletion and fossil fuel depletion. The other impacts are lower due to the lack of salt addition. In this scenario, the cultivation process has a contribution of over 90% to all environmental impact categories as well. The electricity consumption for the PBR is the main contributor during cultivation.

Table 2: Environmental results

Impact[a]	Unit	Basic	Intermediate	Advanced	Alternative
CC	ktonnes (CO_2 to air)	308	161	217	226
OD	kg (CFC-11 to air)	26	13	16	16
TA	tonnes (SO_2 to air)	1,393	580	694	677
FE	tonnes (P to freshwater)	132	37	72	70
ME	tonnes (N to marine water)	97	30	41	36
HT	ktonnes (14DCB to urban air)	166	47	63	57
POF	tonnes (NMVOC to air)	831	305	470	466
PMF	tonnes (PM_{10} to air)	627	213	255	237
TET	kg (14DCB to industrial soil)	31,779	12,271	6,949	5,407
FET	tonnes (14DCB to freshwater)	7,546	2,140	1,774	1,364
MET	tonnes (14DCB to marine water)	6,903	1,851	1,765	1,394
IR	ktonnes (U^{235} to air)	54	30	377	420
ALO	ha year (agricultural land)	2,034	539	444	325
ULO	ha year (urban land)	464	172	122	103
NLT	m^2 (natural land)	51,040	23,657	38,800	40,529
WD	dam^3 (water)	6,036	1,793	6,739	7,044
MD	tonnes (Fe)	37,983	9,639	5,978	3,449
FD	tonnes (oil)	85,463	47,612	59,934	63,178

[a] CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity; POF: Photochemical oxidant formation; PMF: Particulate matter formation; FE: Freshwater eutrophication; ME: Marine Eutrophication; IR: Ionizing radiation; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; ALO: Agricultural land occupation; ULO: Urban land occupation; NLT: Natural land transformation; WD: Water depletion; MD: Mineral resource depletion; FD: Fossil fuel depletion.

The relative importance of the different environmental impact categories to the overall environmental burden is illustrated in Figure 1. This relative importance was assessed by measuring all the environmental impacts at the endpoint level. This way the different environmental impact categories which can be measured at the same endpoint level (i.e. Disability-adjusted life years (DALY), species year, $) can be compared. Accordingly, the impact categories which contribute the most to the respective endpoint level can be identified. The impact categories which have the highest contribution are climate change (CC) and fossil fuel depletion (FD). The impacts of water depletion (WD) and marine eutrophication (ME) are not defined at the endpoint level and are therefore not included in Figure 1.

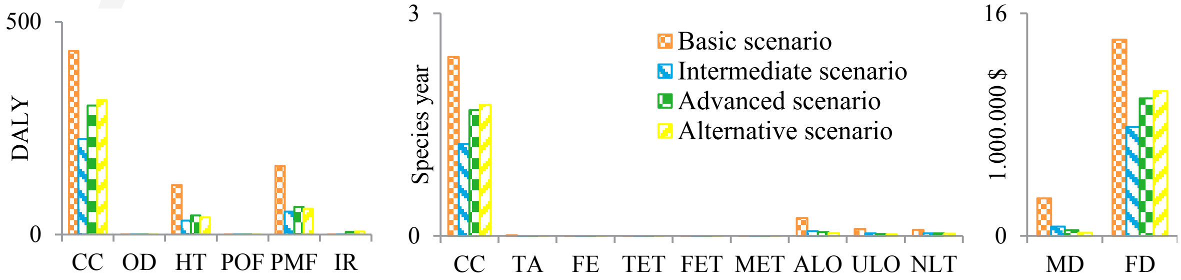

Figure 1: Relative importance of the environmental impact categories (CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity; POF: Photochemical oxidant formation; PMF: Particulate matter formation; FE: Freshwater eutrophication; ME: Marine Eutrophication; IR: Ionizing radiation; TET: Terrestrial ecotoxicity; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; ALO: Agricultural land occupation; ULO: Urban land occupation; NLT: Natural land transformation; WD: Water depletion; MD: Mineral resource depletion; FD: Fossil fuel depletion.)

Table 3 provides the economic results of the assessment over the entire lifetime (10 years). The basic scenario has the lowest NPV, due to the high operational costs. The medium recycling step, introduced in the intermediate scenario, drastically lowers the operational costs. This results in a positive NPV. The use of a PBR for cultivation increases the investment costs and the operational costs due to the high energy requirement during cultivation. Therefore, the advanced scenario is not economically viable. In the alternative scenario, the higher revenues, due to the higher price of astaxanthin compared to β-carotene, compensate for the higher investment and operational costs.

Table 3: Economic results

	Unit	Basic	Intermediate	Advanced	Alternative
NPV	€	-10,657,075	39,504,007	-3,059,254	22,578,733
Investment costs	€	11,135,402	10,728,447	42,330,148	45,275,638
Operational costs	€ year^{-1}	16,803,355	7,124,789	11,197,953	11,003,314
Revenues	€ year^{-1}	16,764,464	16,746,464	16,746,464	22,119,970

The main economic and environmental output categories are displayed in Figure 2. As the contribution of ME and WD at the endpoint level could not be assessed, they were also considered as main output categories. The intermediate scenario has the best score for all main output categories, i.e. combining the highest economic profitability with the lowest environmental impact. Although the alternative scenario has a high NPV, it also has a relatively high environmental impact. The basic scenario has the worst economic and environmental score, although the advanced scenario and the alternative scenario have a higher water depletion potential.

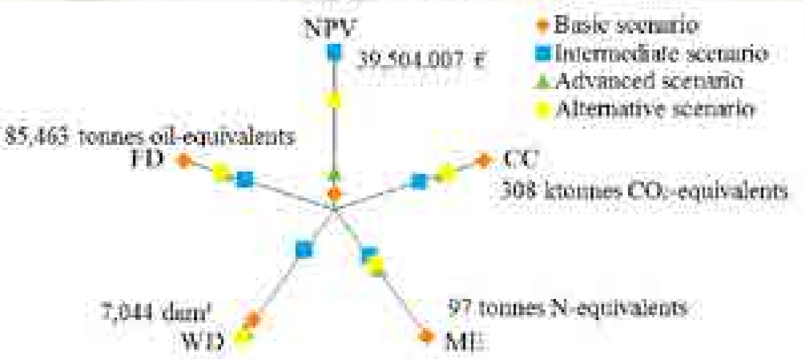

Figure 2: Main economic and environmental impact categories (NPV: Net present value; CC: Climate change; ME: Marine eutrophication; WD: Water depletion; FD: Fossil fuel depletion.)

Table 4 provides the parameters (economic, technical and environmental) with more than 10% impact on the main economic and main environmental output categories. The environmental output parameters were considered relative to the total production scale. The productivity was calculated based on the maximum concentration, the maximum specific growth rate of the species and the solar irradiation. These parameters are identified by almost all output categories as the most important parameters. Improving the productivity will therefore positively influence both the economic profitability and the environmental impact. For the economic profitability, the price of the carotenoid and the upscaling of the PBR are also important parameters. Other important parameters are the salinities of both cultivation stages. The difference between these salinities determines the amount of water and salt that can be recycled. The difference between the cultivation temperature and the surrounding temperature is also crucial as this influences the amount of heating that is required. The most important upstream environmental impacts are the impact of the electricity mix, the upstream impact of the water and the upstream impact of salt production.

5. Discussion

The sensitivity analysis illustrates that the main parameters to improve both the environmental impact and the economic profitability of an algal-based biorefinery are the productivity related parameters. The proposed biorefinery cultivates microalgae species with a relatively low productivity compared to other studies (Brennan and Owende, 2010). However, the selected species can accumulate large concentrations of high-value carotenoids. Using an alternative, faster growing species will therefore have multiple effects on the economic profitability of the biorefineries. The biomass production will increase, but the carotenoid concentration will decrease. The productivity is also influenced by regional characteristics, such as temperature and solar irradiation. A comparison with a biorefinery scenario in a warmer country is therefore an interesting field of further research.

The alternative scenario, i.e. the production of astaxanthin from *Haematococcus pluvialis,* was also assessed by Pérez-López et al. (2014). They analyzed the environmental effect of scaling up the process from a laboratory scale to a pilot scale. In their contribution analysis, they identified the electricity consumption as the main influence on the environmental impact. Pérez-López et al. (2014) only identified direct mass and energy flows as important parameters, therefore, the parameters related to the productivity could not be identified as crucial.

The selection of the functional unit is an important consideration during the interpretation of the results. In our study, the total environmental impact over the entire lifetime of the production process was used as the functional unit. If the mass of carotenoids would be the functional unit, the environmental impact of the alternative scenario would be much larger compared to the advanced scenario, as a smaller amount of carotenoids is produced in the alternative scenario. If the cost of carotenoids would be the functional unit, the alternative scenario would have a lower environmental impact than the advanced scenario, as the revenues from astaxanthin are much higher than the revenues from β-carotene. Moreover, with these functional units, the sensitivity analysis would identify the carotenoid content and price as crucial parameters.

6. Conclusions

This paper performs an environmental techno-economic assessment of four algae-based biorefinery scenarios. The parameters related to the productivity are identified as crucial parameters for both the economic and environmental feasibility of the project. The use of a medium recycling step can reduce the environmental impact and increase the economic profitability of the algal-based biorefinery. The environmental techno-economic assessment provides a methodology to enable an integrated assessment of the technological, economic and environmental feasibility of a new technology. Therefore, it can act as guidance during technology development of new and innovative technologies in the biobased economy.

Table 4: Results sensitivity analysis

Parameter[a]	Basic scenario					Intermediate scenario					Advanced scenario					Alternative scenario				
	NPV	CC	FD	ME	WD	NPV	CC	FD	ME	WD	NPV	CC	FD	ME	WD	NPV	CC	FD	ME	WD
Max. conc.	+23%	-18%	-13%	-42%	-24%		+37%					-13%	-13%	-15%	-12%					
Price carotenoid	+19%					+19%														
Carotenoid cont.	+20%					+20%														
PBR sizing factor											-51%					-46%				
T. cultivation		+29%	+34%					+41%												
T. Belgium							-10%	-12%												
Spec. growth rate												-14%	-14%	-11%	-14%		-16%	-16%	-15%	-16%
Solar irr.												-13%	-14%		-14%		-15%	-15%	-14%	-15%
Imp. electricity												+15%	+15%	+11%	+16%		+16%	+16%	+16%	+17%
Imp. salt				+13%	+14%															
Salinity stage 2				+14%	+12%				+41%	+39%				+14%						
Salinity stage 1									-27%	-26%										
Imp. wastewater					+11%															
Imp. water					+13%															

[a] Abbreviations = Max. conc.: Maximum concentration; cont.: content; T.: Temperature; Spec.: Specific; irr.: irradiation; Imp.: Impact; NPV: Net present value; CC: Climate change; FD: Fossil fuel depletion; ME: Marine eutrophication; WD: Water depletion.

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