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The potential of microalgae biorefineries in Belgium and India: an environmental techno-economic assessment

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Abstract

This study performs an environmental techno-economic assessment (ETEA) for multiple microalgae biorefinery concepts at different locations, those being Belgium and India. The ETEA methodology, which integrates aspects of the TEA and LCA methodologies and provides a clear framework for an integrated assessment model, has been proposed and discussed. The scenario in India has a higher profitability with a NPV of €40 million over a period of 10 years, while the environmental impact in Belgium is lower. The inclusion of a medium recycling step provides the best scenario from both perspectives. The crucial parameters for feasibility are the β-carotene price and content, the upstream environmental impact of electricity and the maximum biomass concentration during cultivation. The identification of these parameters by the ETEA guides future technology developments and shortens the time-to-market for microalgal-based biorefineries.

Keywords: TEA; LCA; process design; *Dunaliella salina*; betacarotene

1. Introduction

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A new and innovative technology in the biobased economy can only thrive if it can positively answer the following three questions: 1) Is it technologically feasible: are all production steps between the source and the end product workable?; 2) Is it economically profitable: can the new technology be produced at a lower cost than its market value?; 3) Is it environmentally sustainable: does the new technology have an acceptable environmental impact?

Biorefineries, where multiple products are valorized out of a biomass feedstock, are an example of such a new and innovative technology. An overview of available biomass residue and wastes for biorefineries in Belgium and India was provided by Cardoen et al. (2015a). However, the use of biomass residues for industrial production can be undesirable if it leads to a decrease in soil fertility due to carbon and nutrient depletion (Cardoen et al., 2015b). A potential feedstock for a biobased refinery that does not impact soil fertility, are microalgae. These small photosynthetic organisms can have a high productivity and can grow on degraded lands. These characteristics give them an advantage over other biomass sources. Most of the current research on microalgae has focused on energy applications. However, the cultivation of microalgae is still too costly to introduce microalgae biofuels to the market and no consensus exists over their potential environmental impact (Quinn & Davis, 2015). Microalgae have another advantage: they are capable of accumulating large amounts of valuable products. The production of high-value products from microalgae is economically viable: multiple companies cultivate microalgae for antioxidants or food supplements (Spolaore et al., 2006). The coproduction of these high-value products in a biorefinery could lead to larger revenues and a lower environmental impact (Chew et al., 2017).

The feasibility of a microalgae production plant is also location-dependent (Davis et al., 2014). Currently, most microalgae cultivation is situated in countries with warm climates, such as Australia, China or the southern locations in the USA (Maeda et al., 2018). The high temperature and solar irradiation creates optimal growth conditions. Locations with more moderate climates, such as Germany, Belgium or Norway, have invested in microalgae production plants as well (Steinrücken et al., 2018). To cope with the less optimal growth conditions, other technologies, such as photobioreactors (PBR), are more frequently used in these settings (Schreiber et al., 2017). Besides the influence on the technological process, the location choice has an impact on the economic and environmental potential of the microalgae biorefinery. For example, the local price of utilities and wages, and the composition of the local electricity mix, alters the feasibility of the project.

Based on a review of the existing economic and environmental assessments of microalgal-based biorefineries, four methodological recommendations were formulated to decrease the wide variety in results (Thomassen et al., 2017). The ETEA methodology, as developed in this study, builds on this literature as it incorporates these four recommendations by 1) providing a sound framework; 2) streamlining the methodology according to the appropriate Technology Readiness Level (TRL); 3) clearly stating methodological assumptions and providing alternative results for the different assumptions; 4) integrating the process design into the methodology.

The newly developed ETEA methodology will be applied to a microalgae biorefinery which valorizes both an antioxidant, β-carotene, and a fertilizer. The biorefinery is based on the microalgae, *Dunaliella salina*, which is already cultivated on a commercial scale. The existing production process is modelled with fertilizer as an additional product based on two locations, Belgium and India. India has a commercial microalgae cultivation plant, where *Haematococcus pluvialis*, *Chlorella vulgaris* and *Spirulina* sp. are produced in open ponds. Moreover, multiple papers, such as Sudhakar et al. (2012), have confirmed India as an excellent location for microalgae cultivation. Belgium has ongoing research on microalgae, focusing mostly on PBR and medium recycling technologies (Taelman et al., 2013). This study will compare among each location three different scenarios, ranging from a low technology scenario using open ponds, an intermediate scenario with medium recycling to a high technology scenario using PBRs. The ETEA assesses if the scenarios can positively answer the three above-stated questions and identifies the main influencing parameters.

The objectives of this study are therefore twofold. The first objective is the development, application and discussion of the ETEA methodology. The second objective is the integrated technological, economic and environmental assessment of different microalgal-based biorefinery concepts in different locations.

2. Materials and methods

2.1. Methodology

The potential of microalgae biorefineries is assessed using the ETEA methodology, which integrates aspects of life cycle assessment (LCA) and techno-economic assessment (TEA) (ISO 14040; Van Dael et al., 2014). By integrating all three dimensions in one methodology, instead of combining separate models, direct linkages, synergies and trade-offs between the dimensions are identified. The term "environmental techno-economic assessment" was selected to highlight the extension of the TEA with an environmental assessment in one integrated model, in contrast to the combination in an environmental and techno-economic assessment. Efforts have been made to combine or integrate these dimensions in one study, for example by Quinn and Davis (2015), and good examples of integrated LCA and TEA studies of biorefineries are available, for example by Gnansounou et al. (2015). However, a clear methodology definition of a fully-integrated assessment, based on best practices, is still lacking.

The TEA methodology was defined by Kuppens (2012) as *"The evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps the decision makers in directing research and development or investments."* The development of new technologies is a stage-gate process, where after each gate a go/no go decision has to be made (Cooper, 1990). The TEA assists in this decision by providing information on the feasibility of the process and the underlying parameters that have the largest influence (Van Dael et al., 2013). The TEA model is an integrated model, with direct linkages between the economic and technological parts. The dynamic character of TEA, where a change in one parameter directly affects all output indicators, is key in identifying the most influencing parameters for a feasible technology. The TEA usually assesses the entire project. The scale and time period is defined and a power relation is often assumed to define the costs for the appropriate scale. As the TEA starts with the calculation of the mass and energy balance, this is an intermediate result. The sensitivity analysis provides insights in which process parameters are crucial for an economically viable process (Van Dael et al., 2014). The TEA model is made in Excel, but inputs from specific process design software, such as Aspen or ChemCad are possible. However, as discussed by Kuppens et al. (2015), the TEA methodology is still missing an environmental sustainability check. The ETEA methodology, as proposed in this study, provides an answer to this issue.

The LCA methodology is a widely used method to analyze the environmental burden of products (Guinée et al., 2002). It is defined by the ISO 14044 norm as a "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.*" The aim of an LCA is to assess the impacts of a product over their entire lifecycle. The functional unit is based on the function of the end product. The process is assumed to be linear and is independent of the time period of the production process. The mass and energy balance are used as an input to the process to construct the life cycle inventory (Guinée et al., 2002). Emissions to the environment are included if they are part of the defined system boundaries. The assessment is often executed in specific LCA software, such as SimaPro or Gabi. The contribution of the different life cycle stages and inputs and outputs to the process can be assessed. However, a sensitivity analysis of the underlying process parameters is usually not performed as these parameters are not included in the main model. Although the main target of LCA studies is the assessment of existing products, the LCA methodology can also be used as a stage-gate process for new technologies where the level of detail will advance in each stage (Villares et al., 2017). Different streamlining methods, such as proxy data, can be used to cope with the limited data availability in each stage (Graedel, 1998). The ETEA methodology uses LCA to calculate the up or downstream environmental impact of each input and output to the technological process. This way, the environmental impact is treated in a similar way as the price of a specific input or output. Accordingly, the environmental assessment can be integrated in the same manner as the economic assessment into a joint, integrated model.

Based on the above, the ETEA methodology is defined as follows: "*The integrated evaluation of the technological performance, economic feasibility and potential environmental impact of a (new) technology and the identification of the most important underlying parameters that aims to help the decision makers in directing research and development or investments*."

The evaluation of a new technology generates the need for a framework concerning the different levels of technological maturity. Accordingly, the stage-gate approach, which has also been used by the TEA and LCA methodologies, is adopted. The different gates of technology development are defined by TRL levels (Mankins, 2009). Each TRL level corresponds to a certain level of data availability and accuracy of the provided information. The chosen TRL level of the ETEA is the minimum of the following two conditions: 1) the maturity of the technology; 2) the required accuracy of the results. In this study the ETEA will be performed at TRL level five, which corresponds to the demonstration stage of the technology, which is the lowest TRL level of the technologies in all different scenarios.

The ETEA includes all life cycle steps influenced by the technology or product. This can be done in a direct way, by specifically including the up and downstream steps in the process design, or in an indirect way, if the up or downstream costs and impacts are already represented, for example in the price. In this study the production process, starting from microalgae cultivation until the purification of the end product, is included in a direct way. The upstream costs and impacts are included indirectly in the price and impact of the process inputs. The downstream costs and impacts of all waste sources are included indirectly by the addition of costs and impacts for the waste treatment. The downstream costs and impacts of the end products are not included as they are assumed to be the same as the reference product. The ETEA will be performed according to the following five steps, which are executed alongside the different TRL levels and lifecycle stages.

Step 1. Market study: This step identifies the different market actors, prices and volumes of the different products. As multiple market studies are available, this step is not elaborated here (Enzing et al., 2014). The market study includes a review of existing technologies as well. This will result in the goal and scope definition of the assessment. The main goal of the ETEA is to identify the crucial parameters that have the highest influence on the technological, economic and environmental feasibility of microalgal-based biorefineries. Therefore, a full range of environmental indicators will be required. The scope of the assessment is further elaborated in the description of the case study.

Step 2. Process Flow Diagram and Mass and Energy balance: In this step the production process is modelled and the different input and output streams are identified and quantified. This step forms the technological backbone of the assessment and is the basis of both the economic and environmental analysis.

Step 3. The economic analysis: The economic profitability is calculated using investment criteria, such as the net present value (NPV). This economic output indicator is used in the interpretation step to identify the crucial parameters. The prices of the inputs and outputs are directly linked to the mass and energy balance to enable a fully integrated model. Data on market prices was updated to 2016 prices by means of the CEPCI index. A regression function, mostly based on a power relation, was constructed to estimate the equipment cost on the appropriate scale (Kuppens et al., 2015). Location factors, were retrieved from the Richardson's International Construction Factors Location Cost Manual, updated to 2016 values and used to adapt the equipment costs to the different process plant locations (Towler & Sinnott, 2013).

Step 4. The environmental analysis: The environmental impact of the different scenarios are quantified using the seventeen midpoint indicators of the ReCiPe 2016 method (Huijbregts et al., 2016). In the current study the environmental impact is calculated relative to the fossil-based reference products: fertilizer and synthetic β-carotene. To calculate which environmental indicators are the most relevant for the scenarios, the contribution of each midpoint indicator to the the endpoint indicators of the ReCiPe methodology is calculated. There are three endpoint indicators: Human health (HH), Ecosystems damage (ED) and Resource availability (RA) (Huijbregts et al., 2016). To ensure the integrated character of the methodology, the characterization factors, calculated with SimaPro using the ecoinvent database, are directly linked to the mass and energy balance, in the same way as for the economic analysis. Infrastructure is taken into account using the six-tenth rule, with the use of the same power exponents as for the economic analysis (Caduff et al., 2014). To differentiate between the two locations, it was assumed that all direct inputs to the process were produced in the specific location, unless the market for the product was global. For most inputs, differentiating on a country-level was not feasible due to data limitation. In these cases, a global characterization factor for India and a European characterization factor for Belgium were used. This assumption was also used for the fossil-based β-carotene production scenario. As the ETEA forms one integrated methodology, the environmental impact is assessed on the same scale as the technological process design and the economic viability. The functional unit equals therefore the entire project.

Step 5. The interpretation step: In this step, the underlying parameters for the economic and environmental indicators are identified. This step includes first a contribution analysis, which assesses which production process has the highest contribution to the output indicators. The second part includes a sensitivity analysis. A Monte Carlo analysis, using the Oracle Crystal Ball software, is used to identify which underlying parameters have the highest influence on the output indicators (Van Dael et al., 2013). Hence, all parameters in the model are varied according to a triangular distribution (-10%; +10%) for 10,000 iterations. The impact of a more realistic distribution for the crucial parameters is further assessed using a what-if analysis or an uncertainty analysis. Based on the results, recommendations can be made for the next iteration.

The integrated ETEA approach harmonizes the differences in approach between the LCA and TEA methods as summarized in Table 1. The LCA model is integrated in the TEA model by an additional step, where the environmental impacts are calculated. The characterization factors are based on inputs from LCA software, but the main model remains in Excel. This enables direct linkages between the different steps, which is not possible if the main model is constructed in different software as done in a combined LCA and TEA approach. In an integrated approach, a change in an input parameter in one dimension is directly translated in the output indicators of all three dimensions. This allows for a full global sensitivity analysis for both the economic and environmental impacts over all underlying process parameters. The TEA is extended to include emissions, with no direct related costs. One integrated model, instead of two combined models enables a faster and cheaper assessment as the technological module is shared.

Environmental and economic assessments can also be combined by the environmental Life Cycle Costing (eLCC) method, defined as: "*Environmental Life Cycle Costing summarizes all costs associated with the life cycle of a product that are directly covered by 1 or more of the actors in that life cycle; these costs must relate to real money flows.*"(Ciroth et al., 2008) The ETEA methodology differs from the combined LCA and eLCC methods in the following ways: 1) the integrated character of the ETEA methodology, which enables the identification of the crucial parameters; 2) the focus on new technologies; 3) the inclusion of temporal aspects.

The ETEA methodology, as developed in this study, is not restricted to the assessment of microalgae biorefineries, but can be applied to broader applications. Applications at other TRL levels are feasible as well. For this case study, the ETEA was performed at

TRL level five. At a lower TRL level, less data will be available which results in a more rough assessment. For example, the environmental assessment can be a screening ETEA with a hotspot analysis where more qualitative data are used. At a higher TRL level, the process design is assessed in more detail, and other analyses, such as a full uncertainty analysis, where the triangular distribution is replaced by a more realistic distribution, can be added. An example of this uncertainty analysis can be found in the computational framework of Gerber et al. (2016), which integrated process design, LCA, TEA and uncertainty analysis, and whom applied this framework to two pathways of microalgae biofuel production.

The ETEA extends the original TEA methodology with an environmental sustainability analysis. However, the social dimension of sustainability has not been incorporated yet. This would be a valuable addition to obtain a full techno-sustainability analysis (Rafiaani et al., 2018).

The proposed ETEA methodology results in multiple economic and environmental indicators. The decision maker can use these results to perform a multi-criteria analysis which results in one final value for each scenario. A multi-criteria method based on a sustainability analysis of biorefineries was proposed by Gnansounou et al. (2017). Another approach to deal with the multiple output indicators would be the extension of the ETEA model with a multi-objective optimization, including both economic and environmental objectives. This way, the optimal microalgae biorefinery process design can be defined from different perspectives.

2.2. Case study

Three different microalgal-based biorefinery designs have been assessed, both in Belgium and in India.

The market share of natural β-carotene is 30% of the global β-carotene market with approximately 10 different suppliers (Enzing et al., 2014). The hypothetical production plant was assumed to have a similar scale to an average supplier, corresponding to 3% of the global β-carotene market. Accordingly, all scenarios produce 11 tons of β-carotene and 128 tons of fertilizer per year over a project lifetime of 10 years. This is also the functional unit for all scenarios.

In the first scenario *Dunaliella salina* is cultivated in open ponds. This cultivation consists of two stages: one stage for optimal biomass production and one nutrient-limiting stage for optimal β-carotene production. The growth of the microalgae was modeled using a logistic growth curve (Jesus & Filho, 2010). The parameters used in this study were based on multiple pilot scale outdoor cultivation studies of *Dunaliella salina* (García-González et al., 2003; Prieto et al., 2011; Tafreshi & Shariati, 2006; Wu et al., 2017). A correction factor for the local temperature and solar irradiation was taken into account (Slegers et al., 2013). In the Belgian scenario, freshwater was used and the wastewater was sent to a wastewater treatment plant. The Indian scenario assumed the use of seawater and the disposal of the wastewater into the sea. In each scenario, the same amount of nutrients per mass of microalgae was provided. No heating was provided in the open pond scenario as the heat would dissipate almost immediately. The microalgae were harvested by means of a centrifuge, washed to decrease the salt content and dried using a spray drier. Subsequently, the β-carotene was extracted using hexane as a solvent. After separation by means of a membrane filtration, the solid fraction went to an evaporation step to retrieve the hexane as a solvent. To estimate the fugitive emissions and the energy requirement of general process steps such as filtration and distillation, the framework of Piccinno et al. (2016) was used. The solid residue was sold as a fertilizer. The liquid fraction went to a vacuum distillation step to purify the β-carotene fraction and enable hexane recycling. The purified β-carotene was sold as a food supplement.

The second scenario assessed the effect of a medium recycling step after each cultivation stage. The medium consists mainly of water and salt. For this preharvesting step, the Integrated Permeate Channel (IPC®) membrane was included in the production process (De Baerdemaeker et al., 2013). According to previous papers, this recycling step has an important impact on the economic feasibility (Monte et al., 2018; Thomassen et al., 2016). The remainder of the production process is similar to the first scenario.

The microalgae were cultivated in a tubular PBR in the third scenario. In the Belgian scenario, the water was heated to 20°C, with a 5% daily heat loss. The growth parameters were based on studies of García-González et al. (2005) and Prieto et al. (2011). The other steps in the process remained the same as for the second scenario.

The price of the equipment and the utilities for all production steps were based on peer-reviewed literature data and price quotes from commercial suppliers. The indirect costs for all equipment was added in accordance to the estimates of Peters et al. (2003). The purity of β-carotene in the end product is 80%. A price range of €215-2,712 per kg was found for β-carotene of varying purities. For this study, a β-carotene price of €1000 per kg was selected. The price of fertilizer was set at €390 per ton, based on personnel communication with a supplier.

All environmental impact parameters were retrieved from the ecoinvent database (Wernet et al., 2016). The reference process for β-carotene was modeled mainly based on patent data and publications. Other inputs and outputs for the different steps of the reference process, such as energy consumption and waste emissions, were estimated using the general assumptions of Hischier et al. (2004). These assumptions are also used in the ecoinvent database and in the study of van Kalkeren et al. (2013). The reference process for fertilizer is taken from the ecoinvent database. The environmental impact of a pump was used as a proxy for the environmental impact of similar equipment such as mixers, blowers and compressors. In a similar way, the environmental impact of a spray dryer was used as a proxy for the evaporator and distillation equipment.

Although this study includes two locations, the assessment of multiple locations is feasible as well. The two locations were chosen to maximize the difference in parameters, while still allowing for accurate and available data. The optimization of the location and the technologies, included in the biorefinery, would be an interesting path for further research. The scenarios are further referred to as 1 Be, 2 Be and 3 Be for the Belgian scenarios and 1 In, 2 In and 3 In for the Indian scenarios.

3. Results and discussion

3.1. Process flow diagram and mass and energy balance

The mass and energy balance is illustrated in Table 2. The water and salt requirement decreased when the medium was recycled. The microalgae reached a higher concentration in the PBR, which further decreased the water and salt requirement. However, in the second Indian scenario, the water consumption increased compared to the first scenario. This is explained by the large influence of evaporation. As the water and salt was recycled, the salinity increased due to evaporation. Freshwater was required to maintain a viable salinity for the microalgae. Salt was only required at the beginning of the project. The PBR in the third scenario did not lose water through evaporation, therefore, freshwater only needed to be added in the washing step. The salt consumption was higher to obtain the optimal salinity in the cultivation stages. Microalgae grew slower in Belgium than in India. Therefore, a larger production plant was required in the three Belgian scenarios. The electricity consumption was much higher in the third scenarios as the PBR required a large amount of energy to pump the microalgae through the tubes.

The land occupation in Belgium was 50 hectares for open ponds and 9 hectares for PBR. According to a report of ILVO, a total of 13.24 hectares of unoccupied greenhouses can be found in the flower region in Belgium (Verhoeve et al., 2015). This could be a potential location for the microalgae cultivation and indicates the feasible scale. The current microalgae cultivation plant of Parry Nutraceuticals in India spans 53 hectares. As the population density is comparable in Belgium and India, the 50 hectares of open pond cultivation are assumed to be a feasible production scale as well.

3.2. Economic Results

The results of the economic analysis are provided in Table 3. The only economic viable scenario in Belgium was the second scenario with open ponds and medium recycling. In India, all scenarios were economically viable under the assumptions made. The yearly revenues were higher than the yearly operational costs in all scenarios. The investment costs were higher for the third scenario than for the second scenario for both locations. Including the medium recycling technology lowered the operational costs. This reduction compensated for the higher investment costs. Overall, the second scenario in India with open pond cultivation and medium recycling was the preferred scenario from an economic point of view.

A study by Ben-Amotz (2008) calculated the annual production costs of the existing NBT *Dunaliella* plant for a scale of 70 tons dry biomass per year. Their results indicated an equipment and yearly operational cost of €63 and €12 per kg dry biomass. These estimates are higher than the €51 and €11 per kg biomass for the second Indian scenario as found in the current study. However, the scale in the current study was twice as large which induces economies of scale to lower the price. A TEA of another algae production process focusing on carotenoids was performed by Panis and Carreon (2016). In their study, astaxanthin was produced out of a *Haematococcus pluvialis* feedstock cultivated in a hybrid cultivation process of PBR and open ponds on two locations, being the Netherlands and Greece. They found that the production of microalgal-based astaxanthin is currently not economically feasible if the carotenoid is used for feed purposes. The production costs in the Netherlands were higher compared to the production costs in Greece as less astaxanthin was produced per hectare. More freshwater, which was the most important mass inflow, was required in Greece compared to the Netherlands. These results are similar to the results of the current study. However, as *Haematococcus pluvialis* is a freshwater alga, no salt was required in the study of Panis and Carreon (2016) and seawater could not be used. The study of Ben-Amotz (2008) calculated the costs for an alternative bio-fuel algal plant as well, which were approximately 50 times lower. Therefore, the results of the current study will not be compared with the results of algal-fuel studies.

3.3. Environmental results

The results of the environmental analysis for the seventeen midpoint categories are provided in Table 4. The environmental impacts that are lower than the reference scenario are bold. The second Belgian scenario had a lower environmental impact compared to the reference scenario on all impact categories except for IRP. This was caused by the high contribution of nuclear energy in the Belgian electricity mix. The second Indian scenario had a positive relative environmental impact on all impact categories except for PMFP and WCP. This is explained by the relatively high contribution of fossil fuels in the Indian electricity mix and the high evaporation rate. The third Indian scenario scored the worst on nine of the seventeen environmental impact categories. The only impact categories for which this scenario had a lower impact than the reference scenario are ODP, SOP and WCP.

There are three feasible scenarios that have a positive NPV and a lower environmental impact compared to the reference scenario on three of the four selected environmental impact indicators, under the assumptions made. The second Belgian scenario is the only scenario that has a positive relative environmental impact on the four impact categories, but has the lowest positive NPV. The first and second Indian scenarios have a relatively high NPV but a worse environmental impact. As the first Indian scenario scores worse on all categories compared to the second Indian scenario, this is not the preferred scenario. The second scenario is in both locations identified as the best scenario, where the Belgian scenario is the most environmental-friendly and the Indian scenario is the most profitable scenario under the assumptions made.

The scenarios with a positive environmental impact compared to the reference scenario do not have a positive absolute environmental impact. Even if the CO_2 used would be originated from flue gas or the atmosphere, there would be between eight and one hundred four times more CO_2-equivalent emissions emitted than captured.

A study by Kyriakopoulou et al. (2015) performed an LCA comparing algal-based and carrot-based β-carotene. They concluded that the production and harvesting of algal-based β-carotene had a higher environmental impact. However, the environmental impact for the extraction process was larger for the carrot-based β-carotene. Therefore, microalgae are considered a better raw material for the recovery of β-carotene than carrots. In general, the environmental impacts as found in the current study are higher than the results from Kyriakopoulou et al. (2015). This can be explained by the lack of a stress stage in the cultivation process. The study of Kyriakopoulou et al. (2015) used the CML2 baseline 2000 method. Therefore, an exact comparison with the results of the current study, where the ReCiPe 2016 method is used, is not feasible.

The endpoint analysis in Figure 1 illustrates which midpoint impact categories have the highest contribution to the endpoint categories. The unit for Human health is the disability-adjusted life years (DALY). The midpoint impact category PMFP has the highest impact on human health. The important midpoint categories for ecosystem damage are GWP and TAP. FFP is the most important impact category for resource availability. Therefore, the rest of the analysis will focus on the following four midpoint categories: PMFP, GWP, TAP and FFP.

3.4. Interpretation: Contribution analysis

The contribution of the different production stages to the investment and operational costs is illustrated in Figure 2a. The contribution to the investment costs was similar for both locations in the three scenarios. In the first scenario the liner, the spray drier and the centrifuge had the highest investment costs. In the second scenario, the centrifuge costs were drastically reduced. This was compensated by the costs of the IPC® membrane in the preharvesting stage. In the third scenario, the investment cost of the PBR during cultivation had the highest contribution. The highest contribution to the operational costs was provided by the cultivation stage and the indirect costs. In the cultivation stage, the salt and water consumption led to a high contribution in the first scenario. In the second scenario, the indirect costs, which were the personnel, insurance and repair costs, are more important than the cultivation costs in Belgium. This was caused by the medium recycling, which reduced the salt and water requirement. The second scenario in India had much lower indirect costs due to lower wages. The main operational costs were the nutrient costs. Although seawater was used, freshwater was required to compensate for the evaporated water. In the third scenario, the electricity cost for the mixing in the PBR had a high contribution. As the investment costs were much higher, the repair and insurance were higher as well, leading to higher indirect costs.

The contribution of the different production stages to the environmental impact categories GWP, PMFP, TAP and FFP is provided in Figure 2b. The cultivation stage had the highest contribution to the four environmental impact categories for the three Belgian scenarios and the first and third Indian scenario. In the second Indian scenario, the impact of the electricity used in the drying stage had a high impact as well. The impact in the cultivation stage in the first scenario was mainly caused by the impact of salt, nutrients and direct CO_2 emission. In the second scenario, the salt consumption was much lower. The electricity use during cultivation in the first two Indian scenarios had a big impact as well. Due to the difference in electricity mix, this impact was lower for the Belgian scenarios. In the third scenarios, the environmental impact in the cultivation stage was almost entirely caused by the upstream impact of the electricity.

Although the climate in India was much better for microalgae production compared to the Belgian climate, the environmental impact in India was higher. This was mainly caused by the difference in electricity mix. The Belgian electricity mix had a relatively high nuclear energy contribution. This was translated into a worse environmental impact in the IRP category. However, this category did not have a high contribution to the endpoint indicators. The Indian electricity mix had a higher contribution of fossil fuels which led to more air pollution. This was translated into a high environmental impact in the PMFP category. As the third scenario had the highest energy consumption, this was the worst scenario in almost all categories. If the assumption was made that renewable energy was used with no related environmental impact, the second and third scenarios would have a lower environmental impact than the reference scenario for all impact categories, except for WCP in the second Indian scenario. The third scenario would score better than the second scenario in Belgium and become the preferred scenario from an environmental point of view. The second scenario would score better in India than in Belgium on most categories due to the lower salt and water requirements.

3.5. Interpretation: Sensitivity analysis

The relative influence of the crucial parameters to the output indicators is provided in Table 5. A positive influence signifies that an increase in this parameter will lead to an increase in the corresponding output indicator. Only the parameters that contribute more than 10% to the variation of the output indicators are provided in the table. The most influential parameters for the NPV were the β-carotene content and the β-carotene price per kg. The maximum biomass concentration in the cultivation, one of the underlying growth parameters, was identified as crucial for both the economic and the environmental indicators. In the first Belgian scenario, the salt impact and consumption were important for the environmental indicators. In the second Belgian scenario, the growth parameters played a more important role. The impact of the electricity was important for all Indian scenarios. This was also a crucial parameter in the third scenario for both locations, alongside the energy consumption during the mixing in the PBR.

The price of β-carotene has a wide range, but is identified as a crucial parameter. It can also have a different value depending on the location. Therefore, a what-if analysis is performed to assess the impact of this price on the NPV (Figure 3). The minimum price to obtain a positive NPV varies between €258 per kg for the second Indian scenario to €1,342 per kg for the third Belgian scenario. This is still in the price range of €215 to €2,712 per kg. Although the third Belgian scenario has a negative NPV for the β-carotene price assumed in this study, it can still be an economically viable scenario. The price curves of different scenarios at the same locations run in parallel until taxes have to be paid in one of the scenarios. The price curves return to a parallel path when taxes are paid in all scenarios. The curves of the same scenario at different locations do not run parallel due to differences in tax, inflation and interest rates. If the β-carotene price reaches € 2,878 kg^{-1}, the NPV of the second scenario becomes the highest NPV.

Although a large amount of the microalgae research focusses on biofuels, this study does not look at energy applications of microalgae. A biorefinery producing both biofuels and antioxidants seems to be a difficult concept due to the disparate market size. Moreover, the microalgae species that can accumulate high-value products, are not necessarily suited for biofuel production. Although fertilizer was chosen as an intermediate product in the proposed biorefinery, the revenues are only 0.4% of the revenues from β-carotene. The environmental impact of the reference fertilizer is less than 3% of the reference β-carotene. If the biorefinery would only produce fertilizer, it would not be feasible from both an economic and environmental perspective. The set-up of different viable biorefineries, such as the ones proposed in this study, may reduce the costs and the uncertainty related to the start-up of new biorefineries and increase research funding opportunities. Although the next biorefinery would still be focused on at least medium value products, energy applications may become feasible on a longer term.

4. Conclusions

The ETEA methodology enables the direct comparison of technological, economic and environmental criteria for a feasible microalgae biorefinery. Different synergies and trade-offs are identified which provide essential information for the further improvement of the process. As multiple scenarios were technologically feasible, economically profitable and environmentally sustainable, a viable microalgae biorefinery seems to be a possible route for the future.

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Appendix A. Supplementary information

Supplementary information, including all input data, the detailed process flow diagrams and the results for the other midpoint categories and alternative functional units, can be found in the online version of this paper.

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Table 1. Differences in approach between a combined LCA and TEA and an ETEA

	(Combined) LCA	(Combined) TEA	ETEA (integrated)
Functional unit	Product	Project	Project
Lifecycle	Entire lifecycle	Process	Entire lifecycle
Economies of scale	Linear	Power relation	Power relation
Time	Independent	Period defined	Period defined
TRL level	Late	Early	All levels
Mass and energy balance	Input to the model	Intermediate result	Intermediate result
Sensitivity analysis	Optional	Required	Required
Emissions	Included	Not included	Included
Software main model	LCA software	Excel	Excel
Process parameters in the sensitivity analysis	Inputs and outputs	Underlying parameters	Underlying parameters

Table 2. Mass and energy balance of the six scenarios over the total lifetime (10 years)

Parameter	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
Input							
Salt	tons	530,277	26,040	20,846	235,780	1,890	16,108
Fresh water	m³	3,996,913	552,079	509,823	366,199	4,427,101	366,199
Nutrients	tons	5,173	5,173	5,173	5,173	5,173	5,173
CO_2	tons	6,699	6,699	4,268	6,696	6,696	4,268
Hexane	tons	94	94	94	96	96	94
Inoculum	tons	2	2	0.6	0.9	0.9	0.6
Electricity	MWh	34,968	31,615	355,526	32,313	29,196	358,653
Heat	MWh	0	0	6,683	0	0	0
Land	ha	50	50	9	23	23	9
Output							
Fertilizer	tons	1,285	1,285	1,285	1,285	1,285	1,285
β-carotene	tons	113	113	113	113	113	113
Wastewater	m³	4,241,721	563,958	518,899	4,005,941	536,921	518,899

Table 3. Economic results of the six scenarios over the total lifetime (10 years)

Parameter	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
NPV	10^6 €	-7	25	-29	33	40	2
Investment costs	10^6 €	17	18	47	7	8	31
Operational costs	10^6 € yr^{-1}	10	5	10	3	2	6
Revenues	10^6 € yr^{-1}	11	11	11	11	11	11

Table 4. Absolute environmental impact results over the total lifetime (10 years)

Parameter[a]	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In	Ref Be	Ref In
GWP	10^7 kg CO_2-eq	**14**	**4**	**12**	**13**	**8**	53	26	26
ODP	10^2 kg CFC_{11}-eq	**2**	**1**	**2**	**2**	**1**	**3**	7	7
IRP	10^6 kBq Co-60-eq	57	18	135	19	**2**	14	9	6
HOFP	10^4 kg NOx-eq	**38**	**8**	**20**	**33**	**19**	138	43	44
PMFP	10^4 kg PM2.5-eq	**22**	**5**	**10**	56	44	428	31	35
EOFP	10^4 kg NOx-eq	**39**	**9**	**21**	**34**	**20**	140	45	46
TAP	10^5 kg SO_2-eq	**6**	**2**	**3**	**7**	**4**	31	23	24
FEP	10^4 kg P-eq	9	**2**	**3**	8	**4**	32	6	6
TETP	10^4 kg 1,4-DCB-eq	35	**8**	**11**	19	**7**	14	11	11
FETP	10^6 kg 1,4-DCB-eq	12	**2**	4	7	**3**	12	4	4
METP	10^6 kg 1,4-DCB-eq	17	**3**	6	10	**4**	16	5	5
HTPc	10^6 kg 1,4-DCB-eq	11	**2**	**4**	7	**3**	18	6	6
HTPnc	10^9 kg 1,4-DCB-eq	14	**3**	**4**	8	**3**	11	4	4
LOP	10^6 m² yr	12	**3**	14	6	**2**	10	3	3
SOP	10^4 kg Cu-eq	178	**36**	77	88	**26**	**39**	67	66
FFP	10^6 kg oil-eq	**37**	**10**	**36**	**28**	**16**	110	63	59
WCP	10^5 m³ water-eq	**33**	**7**	**15**	101	57	**34**	39	38

[a] GWP = Global warming potential; ODP = Ozone depletion potential; IRP = Ionizing radiation potential; PMFP = Particulate matter formation potential; EOFP = Photochemical oxidant formation potential for ecosystems; HOFP = Photochemical oxidant formation potential for humans; TAP = Terrestrial acidification potential; FEP = Freshwater eutrophication potential; HTPC = Human toxicity potential cancer; HTPnc = Human toxicity potential non-cancer; TETP = Terrestrial ecotoxicity potential; FETP = Freshwater ecotoxicity potential; METP = Marine ecotoxicity potential; LOP = Agricultural land occupation potential; WCP = Water consumption potential ; SOP = Surplus ore potential; FFP = Fossil fuel potential.

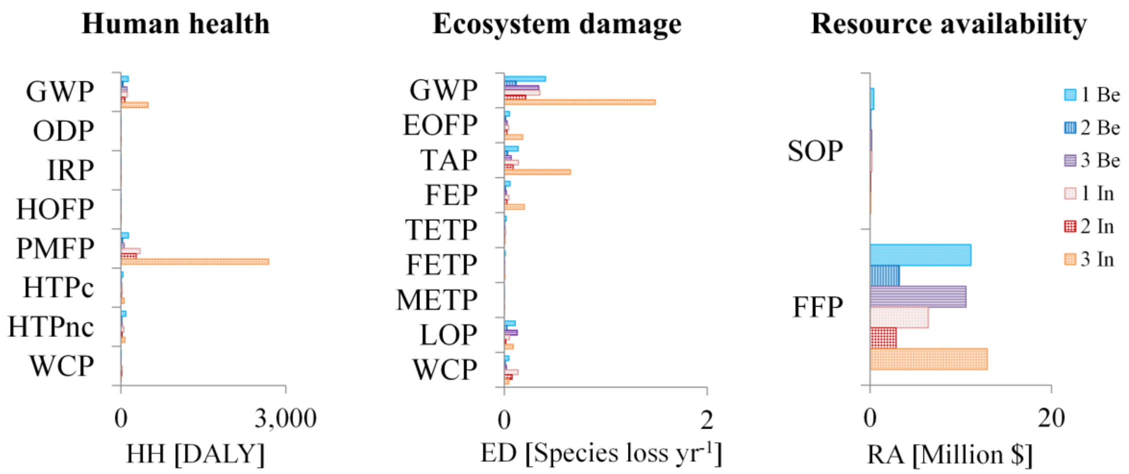


Figure 1. Endpoint analysis

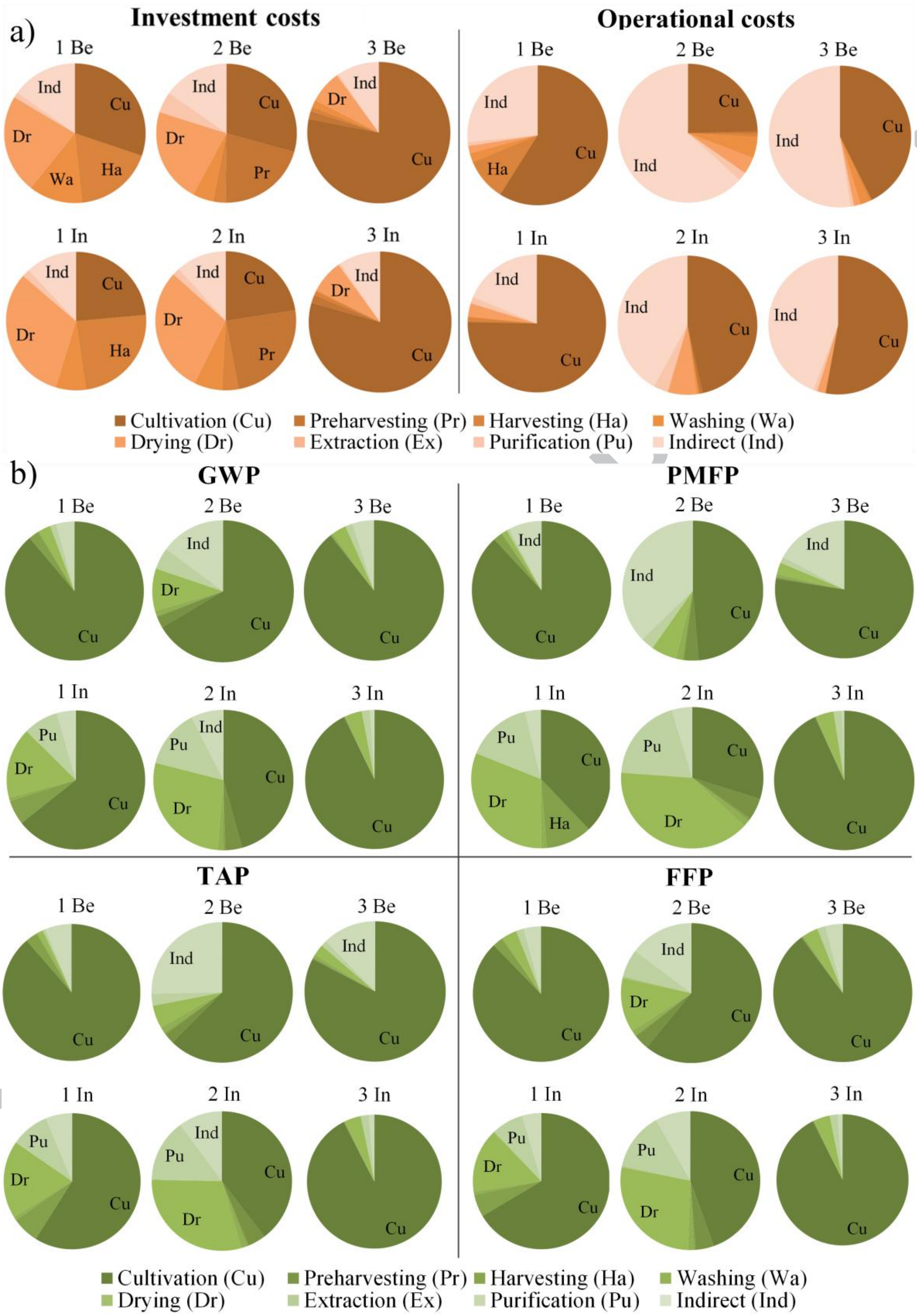


Figure 2. Contribution analysis; (a) economic results; (b) environmental results

Table 5. Results sensitivity analysis (%)

	1 Be NPV	GWP	PMFP	TAP	FFP	1 In NPV	GWP	PMFP	TAP	FFP
β-c. content[a] [%]	+26					+40				
β-c. price[a] [€ kg^{-1}]	+26					+39				
Max. conc.[b] [g l^{-1}]	+10	-18	-17	-16	-19		-16		-16	-19
r[c] [day^{-1}]		-10	-10		-11					
Sal. stress[d] [M]		+23	+24	+22	+21					
Salt [imp. kg^{-1}][e]		+21	+22	+23	+21		+13		+11	+14
Solar irr.[f] [%]		-10			-10					
El.[g] [imp. kWh^{-1}][e]							+11	+40	+14	
Sal. water[d] [g l^{-1}]							-15		-14	-17
W. conc.[h] [g l^{-1}]								-10		
	2 Be NPV	**GWP**	**PMFP**	**TAP**	**FFP**	**2 In NPV**	**GWP**	**PMFP**	**TAP**	**FFP**
β-c. content[a] [%]	+35					+40				
β-c. price[a] [€ kg^{-1}]	+30					+39				
Max. conc.[b] [g l^{-1}]		-19	-20	26	-21					
r[c] [day^{-1}]		-11	-11	-15	-13					
Solar irr.[f] [%]		-11	-11	-14	-13					
CO_2 upt.[i] [%]		-11								
Salt [imp. kg^{-1}] [e]			+13							
El.[g] [imp. kWh^{-1}][e]							+39	+46	+42	+36
W. conc.[h] [g l^{-1}]							-11	-14	-13	-10
Op. rate[j] [%]					-11					
Drying E.[k] [GJ t^{-1}]								-11	+10	
	3 Be NPV	**GWP**	**PMFP**	**TAP**	**FFP**	**3 In NPV**	**GWP**	**PMFP**	**TAP**	**FFP**
β-c. content[a] [%]	+21					+24				
β-c. price[a] [€ kg^{-1}]	+20					+23				
Max. conc.[b] [g l^{-1}]	+16	-21	-21	-21	-21	+12	-21	-21	-21	-22
El.[g] [imp. kWh^{-1}][e]		+23	+23	+22	+22		+23	+23	+22	+23
Op. rate[j] [%]										
Mix. cul.[l] [W m^{-3}]		+17	+18	+18	+18		+19	+18	+19	+18
Mix. cul.[l] [h]		+19	+18	+18	+19		+19	+20	+20	+20

[a] β-c. = β-carotene; [b] Max. conc. = Maximum microalgae concentration during cultivation; [c] r = maximum specific growth rate; [d] Sal. = Salinity; [e] imp. = environmental impact; [f] Solar irr. = Solar irradiation correction factor; [g] El. = Electricity; [h] W. conc. = biomass concentration after washing step; [i] CO_2 upt. = CO_2 uptake rate; ; [j] Op. rate = Operational rate; [k] E. = Energy; [l] Mix. cul.= Mixing during cultivation.

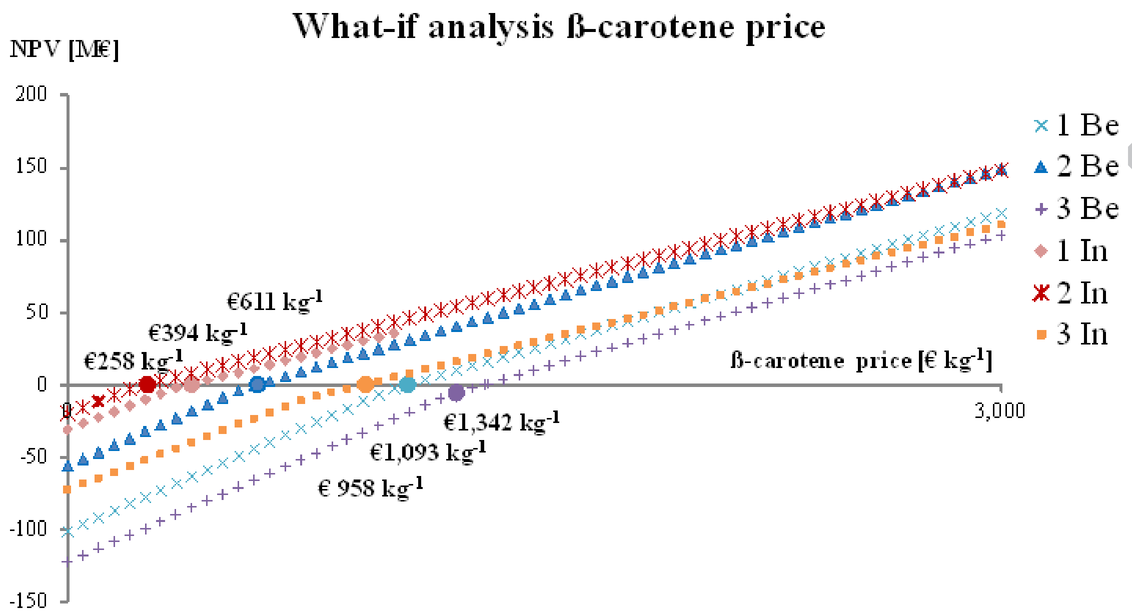
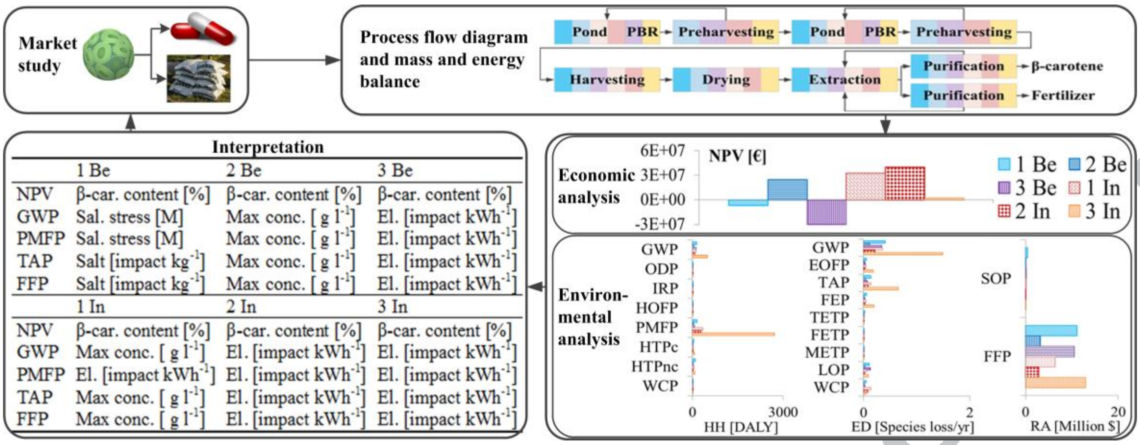


Figure 3. What-if analysis β-carotene price


Market study
Process flow diagram and mass and energy balance
Pond
PBR
Preharvesting
Harvesting
Drying
Extraction
Purification
β-carotene
Fertilizer
Economic analysis
NPV [€]
6E+07
3E+07
0E+00
-3E+07
1 Be
2 Be
3 Be
1 In
2 In
3 In
Environ-mental analysis
GWP
ODP
IRP
HOFP
PMFP
HTPc
HTPnc
WCP
EOFP
TAP
FEP
TETP
FETP
METP
LOP
SOP
FFP
HH [DALY]
ED [Species loss/yr]
RA [Million $]
Interpretation
1 Be
2 Be
3 Be
NPV β-car. content [%] β-car. content [%] β-car. content [%]
GWP Sal. stress [M] Max conc. [g l-1] El. [impact kWh-1]
PMFP Sal. stress [M] Max conc. [g l-1] El. [impact kWh-1]
TAP Salt [impact kg-1] Max conc. [g l-1] El. [impact kWh-1]
FFP Salt [impact kg-1] Max conc. [g l-1] El. [impact kWh-1]
1 In
2 In
3 In
NPV β-car. content [%] β-car. content [%] β-car. content [%]
GWP Max conc. [g l-1] El. [impact kWh-1] El. [impact kWh-1]
PMFP El. [impact kWh-1] El. [impact kWh-1] El. [impact kWh-1]
TAP Max conc. [g l-1] El. [impact kWh-1] El. [impact kWh-1]
FFP Max conc. [g l-1] El. [impact kWh-1] El. [impact kWh-1]

The potential of microalgae biorefineries in Belgium and India: an environmental techno-economic assessment

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Highlights

- A new methodology is introduced, integrating techno-economic analysis and LCA
- Multiple microalgal-based biorefinery concepts in Belgium and India are assessed
- Including a medium recycling membrane is important for profits and sustainability
- The β-carotene content and price are the most crucial parameters for profits
- The growth parameters in the cultivation stage are crucial for both dimensions