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Environmental assessment of Dunaliella-based algae biorefinery concepts

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Environmental assessment of *Dunaliella*-based algae biorefinery concepts

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1 Executive Summary

The EU funded project D-Factory "*The micro algae biorefinery*" seeks to demonstrate a sustainable CO_2 algae biorefinery based on the cultivation and processing of the alga *Dunaliella salina* for natural products and potentially multiple markets. So far, *Dunaliella salina*, which grows in highly concentrated saltwater, is cultivated only for β-carotene production and sold as capsules containing unprocessed dried algae powder. This project aims at generating additional value by separating individual high-value carotenoids and their isomers present in the powder to be able to serve customers according to their specific needs. Furthermore, lower value biomass fractions are put into use as new co-products.

Within the sustainability assessment of the project, IFEU – Institute for Energy and Environmental Research Heidelberg, Germany, assessed the environmental impacts of the newly devised processes. It consists of an assessment of global and regional impacts in a screening life cycle assessment (LCA see chapter 3.2 for methodology) and an analysis of local environmental impacts by life cycle environmental impact assessment (LC-EIA, see chapter 3.3 for methodology). Both assessments are based on scenarios for 2025 to support decisions to be made during the implementation process.

The most important insights are summarised below as key statements with references to background information. Concrete recommendations to businesses, science, policymakers and consumers deduced from these insights can be found in chapter 7.

1. ***Dunaliella* algae cultivation and processing require substantial resources in addition to sunlight and CO_2 and are therefore not intrinsically environmentally friendly.**

   

   The extraction of valuable substances such as carotenoids from *Dunaliella* algae, produced with the aid of sunlight and abundantly available CO_2, is a very promising concept. However, if algae are to be cultivated and harvested in sufficient concentrations, substantial energy and material inputs will be needed (chapter 5.1). Overall, algae cultivation – similar to traditional agriculture – is not possible without the input of limited resources and without significant environmental burdens (chapter 5.2.3). Algae-based products are therefore not intrinsically environmentally friendly, nor do they necessarily contribute to mitigating climate change just because algae consume CO_2.

2. **The largest contributions to environmental burdens of algae cultivation and harvesting have been successfully reduced.**

   

   In itself, the extraction of valuable substances from *Dunaliella* algae in algae biorefineries causes practically no environmentally relevant emissions. They primarily arise from the provision of precursor products and the energy required by the biorefinery.

   Before optimisation, the environmental burdens of algae biomass production were dominated by the brine used to produce the medium and the electricity for algae cultivation and harvesting (chapter 5.1). The identified optimisation measures can reduce these contributions by 99% and 85% respectively. Overall, savings of up to 90% were achieved for most environmental impacts of algae biomass production (chapter 5.2).

- Efficient medium recycling was facilitated by the introduction of membrane pre-concentration. It may be possible to further improve recycling rates by the use of a new centrifugation technology, which can harvest algae cells essentially intact and thus reduces impurities in the extracted medium. In addition, the environmental burdens of brine provision can be considerably reduced by integration with salt production or seawater desalination facilities, depending on the site. Intensive cultivation of hypersaline algae involving low environmental burdens therefore requires a site-specific medium recycling concept and integration with existing salt processing facilities.
- Electricity use within the facility depends on numerous different parameters. It is possible to directly reduce this use by adopting membrane pre-concentration. Additional reductions per unit of product are possible by lowering product losses. Electricity provision can be considerably more environmentally friendly if solar electricity is generated on-site using photovoltaics, in particular because electricity demand and generation are both at their highest when solar irradiation is highest. Even though this partially negates the land use savings by other measures, from an environmental perspective as large a proportion of electricity use as possible should be covered by on-site solar electricity generation.

3. **The analysed version of downstream processing to separate algae extracts into several products was found to be environmentally harmful. In response, a new approach was found within the project that promises to be much more resource-efficient and environmentally friendly.**
The environmental impacts over the entire life cycle of the assessed scenarios are undoubtedly dominated by the downstream processing energy and solvent demand. From an environmental perspective, the benefits of additional products do not balance the expenditures required for the purification method investigated here. Also in response to this result, a new modular high-performance countercurrent chromatography (HPCCC) system was developed within this project that is expected to increase resource efficiency and reduce environmental impacts profoundly. The adequacy of improvements remains to be confirmed e.g. in a follow-up environmental assessment once sufficient experience is gained for reliable quantitative modelling. As a fallback option, the unfractionated carotenoid extract could alternatively be marketed as main product.

4. **Local ecological impacts of *Dunaliella* algae cultivation can be reduced by adopting appropriate concepts.**

In addition to global and regional environmental impacts, which can be analysed and optimised using life cycle assessment, cultivating *Dunaliella* algae for algae biorefineries can also cause significant local environmental impacts on the environmental factors land, soil, water and biodiversity (chapter 6.1). This particularly applies to:

- Freshwater use: On one side, it is possible to reduce the water-related impacts by the technical design of the facility – among other things by efficient medium recycling, the introduction of membrane pre-concentration and the use of a new centrifugation technology. If rigorously optimised, more water could even be saved by replacing products from irrigated agriculture with algae-based co-products than freshwater needed for algae cultivation. On the other side, sufficient local (blue) water availability must be guaranteed despite possible net water savings, in particular at inland sites. Existing water uses in a catchment area must be taken into consideration.

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* Disposal of high salt content wastewater: here, an ecologically optimised saltwater disposal concept should be compiled, in particular for inland sites. The risk associated with saltwater disposal is expected to be lower at coastal sites.
* Quantitative and qualitative land use: the extent of land use can be reduced by the technical design of the facility, for example by minimising wastewater and thereby the area required for wastewater treatment. Because algae cultivation using raceways leads to complete ground sealing, the impacts of this qualitative alteration should be minimised, for example by utilising previously sealed disused industrial sites instead of agricultural land.

5. **The number and quantity of marketable co-products from *Dunaliella* algae were successfully increased during the project. This can avoid environmental burdens elsewhere, if conventional products are substituted.**

The project was based on an existing facility in Eilat, Israel, in which only β-carotene is marketed as a product and about half of the algae biomass is treated as wastewater. This waste fraction could be reduced to about 10% of the organic matter contained in algae biomass. Co-products such as extracted algae biomass generated as a result can e.g. be used as feeds. If these replace conventional feeds, the thus saved agricultural land may be up to 10 times the size of the land occupied by algae cultivation (chapter 5.2).

6. **A novel pharmaceutical active ingredient may have been created with the production of pure *9-cis* β-carotene. The health benefit to society cannot be scientifically balanced against the environmental burdens for its production. However, the environmental burdens can be within the range associated with different health-promoting natural substances.**

Clinical tests to demonstrate the efficacy of *9-cis* β-carotene in cardiovascular disease are currently being initiated. If they are successful, *9-cis* β-carotene would clearly be the main product of a future algae biorefinery employing the D-Factory concept. This substance can only be produced in notable quantities using algae, specifically *Dunaliella salina*, at least at the moment. Its isolation from algae in the achieved purity was demonstrated for the first time in this project. Under these circumstances, a novel health benefit can be delivered by a future *Dunaliella*-based algae biorefinery. This valuable social asset cannot be evaluated in the context of an environmental assessment. However, because no exceptionally large environmental impact with clearly negative health impacts elsewhere is to be expected in particular if approaches for redesigning downstream processing can be realised (Figure 5-17), societal acceptance of caused environmental burdens is highly probable. If a D-Factory algae biorefinery is subsequently built, at least the most important identified environmental improvements should be implemented. These are rigorous recycling of the cultivation medium, utilisation of extracted biomass as a feed and providing a large proportion of the electricity demand by solar electricity generated on-site. In particular, the carotenoid extract should only be fractionated into all its constituents if the newly developed downstream processing technology is successful or if only pure *9-cis* ß-carotene turns out to be effective as a drug. The enormous environmental burdens caused by the quantitatively analysed version of downstream processing are completely disproportionate to the burdens that may be saved thanks to additional co-products.

7. **If the efficacy of *9-cis* β-carotene cannot be confirmed in clinical tests, construction of a biorefinery exactly as described in the scenarios investigated in this study cannot be recommended from an environmental perspective. Instead, optimisations including the implementation of a new downstream processing technology would have to be realised at scale.**

Based on current knowledge, it cannot be expected that an algae biorefinery adopting the process design quantitatively analysed in this study can contribute to an overall reduction in environmental burdens (chapter 5.3.1). This is only feasible if the downstream processing technology newly developed in this project can be implemented as expected and the rest of the value-added chain is highly optimised when established.

8. **If co-products are efficiently utilised, algae biorefineries can indirectly release more land than they occupy. This can mitigate competition for land use.**

Although algae cultivation does not require fertile land, it has certain limitations with regard to the availability of water, qualified personnel and access to supply networks. An additional strict limitation to infertile and unused land may represent a hurdle for large scale algae cultivation in Europe. Resorting to fertile land use instead would increase competition for agricultural land and exacerbate related problems such as the consequences of indirect land use change. In the worst case, this can lead to deforestation in other parts of the world. A similar effect is known from ground-mounted photovoltaic systems, the land use of which is limited by funding regulations in some EU member states. They additionally compete with algae for the same infertile land with high solar irradiation.
However, in contrast to photovoltaics, co-products from algae cultivation, in particular feeds, may substitute for agricultural products. This can lead to agricultural land savings up to 10 times greater than the land needed for algae cultivation (Figure 5-16). If this was to help avoid the conversion of rainforest into new agricultural land, the greenhouse gas emissions saved in this way may, under some circumstances, even exceed the emissions from algae production. It is therefore vital that all algae biomass fractions are utilised. In this case, sealing of a small area for algae cultivation, with the associated local environmental disadvantages, could be justified if much more land becomes available and if part of that is used as an ecological compensation site. Despite potential restrictions to large scale algae cultivation in Europe, we urgently recommend the strict use of only infertile land for such cultivation facilities.

9. **A focus on high-value algae-based products instead of mass products can mitigate potential future competition about CO_2.**
If the decarbonisation of society is to be truly progressed such that the objectives of the Paris climate agreement are seriously pursued or achieved, only very few point sources of CO_2-containing exhaust gases such as cement factories or steel plants may remain within a few decades (chapter 8.5.1). In addition to algae facilities, there will be competition from other technologies such as power-to-X and carbon capture and storage (CCS). Therefore, algae cultivation priorities should focus on high-value products such as pharmaceuticals instead of mass production.


2 Goals of the project and of this report

2.1 Goal of the project

The EU funded project D-Factory "*The micro algae biorefinery*" seeks to demonstrate a sustainable CO_2 algae biorefinery based on the cultivation and processing of the alga *Dunaliella salina* for natural products and potentially multiple markets. So far, *Dunaliella salina*, which grows in highly concentrated saltwater, is cultivated only for β-carotene production and sold as capsules containing unprocessed dried algae powder. This project aims at generating additional value by separating individual high-value carotenoids and their isomers present in the powder to be able to serve customers according to their specific needs. Furthermore, lower value biomass fractions are put into use as new co-products.

This project includes an integrated sustainability assessment [Keller et al. 2017]. It analyses the implications for sustainability associated with D-Factory systems, shows optimisation potentials and identifies the options that are the most sustainable for delivering value from the chosen alga, *Dunaliella salina* in an industrial setting.

2.2 Goal of this report

This report analyses all relevant environmental impacts of potential future value chains according to the D-Factory concept within the framework of an integrated sustainability assessment [Keller et al. 2017]. This study consists of a screening life cycle assessment (LCA) and a life cycle environmental impact assessment (LC-EIA). It answers the environmental aspects of the following key questions set out for the integrated assessment of sustainability:

- How does a future D-Factory plant, using mature technology, perform regarding environmental, economic and social impacts, compared to a conventional provision of equivalent products?
- How can the impacts of a future D-Factory plant be further improved?
  - Which unit processes determine the results significantly and what are the optimisation potentials?
  - Which is the best option for algae cultivation and harvesting?
  - Which downstream processes should proceed after algae harvesting, i.e. which product portfolio shows the best environmental, economic and social footprint?
  - Which of the technologies and applications studied in the D-Factory project, which could not be included into main quantitative sustainability assessment scenarios, have the potential to improve the environmental, economic and social impacts substantially if they should be included at a later stage?
- What is the influence of different uses and accounting methods for the main product *9-cis* β-carotene?
- Are there any constraints or bottlenecks that could hinder the large-scale deployment of D-Factory biorefineries?

3 Methodological approach

The sustainability analysis in D-Factory is based on common goal, scope, definitions and settings for the technological, environmental and socio-economic analyses. They are a prerequisite of an overall sustainability assessment and highly affect the assessment results. They are described in chapter 3.1. Specific definitions and settings that are only relevant for LCA and LC-EIA in the environmental assessment are described in chapters 3.2 and 3.3, respectively.

3.1 Common definitions and settings

The analysis of the life cycles within D-Factory follows the ILCSA methodology [Keller et al. 2015]. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009]. The following common definitions and settings apply to all parts of the integrated sustainability assessment:

3.1.1 System boundaries

System boundaries specify which unit processes are part of the product system and thus included into the assessment, e.g. whether the entire or a partial life cycle will be analysed.

The sustainability assessment of the D-Factory system will take into account the **entire value chain (life cycle) from cradle to grave**, i.e. from algae cultivation to the distribution and usage of final products including land use change effects (Figure 3-1). Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another. In other words, no impact should escape.

Such shifting of burdens can also occur if impacts of **infrastructure** provision are significantly different between the compared pathways. The impacts of e.g. required roads may be less relevant and comparable between alternatives but infrastructure for algae cultivation is expected to be important, especially if photobioreactors are involved. To provide a balanced picture, infrastructure elements for algae cultivation and biorefinery are always taken into account for all pathways. Yet, only relevant infrastructure specific for the investigated processes is assessed explicitly. This in particular includes infrastructure for algae cultivation. Infrastructure that is used for other purposes as well (e.g. roads for transportation) or that is similar for the investigated scenarios and conventional reference systems (e.g. office buildings) is not assessed explicitly if the impact on the final results is negligible.

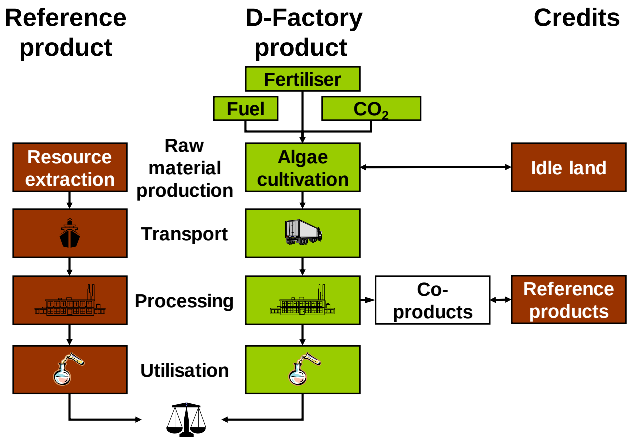

Figure 3-1: Schematic illustration of the life cycle comparison of the D-Factory plant (green) with conventional provision of products such as dietary supplements or chemicals (brown).

3.1.2 Technical reference

The technical reference describes the technology to be assessed in terms of development status/maturity. Scenarios of potential future D-Factory plants will be based on mature technology. Measured data (as far as available) from experiments and demo scale trials will only be used to validate the scenarios but will not be used directly for the assessment for two reasons:

1. It is not meaningful to compare immature processes with mature conventional processes producing the same products.
2. An assessment based on measured data requires routine operations for several years to average weather influences on cultivation. This is not possible because the project time does not allow this.

3.1.3 Time frame

The D-Factory system must be described not only in space but also in time. The time frame of the assessment determines e.g. the development status of biorefinery technology. Likewise, the environmental impact associated with conventional products changes over time (hopefully decreasing), e.g. greenhouse gas emissions associated with electricity generation.

The D-Factory project intends to install and operate a demo plant by its conclusion in 2017. Optimised routine operations of this unit will take a few seasons to be established. A mature technology bigger scale plant could thus be operational around 2025, which is set as a reference year.

3.1.4 Geographical coverage

Geography plays a crucial role in many sustainability assessments, determining e.g. productivity of algae cultivation, transport systems and electricity generation. In this study, the location of the demo site in Monzón, Spain, is taken as a blueprint setting. To be able to derive conclusions valid for further plants according to the D-Factory concept in suitable locations elsewhere in Europe, generalised European background data is used as far as possible.

3.1.5 Functional unit, co-product handling and reference units

The functional unit is a key element of integrated life cycle sustainability assessment (ILCSA). It is a reference to which the environmental, social and economic effects of the studied system are related. It quantifies the function (i.e. utility) of the product(s) provided by the investigated system.

A central characteristic of a biorefinery, as assessed in D-Factory, is the provision of several products with different functions. These are each compared to a conventional equivalent product on the basis of a functional unit which is specific for each comparison. As an exception, all standard scenarios of this study produce the novel product *9-cis* β-carotene as the main product. This is based on the scenario setting that a novel health effect of purified *9-cis* β-carotene as a pharmaceutical will be demonstrated in a clinical trial to come. All pharmaceuticals that are currently used in conditions targeted by *9-cis* β-carotene will result in other health benefits. Thus, *9-cis* β-carotene adds a new benefit (or function in terms of a life cycle comparison), which cannot be compared to any existing product. This leads to the following procedure for life cycle comparisons in scenarios that produce purified *9-cis* β-carotene for the pharma market: 1 tonne of purified *9-cis* β-carotene will be defined as functional unit and all co-products will receive credits according to the burdens that are avoided by replacing conventional equivalent products (substitution approach). The resulting remaining burdens are attributed to purified *9-cis* β-carotene.

In an excursus, analysis will include what the results look like if clinical studies should not result in novel health benefits. In this case, *9-cis* β-carotene will be treated as any other β-carotene in the life cycle comparison. Following the system expansion approach, the biorefinery will be assessed based on a combined functional unit reflecting all functions. Biorefinery layouts with different product portfolios and thus different combined functional units will be compared based on a suitable common reference unit depending on the question to be answered. An area-based reference unit (1 ha·a) is used in this case.

3.2 Specific definitions and settings for LCA

The screening life cycle assessment (LCA) is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. In the following, specific settings and methodological choices are detailed.

3.2.1 Settings for Life Cycle Inventory (LCI)

Data sources

D-Factory biorefineries require a multitude of data for calculating the different scenarios.

Primary data:

Consistent scenarios on algae cultivation and conversion processes for mature technology in 2025 were defined based on inputs from all D-Factory partners. The underlying data from D-Factory partners are expert estimates mainly based on pilot scale testing but partially also on demo scale tests and lab scale experiments. Data was supplemented by literature data where necessary. A summary of this data can be found in the annex (chapter 8.4). An important limitation is that only efficiencies but no suitable data on material and energy consumption of processing steps following supercritical CO_2 extraction of dry algae biomass (downstream processing) were available from partners or literature. Therefore, the screening LCA is incomplete in this regard and systematically underestimates the impacts of the D-Factory systems.

Secondary data:

Data on background processes (provision of non-biomass material inputs and conventional reference products of the D-Factory products) are based on the IFEU internal database [IFEU 2017] and the ecoinvent database [Ecoinvent 2017].

A summary of the most important input data can be found in chapter 8.4 in the annex.

Attributional vs. consequential modelling

The sustainability assessment can follow a consequential or attributional approach, which has implications for co-product handling, especially in LCA. Consequential modelling is more extensive and "aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy" according to ILCD Handbook [JRC-IES 2010a]. The identification of the most appropriate LCA approach is closely linked to the decision-context. Based on guidelines in the ILCD handbook, consequential modelling is applied in this assessment.

This has consequences for the assessment of co-products and indirect effects:

Co-products handling

See chapter 3.1.5.

Indirect effects such as indirect land use change

New systems using biomass can indirectly affect the environmental by withdrawing resources from other (former) uses. This can result in appropriation of biomass or land formerly not extracted or used by man, respectively. This can lead to indirect land use changes (iLUC): Biomass formerly used for other purposes (e.g. as food or feed) has to be produced elsewhere (e.g. outside of Europe) if it is now used for new products. This can indirectly cause a clearing of (semi-)natural ecosystems and hence changes in organic carbon stocks, damages to biodiversity etc. There is an ongoing international debate about these effects, mainly focussing on organic carbon stocks. Since the estimates on so called iLUC factors regarding carbon stocks are less certain and less is known about the influence of iLUC on other environmental impact categories, quantitative iLUC effects are only reported separately and only for the impact category global warming. Additionally, they are discussed qualitatively in the LC-EIA part. For other potentially limited resources, please refer to chapter 8.5 in the annex.

Biogenic carbon

There are two possible sources for carbon dioxide (CO_2) emissions: (recent) mostly biogenic or fossil carbon stocks. For the carbon contained in the assessed products, the amount of CO_2 released into the atmosphere throughout the whole life cycle equals the amount of CO_2 that has been taken up by the algae recently (short carbon cycle). The CO_2 fed to the algae is derived from exhaust gases of processes using fossil carbon sources. However, this CO_2 would otherwise have been released to the atmosphere. Therefore, the life cycle of CO_2 taken up by algae and later on released to the atmosphere is carbon neutral, i.e. it does not affect global warming. This carbon is accounted for but for clarity its uptake and emissions are not displayed in the result graphs.

3.2.2 Settings for Life Cycle Impact Assessment (LCIA)

Impact categories: Midpoint vs. endpoint level

Life cycle impact assessment (LCIA) methods exist for midpoint and for endpoint level. There are advantages and disadvantages associated with both levels. In general, on midpoint level a higher number of impact categories are differentiated and the results are more accurate and precise compared to the three Areas of Protection at endpoint level that are commonly used for endpoint assessments. Within the D-Factory project, the impacts are assessed at midpoint level only. To provide the highest possible transparency for decision support, no endpoint impact assessment is done.

Selection of relevant midpoint-level impact categories

The LCA assesses the midpoint indicators tick-marked in Table 3-1. The selected impact categories are well-established categories in life cycle assessments [JRC-IES 2010b]. Regarding the LCIA methods, the CML methods were selected as preferred choice because they cover all impact categories in a consistent way [CML 2016].

Deviating from this principal selection, ozone depletion is assessed according to [Ravishankara et al. 2009], which in contrast to the CML method takes the impact of N_2O emissions on ozone depletion into account. In all assessed scenarios, the contribution of N_2O emissions to ozone depletion is at least about 10-fold higher than the contributions of all other substances together according to this impact assessment method. The reason is that biomass related systems are assessed, which lead to considerable N_2O emissions throughout their life cycles. The exact impact of N_2O on ozone depletion is still debated in the scientific community but if the order of magnitude suggested by [Ravishankara et al. 2009] is correct, then N_2O emissions are dominating this environmental impact for the assessed systems. Therefore, the CML impact assessment method, which does not take N_2O emissions into account, was considered to lead to distorted conclusions and the impact assessment method according to [Ravishankara et al. 2009] was used instead.

Some impact categories, which are not tick-marked in Table 3-1, are excluded because they are i) irrelevant for the D-Factory biorefinery concept (e.g. ionising radiation) or ii) still under methodological development (e.g. human toxicity and ecotoxicity, resource depletion: water and land use; classified as level II/III or III in the ILCD Handbook). Please note that in this environmental assessment „Land use“ and „Resource depletion: water“ are analysed on the level of the life cycle inventory within the LCA with a separate discussion of qualitative impacts within the LC-EIA. The LC-EIA is meant to supplement the LCA which is known to be less suitable for addressing local environmental impacts, especially in areas where methodological development of LCA is still ongoing. Moreover, LCI data quality for 2025 is limiting particularly for human toxicity and ecotoxicity, which cover an extensive list of substances. The data available today is not suitable to derive results, which are balanced enough for decision support. Therefore, these categories are excluded from the LCA. Instead important ecotoxicity impacts on biodiversity, land use and “resource depletion: water” are covered within the LC-EIA part.

Table 3-1: Environmental impact categories covered in D-Factory

Environmental impact category	Covered by LCA	Covered by LC-EIA
Global warming	✓	–
Ozone depletion	✓	–
Human toxicity (general)	–	–
Human toxicity (respiratory inorganics, PM10)	✓	–
Ionising radiation	–	–
Photochemical smog (ozone formation)	✓	–
Acidification	✓	–
Eutrophication	✓	–
Ecotoxicity	–	(✓)
Land use	–	✓
Resource depletion: water	–	✓
Resource depletion: non-renewable energy	✓	–

Normalisation

Normalisation helps to better understand the relative magnitude of the results for the different environmental impact categories. To this end, the category indicator results are set into relation with reference information. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected area.

In the D-Factory LCA study, the environmental advantages and disadvantages are related to the environmental situation in the EU25+3. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called inhabitant equivalent (IE). The reference values are presented in Table 8-3 in the annex for all environmental impact categories.

Weighting

Weighting is not applied. Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis.

3.3 Specific definitions and settings for LC-EIA

There are a number of environmental management tools which differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (LCA), for example, addresses potential environmental impacts of a product system (see chapter 3.2). However, for a comprehensive picture of environmental impacts, also local/site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these local/site-specific impacts are not yet covered in standard LCA studies. Thus, for the time being, LCA has to be supplemented by elements borrowed from other tools.

The methodology applied in D-Factory borrows elements from environmental impact assessment (EIA) [and partly from strategic environmental assessment (SEA)] and is therefore called life cycle environmental impact assessment (LC-EIA) [Keller et al. 2014; Kretschmer et al. 2012].

3.3.1 Introduction to EIA methodology

Environmental impact assessment (EIA) is a standardised methodology for analysing proposed projects regarding their potential to affect the local environment. It is based on the identification, description and estimation of the project's environmental impacts and is usually applied at an early planning stage, i.e. before the project is carried out. EIA primarily serves as a decision support for project management and authorities which have to decide on approval. Moreover, it helps decision makers to identify more environmentally friendly alternatives as well as to minimise negative impacts on the environment by applying mitigation and compensation measures.

The environmental impacts of a planned project depend on both the nature/specifications of the project (e.g. a biorefinery plant housing a specific production process and requiring specific raw materials which have to be delivered) and on the specific quality of the environment at a certain geographic location (e.g. occurrence of rare or endangered species, air and water quality etc.). Thus, the same project probably entails different environmental impacts at two different locations. EIA is therefore usually conducted at a site-specific/local level. These environmental impacts are compared to a situation without the project being implemented ("no-action alternative").

Regulatory frameworks related to EIA

Within the European Union, it is mandatory to carry out an environmental impact assessment (EIA) for projects according to the Council Directive 85/337 EEC of 27 June 1985 "on the assessment of the effects of certain public and private projects on the environment" [CEC 1985]. This Directive has been substantially amended several times. In the interests of clarity and rationality the original EIA Directive has been codified (put together as a code or system, i.e. in an orderly form) through Directive 2011/92/EU of 13 December 2011 [European Parliament & Council of the European Union 2011]. The latter has once again been amended in 2014 through Directive 2014/52/EU of 16 April 2014 [European Parliament & Council of the European Union 2014].

EIA methodology

An EIA covers direct and indirect effects of a project on certain environmental factors. The list of factors has been substantially altered with the 2014 amendment (addition and deletion of factors) [European Parliament & Council of the European Union 2014] and currently covers the following ones:

- population and human health
- biodiversity (previously: fauna and flora)
- land (new), soil, water, air and climate
- material assets, cultural heritage and the landscape
- the interaction between these factors

Please note: the relatively new factor "land" is indirectly addressed in the conflict matrices (via the factors "soil" and "landscape") since implementing rules for the new factor "land" are lacking or under development. Moreover, we continue to address the two factors "fauna" and "flora" separately, since we think that "biodiversity" alone wouldn't cover all aspects that were previously addressed under "fauna" and "flora" (e.g. the conservation/Red List status of species). This way, more specific recommendations can be derived.

An EIA generally includes the following steps:

- Screening
- Scoping
- EIA report
  - Project description and consideration of alternatives
  - Description of environmental factors
  - Prediction and evaluation of impacts
  - Mitigation measures
- Monitoring and auditing measures

<u>Screening</u>

Usually an EIA starts with a screening process to find out whether a project requires an EIA or not. According to Article 4 (1) and Annex 1 (6) of the EIA Directive, an EIA is mandatory for "Integrated chemical installations, i.e. those installations for the manufacture on an industrial scale of substances using chemical conversion processes, in which several units are juxtaposed and functionally linked to one another and which are"

- "for the production of basic plant health products and of biocides" (6d) or
- "for the production of basic pharmaceutical products using a chemical or biological process" (6e).

Referring to Annex 1 (6) of the EIA Directive, an EIA would be required if a D-Factory facility was implemented.

<u>Scoping</u>

Scoping is to determine what should be the coverage or scope of the EIA study for a project as having potentially significant environmental impacts. It helps in developing and selecting alternatives to the proposed action and in identifying the issues to be considered in an EIA. The main objectives of the scoping are:

- Identify concerns and issues for consideration in an EIA.
- Identify the environmental impacts that are relevant for decision-makers.
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis.
- Determine the assessment methods to be used.
- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues.

EIA report

An EIA report consists of a project description, a description of the status and trends of relevant environmental factors and a consideration of alternatives including against which predicted changes can be compared and evaluated in terms of importance.

- Impact prediction: a description of the likely significant effects of the proposed project on the environment resulting from:
  - The construction/installation of the project; temporary impacts expected, e.g. by noise from construction sites.
  - The existence of the project, i.e. project-related installations and buildings; durable impacts expected e.g. by loss of soil on the plant site.
  - The operation phase of the project; durable impacts expected, e.g. by emission of gases.

Prediction should be based on the available environmental project data. Such predictions are described in quantitative or qualitative terms considering e.g.:

- Quality of impact
- Magnitude of impact
- Extent of impact
- Duration of impact

Mitigation measures are recommended actions to reduce, avoid or offset the potential adverse environmental consequences of development activities. The objective of mitigation measures is to maximise project benefits and minimise undesirable impacts.

Monitoring and auditing measures

Monitoring and auditing measures are post-EIA procedures that can contribute to an improvement of the EIA procedure.

Monitoring is used to compare the predicted and actual impacts of a project, so that action can be taken to minimise environmental impacts. Usually, monitoring is constrained to either potentially very harmful impacts or to impacts that cannot be predicted very accurately due to lack of baseline data or methodological problems.

Auditing is aimed at the improvement of EIA in general. It involves the analysis of the quality and adequacy of baseline studies and EIA methodology, the quality and precision of predictions as well as the implementation and efficiency of proposed mitigation measures. Furthermore, the audit may involve an analysis of public participation during the EIA process or the implementation of EIA recommendations in the planning process.

3.3.2 The LC-EIA approach in D-Factory

Within this project, a set of different technological concepts for provision of high-value products from microalgae is analysed. Each concept is defined by its inputs, the conversion, the downstream processes and the final products. This is also reflected in the objectives of the sustainability assessment in WP 9: the aim is to qualitatively assess the impacts associated with each of the (hypothetical) investigated concepts (in the sense of technological concepts) at a generic level. The assessment is not meant to be performed for a planned algae cultivation facility at a certain geographic location.

Environmental impact assessment (EIA), however, is usually conducted specifically for a planned (actual) project (see previous chapter 3.3.1). For the purpose of the D-Factory project, which neither encompasses the construction of an actual algae cultivation facility nor the construction of a downstream processing plant (only existing demo facilities are used), it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures will be omitted within D-Factory. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the D-Factory systems at a generic level.

The elements of EIA used in this project are shown in Figure 3-2.

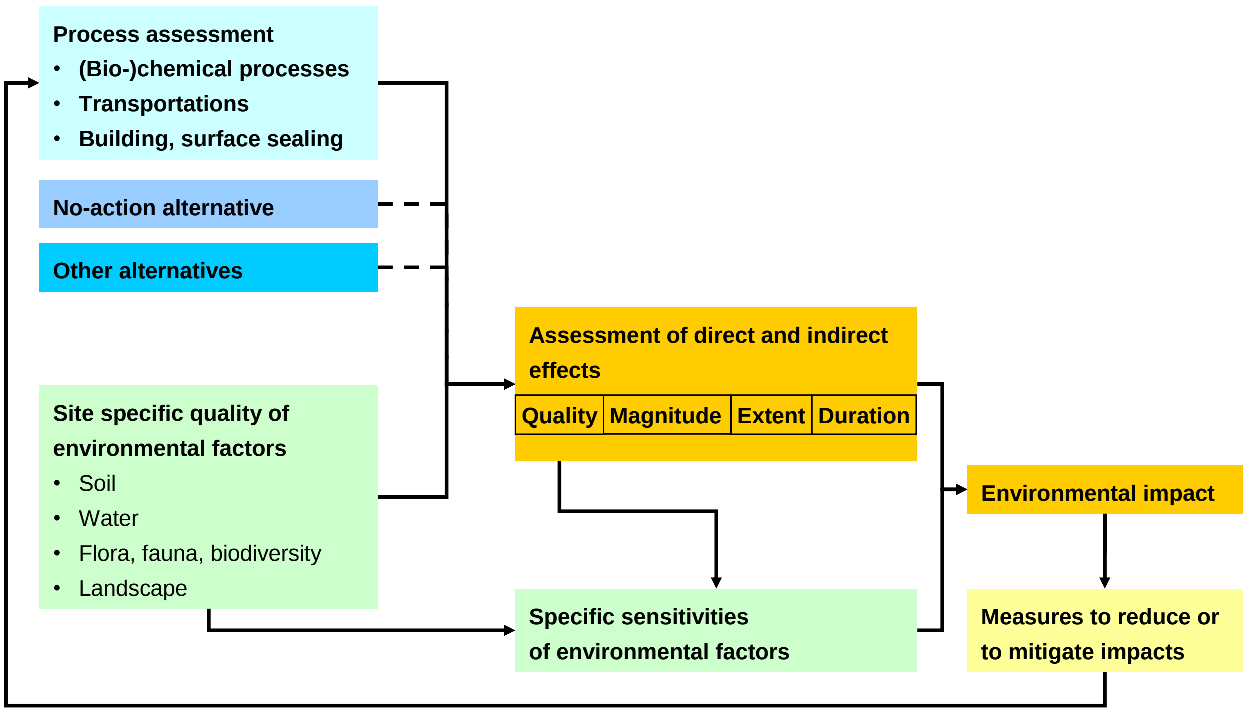

Figure 3-2: Structure of an LC-EIA in the D-Factory project.

Reference systems

Generally, an EIA compares a planned project to a so-called "no-action alternative" (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as an algae cultivation facility or a downstream processing facility. Production sites for raw material inputs (e.g. biomass) and/or the impacts associated with the end use of the manufactured products are usually not considered.

For D-Factory, the scope, and therefore also the reference system, of the LC-EIA was chosen to encompass all life cycle stages from raw material production through algae cultivation and conversion up to the use of the manufactured products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA. Since the use of the manufactured products is equivalent in all scenarios and not expected to be associated with significant environmental impacts, the related impacts are set zero in this assessment.

Impact assessment

The assessment of local environmental impacts along the life cycle is carried out as a qualitative benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of algae cultivation sites and conversion facilities.

For this qualitative impact assessment, so-called conflict matrices are used. These present in an aggregated manner the types of risk associated with each of the scenarios including a ranking of the impacts into five categories from A (low risk) to E (high risk). An example is given in the following Table 3-2.

Table 3-2: Comparison of scenarios regarding the risks associated with their implementation

Type of risk	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
Soil erosion					
Soil compaction					
Eutrophication					
Accumulation of pesticides					
Depletion of groundwater					
Pollution of groundwater					
Pollution of surface water					
Loss of landscape elements					
Loss of habitat/biodiversity					

Categories (A = low risk, E = high risk): A B C D E

For dedicated crops, which are cultivated to provide the reference products of the D-Factory system, crop-specific conflict matrices were used. An example is provided in the following Table 3-3.

In these crop-specific conflict matrices the environmental impacts of biomass cultivation are compared to a reference systems (relative evaluation) and evaluated as follows:

- “positive”: compared to the reference system, biomass cultivation is more favourable
- “neutral”: biomass cultivation shows approximately the same impacts as the reference system
- “negative”: compared to the reference system, biomass cultivation is less favourable.

Finally, mitigation measures could be deducted from these conflict matrices. However, since D-Factory is not targeting a specific location, mitigation measures are omitted.

Table 3-3: Risks associated with the cultivation of a specific annual/perennial crop

Type of risk	Affected environmental factors								
	Ground water	Surface water	Soil	Plants/Biotopes	Animals	Climate/Air	Landscape	Human health/ recreation	Biodiversity
Soil erosion									
Soil compaction									
Eutrophication									
Accumulation of pesticides									
Pollution of groundwater									
Pollution of surface water									
Loss of landscape elements									
Loss of habitat/biodiversity									

Categories: positive - neutral – negative

4 Analysed systems

This chapter gives an overview of the processes studied in the D-Factory project (chapter 4.1), the scenarios depicting potential future D-Factory value chains (chapter 4.2) and the products produced in these scenarios as well as the conventional reference products they compete with (chapter 4.3). For further details please refer to the original report this chapter summarises [Harvey 2017].

4.1 Processes

Figure 4-1 describes the nature of processes that have been studied in the D-Factory project and might feasibly deliver the 14 products described for an industrial-scale D-Factory biorefinery. The scenarios described in chapter 4.2 each depict a subset of the partially mutually exclusive options shown here, which are partially used in a sequence deviating from this overview chart. Please refer to schemes of final scenarios in the annex for details (chapter 8.3).

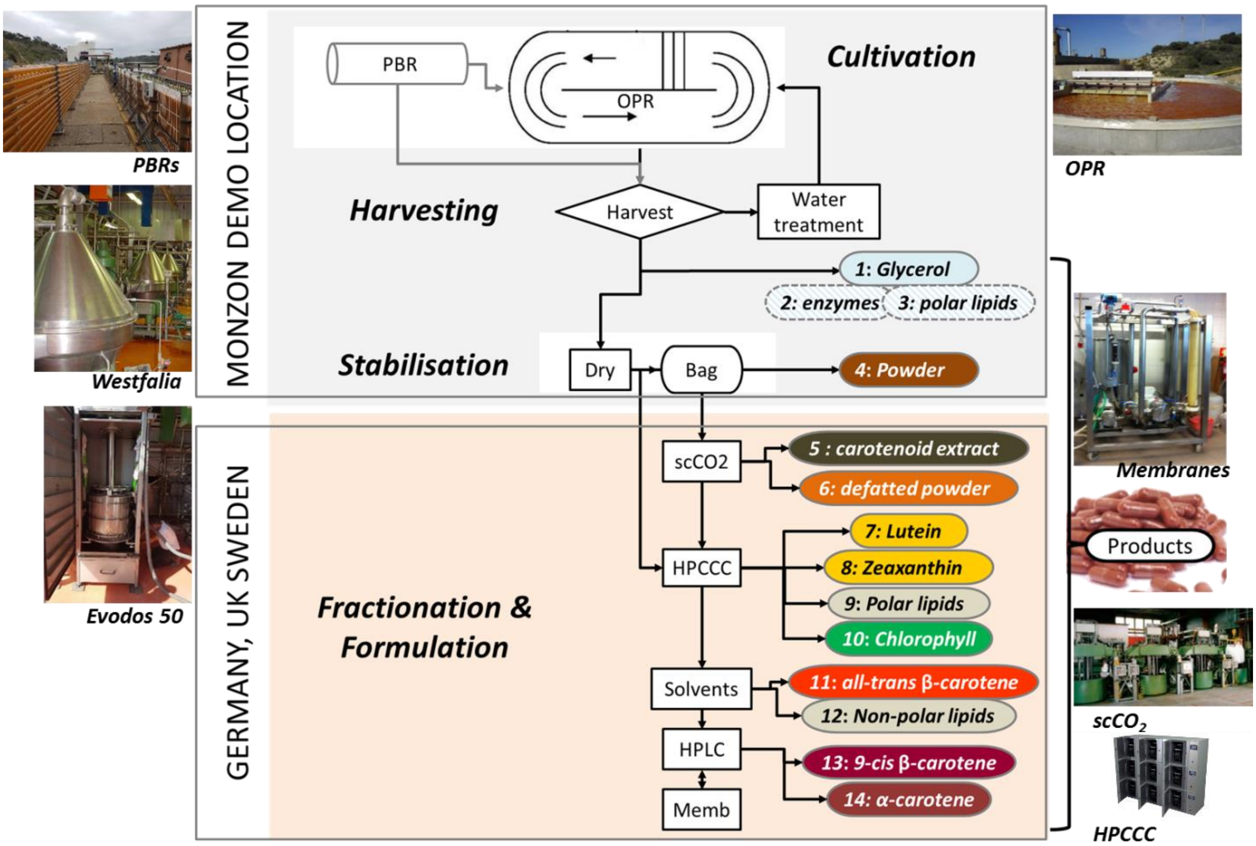

Figure 4-1: Schematic to summarise products and processes studied within the D-Factory project.

Algae cultivation

Algae are cultivated in hypersaline media using open raceways with paddle wheels. Algae are harvested by partially or completely draining the raceways. Inoculation is done by stepwise dilution of cultures from several sizes of smaller raceways. Alternatively, closed photobioreactors may be used for inoculation to protect the inoculum from contaminations and thus to restart cultures faster after a possible collapse.

Central biorefinery processes

In brief, after culture in raceways, with or without inoculation using photobioreactors (PBRs), there is a series of processes which for convenience are grouped in blocks as follows (Figure 4-1):

BLOCK 1*:* Biomass is harvested using spiral-plate centrifuge (such as provided by the project partner Evodos) or a conventional disc-stack centrifuge. These centrifuges are not equivalent: spiral-plate systems aim at harvesting cells intact in preparation for subsequent controlled cell rupture for **GLYCEROL** (Product 1), **ENZYMES** (Product 2), **POLAR LIPOPOLYSACCHARIDES** (Product 3), whereas disc-stack systems aim to concentrate cells but cause cell rupture and release these water-soluble components to the effluent stream for subsequent waste management before recycle or discharge.

The recovery and analysis of cytosolic enzymes and lipids from spiral-plate-harvested material under conditions of controlled cell rupture requires verification, hence in Figure 4-1 these products are shown in hatch. Membrane pre-concentration is used in some scenarios to remove large parts of the medium before centrifugation.

BLOCK 2*:* The water-insoluble lipophilic biomass collected at the centrifuge is stabilised by drying to a **POWDER** (Product 4), with or without prior washing to remove salt. Dryers are either spray-driers or lyophilisers. These are also not equivalent: Spray-drying involves use of a hot drying gas, which can denature enzymes and produces a fine (100-300μm) free-flowing powder. This is suitable for processing with chemical petroleum solvents but nevertheless still needs improvements for processing with supercritical CO_2 (scCO2), whereas lyophilisers use a combination of reduced pressure and enough heat for ice to sublime from pre-frozen material and the resultant powders are well-suited to $scCO_2$ processing.

BLOCK 3*:* Product 4 POWDER is extracted with $scCO_2$ or sequentially with solvents of increasing polarity to give **CAROTENOID EXTRACTS** enriched in lipophilic carotenoids, chlorophyll and lipids (Product 5). Residual biomass, namely **DEFATTED POWDER** (Product 6) after solvent/scCO2 extraction may contain salt in addition to organic matter if pastes are not washed prior to drying. If solvent is used the defatted powder needs to be desolventized.

BLOCK 4*:* Further processing of carotenoid extracts using polar solvents generates fractions enriched in **POLAR LIPIDS** (product 9), the xanthophylls **LUTEIN** (product 7) and **ZEAXANTHIN** (product 8) and **CHLOROPHYLLS** (product 10), which are separated using HPCCC.

BLOCK 5*:* Processing of the remainder extract with non-polar solvents will deliver a fraction enriched in non-polar lipids and mixtures of carotenes which are separated from each other using a combination of temperature- or solvent-dependent precipitation followed by HPLC (high performance liquid chromatography). Products 11-14 are **ALL-TRANS β-CAROTENE, 9-CIS β-CAROTENE, α-CAROTENE** and **NON-POLAR LIPID**

BLOCK 6*:* Solvents are removed from all final products using membranes and reused by recycling within the process itself using solvent resistant membranes specific for the solvents used. The chemical petroleum solvents primarily used for first extraction are Acetone and Heptane, followed eventually by Ethanol. The solvents used for HPCCC separation (BLOCK 4) include Heptane, Water, Methanol/Ethanol and may include small quantities of Ethyl Acetate or another solvent in order to prepare the biphasic partitioning system.

At the end of the processing steps, all solvents are recovered using a combination of solvent-resistant membranes and evaporation/condensation.

Utility provision, wastewater management

In standard scenarios, power is provided by the grid. Alternatively, on-site solar power can be generated with photovoltaics installations.

Brine for preparation of hypersaline algae growth medium is provided in standard scenarios by infusing freshwater through wells into underground salt deposits, which are relatively close to the surface. The brine pumped from these wells has to be supplemented with magnesium to reach magnesium concentrations similar to seawater. Alternatively, brine from existing seawater desalination plants for freshwater production can be used depending on the location. As a further alternative, mined rock salt can be dissolved in freshwater.

The amount and degree of contamination of wastewater varies strongly between scenarios. Outputs have in common that they contain high loads of salt, which may make it unsuitable for treatment in municipal wastewater systems. In the scenarios analysed here, hypersaline wastewater to be disposed is treated by aerobic wastewater treatment on site to largely eliminate organic matter. Depending on the location, it is then either injected into underground caverns left over after exploitation of salt deposits or discharged to the sea following local regulation.

4.2 Scenarios on algae cultivation and use

Table 4-1 and Figure 4-2 give and overview of the scenarios analysed in this study. Detailed process schemes for each scenario can be found in chapter 8.3 in the annex. These scenarios were selected for detailed analysis from a much bigger set of scenarios. Additional information and further scenarios can be found in [Harvey 2017][1].

Table 4-1: Overview of the analysed scenarios

No.	Short description
1	Initial configuration: 1. Disruptive algae harvesting with disc-stack centrifuge without membrane pre-concentration including wash to remove salt. 2. Biomass is dried - drying step uses spray drying. 3. Supercritical CO_2 and organic solvents to fractionate extracts into increasingly pure preparations of high-value compounds.
2	Membrane pre-concentration: Scenario 1 with membrane technology as a pre-concentration step for harvesting cells to lower energy costs and permit effluent recycle.
3	Whole cell harvesting: Scenario 2 with Evodos-type spiral plate centrifuge for harvesting intact whole cells and controlled cell rupture using water, which also washes biomass to remove salt.
4	Glycerol recovery: Scenario 3 with recovery of glycerol after controlled cell rupture using water. Electrodialysis introduced to recover glycerol.
5	Shorter downstream processing: scenario 3 without separation of carotenes into α-carotene and *9-cis* β-carotene.
6	No carotenoid separation: scenario 3 without separation of carotenoid extract into seven products including *9-cis* β-carotene.

[1] Correspondence of scenario numbers to the original set of scenarios: 1 = 1d, 2 = 1c, 3 = 1 base case, 4 = 1f, 5 = 1h, 6 = 1g.

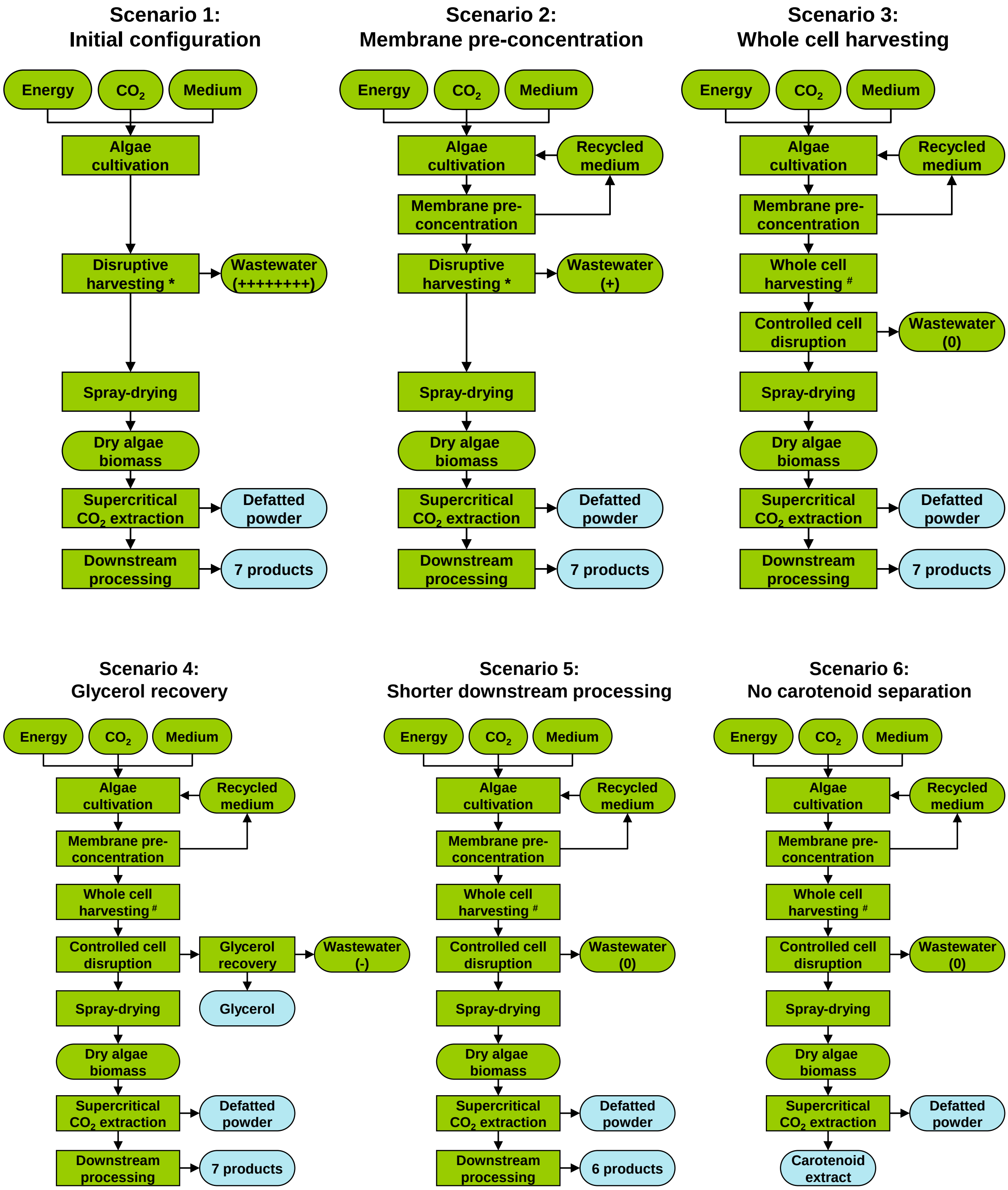

Figure 4-2: Overview schemes on the scenarios analysed in this study. *: by disc-stack centrifuge; #: by spiral-plate centrifuge; amounts and organic loads of wastewater are delineated by symbols +/0/-.

4.3 Products and reference products

Table 4-2 summarises all products that are produced in the analysed scenarios. For details, please see chapter 8.3. Each product is compared to a reference product of equivalent function. If a novel health benefit is confirmed for *9-cis* β-carotene in clinical trials, it cannot be compared to any existing product (see chapter 3.1.5 for methodological details). This is the case in all standard scenarios. In a sensitivity analysis, the other case without a novel benefit is analysed.

Table 4-2: Overview of products and reference products

Products	Market	Reference product
Polar-lipids, non-polar lipids, free fatty acids	Specialist animal feed Surfactants	Rapeseed oil
Defatted powder	Feed	Soy + cereals
Lutein	Nutraceutical	Lutein purified from marigold
Zeaxanthin	Nutraceutical	Zeaxanthin purified from marigold
Chlorophyll	Food colorant	Extracts from green plants such as spinach
All trans β-carotene	Food colorant	Synthetic all trans beta carotene
9-cis β-carotene*	Pharmaceutical Sensitivity: Nutraceutical	Standard: none (novel product) Sensitivity: like all-trans β-carotene
α-carotene	Nutraceutical	Like all-trans β-carotene
Glycerol	Multiple	Generic substituted chemicals

*: In some scenarios, mixtures containing *9-cis* β-carotene are not separated further (carotenoid extract resulting from supercritical CO_2 extraction and carotene extract resulting from HPCCC). They are only used for providing *9-cis* β-carotene. They are thus set not to replace e. g. other lutein products even if the mixture contains lutein because the consumer would not take lutein capsules instead.

5 Results and conclusions: LCA

Life cycle assessment (LCA) was used in this study to determine **global and regional environmental impacts**. A complementary analysis of local environmental impacts can be found in chapter 6.

All scenarios summarised in Table 4-1 were analysed by a screening LCA for the potential environmental impacts. Chapter 5.1 details for an exemplary scenario how various inputs and processes contribute to the overall result and how it is compared to a basket of reference products. Chapter 5.2 analyses how impacts can be reduced and which variant of the D-Factory concept causes lowest environmental impacts. Finally, results and conclusions are summarised and placed into context in chapter 5.2.3.

5.1 Contributions of inputs and processes

The overall screening LCA results for each scenario and each environmental impact category consist of contributions by many individual processes, inputs and life cycle stages. The results are detailed exemplarily for one scenario and impact category in Figure 5-1.

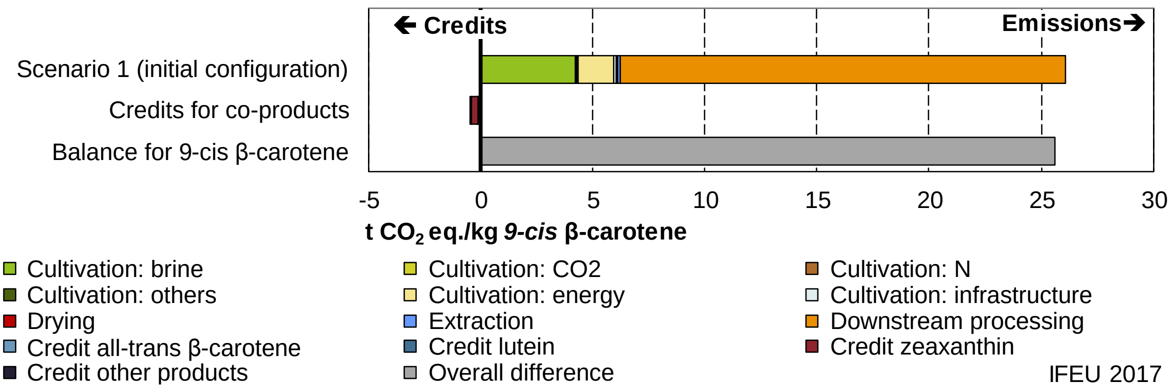

Figure 5-1: Contribution of inputs, processes and replaced reference products on the carbon footprint of the exemplary scenario 1 “initial configuration”. Boundary conditions: Conservative performance, power from the grid.

How to read Figure 5-1:

In the initial configuration, scenario 1 causes about 26 t of greenhouse gas emissions per kilogram *9-cis* β-carotene (expressed in CO_2 equivalents, first bar). The biggest contribution is caused by downstream processing of the extracted algae oil (about 20 t CO_2 eq., orange section) followed by the production of brine, which is needed for cultivation (about 4 t CO_2 eq., green section). On the other hand, about 0.5 t of greenhouse gas emissions are avoided by credits for co-products (second bar). This results in additional net greenhouse gas emissions of about 25.5 t CO_2 eq. per kilogram *9-cis* β-carotene (see third bar).

In this scenario, the production of *9-cis* β-carotene and its co-products causes the emissions shown in the first bar. The avoided emissions shown in the second bar are credited to the system because co-products replace conventional reference products. The remaining emissions are attributed to *9-cis* β-carotene.

In this exemplary scenario, as in most standard scenarios, downstream processing (DSP) dominates environmental impacts by far (Figure 5-1). Largest impacts result from the last processing step. In that step, preparative HPLC (high performance liquid chromatography) is used to separate *9-cis* β-carotene from α-carotene. Further important sources of greenhouse gas emissions are electricity generation for algae cultivation and the provision of brine for medium preparation. *Dunaliella salina* requires a hypersaline medium that can be prepared in several ways. This scenario contains the provision of brine by infusing freshwater through wells into underground salt deposits. The brine pumped from these wells has to be supplemented with magnesium to reach magnesium concentrations similar to seawater.

These results reveal dominant contributions to environmental impacts ('hot spots') that should be optimised with priority (chapter 5.2). Further contributions to greenhouse gas emissions and other environmental impacts to be optimised are also discussed in chapter 5.2.

5.2 Optimisation of environmental performance

The environmental impacts of a non-optimised concept for algae cultivation and use are dominated by few processes (see Figure 5-1 in chapter 5.1). Research in the project has shown that each of these dominant contributions can be reduced enormously. Such an optimisation makes another contribution to become dominant and to be addressed with high priority. Despite the fact that downstream processing clearly contributes most to environmental impacts, optimisation of algae cultivation, which ranks second in contributions, is analysed first (chapter 5.2.1). The reason is that upstream processes can influence downstream processes and therefore cultivation needs to be set before optimising processing of algae biomass (chapter 5.2.3). This main line of analyses is supplemented by excursuses on inoculum production in photobioreactors (chapter 5.2.2) and optimisation potentials by introducing further products (chapter 5.2.4).

5.2.1 Optimisation of algae biomass production

Algae biomass production includes the processing steps of cultivation, harvesting and drying of algae biomass. Its optimisation started from a simplified cultivation concept depicted in scenario 1 "initial configuration" (see also Table 4-1). It contains basic features of the process established in an existing algae cultivation plant in Eilat, Israel but not its adaptation to local conditions such as cultivation medium preparation from locally available resources. The site at Monzón in northern Spain, which is the location of the algae cultivation demo facility in the D-Factory project, serves as exemplary location for the scenarios analysed here. The analysis is however designed so that conclusions can be transferred to other suitable locations in Europe.

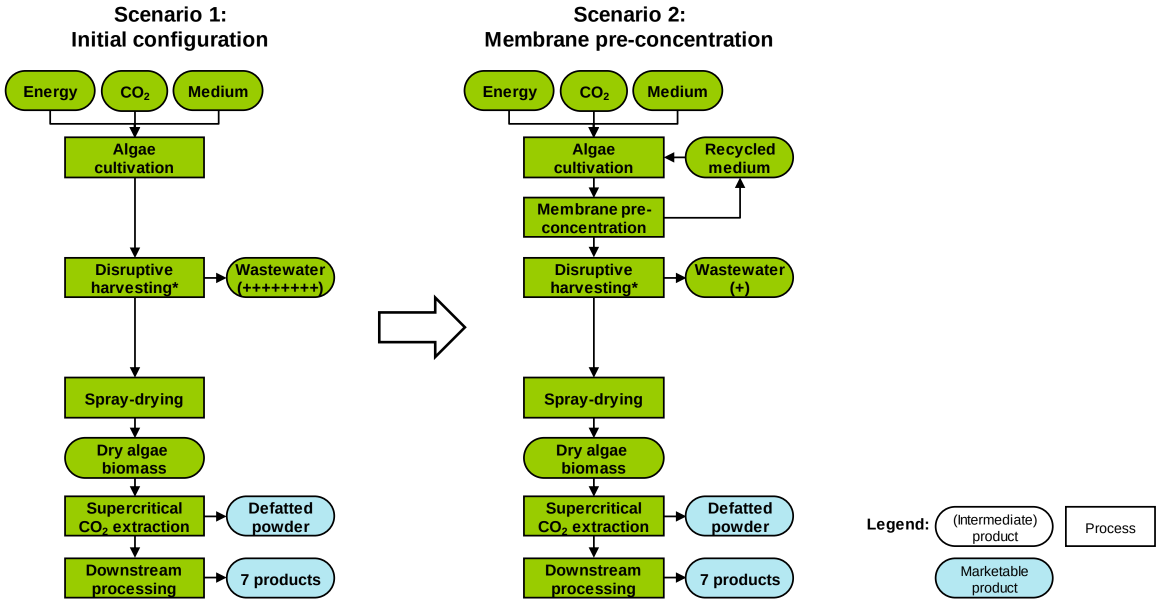

Figure 5-2: Simplified scheme of the optimisation steps from scenario 1 to scenario 2. *: By a disc-stack centrifuge. For a list of products please refer to Table 4-2 and for detailed process schemes please see the annex (chapter 8.3).

In a first step, membrane pre-concentration of algae in medium as drained from the raceway is added before the final harvesting step by centrifugation (Figure 5-2). This allows a reduction in power consumption and a recycling of the clean filtrate for medium preparation without major further treatment. This membrane pre-concentration has been studied but not yet fully established in the D-Factory project. Recycling of the centrifuge effluent could be possible, too, but would require energy and/or material intensive treatment because it contains high loads of organic material from cell debris (option not depicted in analysed scenarios).

Membrane pre-concentration could significantly lower environmental burdens of algae biomass production[2] once established (Figure 5-3). This mainly results from a massive reduction in brine consumption and significant reduction in power demand. Furthermore, land use is reduced by smaller areas for wastewater treatment. These results underline that a cultivation of algae with reasonable environmental impacts requires a clear strategy for medium recycling.

[2] For clarity, Figure 5-3 and all corresponding following figures in chapter 5.2.1 only show emissions and expenditures of algae biomass production including algae biomass drying as last step. Downstream processing of this biomass is analysed and displayed in chapter 5.2.3.

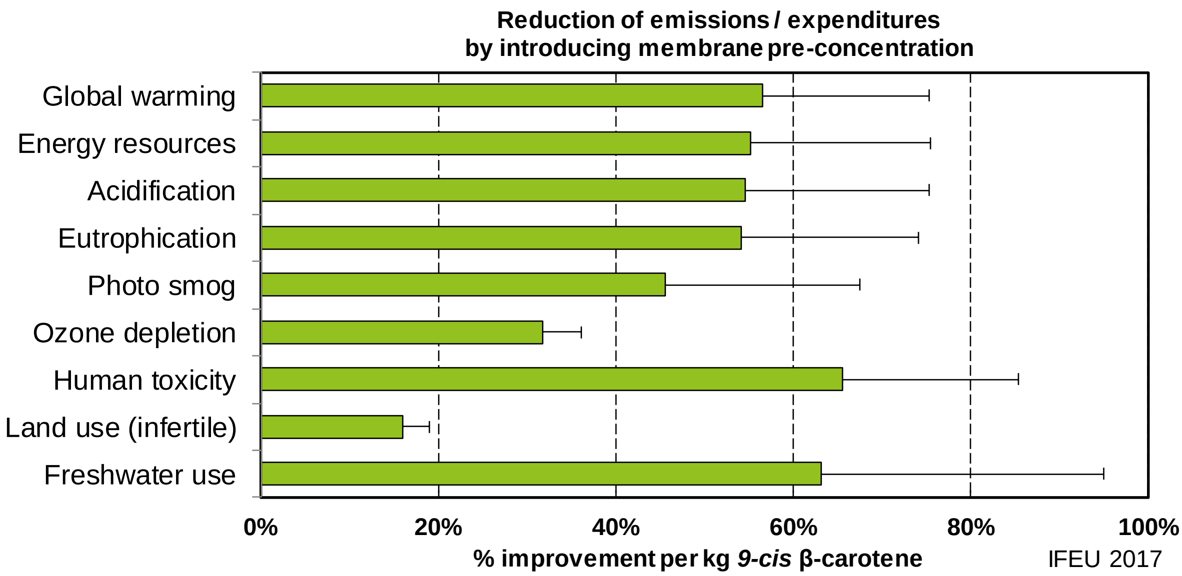

Figure 5-3: Reduction of emissions and expenditures of resources, respectively, of algae biomass production[2] by introducing membrane pre-concentration (scenario 1 “initial configuration” vs. scenario 2 “membrane pre-concentration”). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

How to read the first bar in Figure 5-3:

The contribution to global warming (i.e. the emissions of greenhouse gases) caused by the production of the intermediate dried algae biomass in an algae biorefinery according to the D-Factory concept can be reduced by about 55 – 75 % by introducing membrane pre-concentration. Emissions by further processing steps, in particular downstream processing (see also Figure 5-1), are not included in this graph because they are not optimised in this chapter. The range of savings arises because both scenarios are compared under optimistic and conservative conditions, respectively. In one case, this leads to about 75 % savings of greenhouse gas emissions and in the other case to about 55 % reductions.

Further direct savings potentials for electricity in this algae biorefinery are limited. Mixing of the culture and harvesting by centrifugation have to be primarily optimised for efficiency to guarantee high product yields. This can indirectly lead to lower power consumption per amount of product because higher algae concentrations require less medium to be prepared, handled and removed and lower losses increase product yields. Due to complex relationships of parameters, these effects could not be analysed in isolation but instead contribute to wider ranges of results (see also Figure 5-15).

A next optimisation step replaces disruptive algae cell harvesting by a conventional disc-stack centrifuge by a spiral-plate centrifuge such as provided by the project partner Evodos (Figure 5-4). This allows gentler conditions and the harvest of mainly undisrupted whole algae cells. The harvested biomass thus contains all parts of the algae cells and not only the membrane fraction as in disruptive harvesting. Furthermore, the effluent contains much less organic matter once the system is properly established. This reduces efforts for wastewater treatment and may open possibilities for further medium recycling.

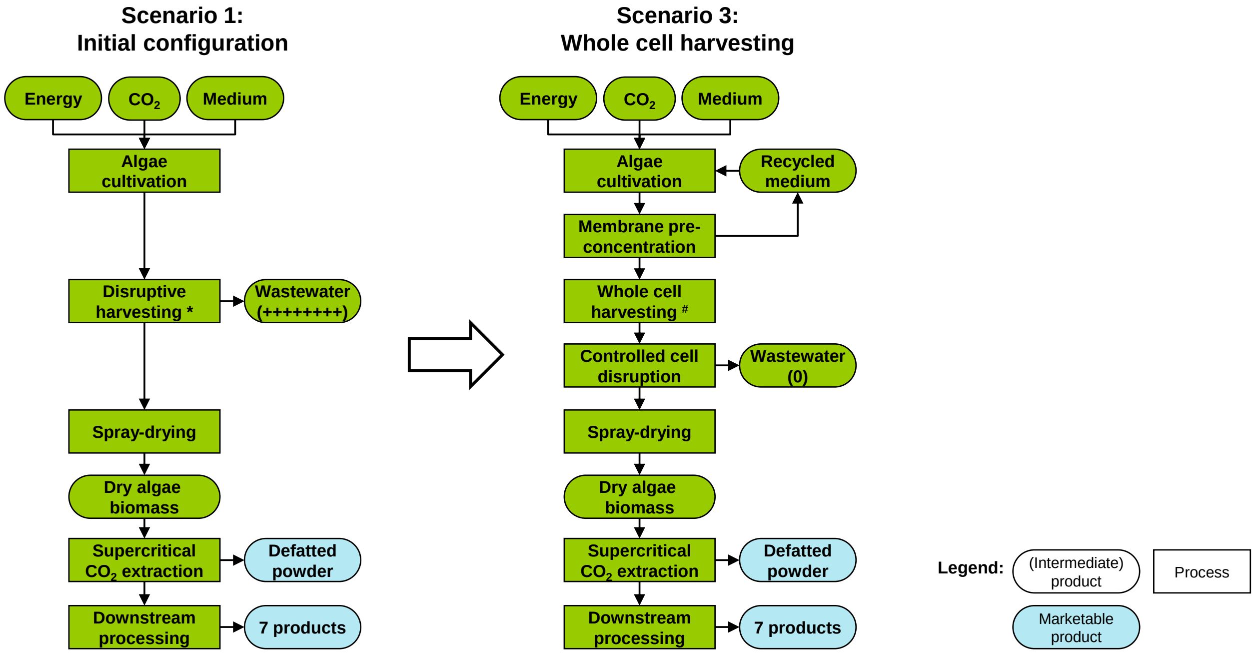

Figure 5-4: Simplified scheme of the optimisation steps from scenario 1 to scenario 3. *: By a disc-stack centrifuge, #: by an Evodos-type spiral-plate centrifuge. For a list of products please refer to Table 4-2 and for detailed process schemes please see the annex (chapter 8.3).

This results in yet higher emission savings per kg of *9-cis* β-carotene (Figure 5-5) and increased emission credits for co-products[3] (Figure 5-6). Co-products replace other conventional products and thus avoid emissions elsewhere (see also second bar in Figure 5-1). Particularly high improvements regarding the avoided use of agricultural land result from the production of more zeaxanthin. It is otherwise extracted from cultivated marigold flowers, which contain only small amounts of this carotenoid. Both changes lead to an improvement of the net environmental impacts of *9-cis* β-carotene production and use.

[3] Most co-products (and products) are only produced in processing steps following algae biomass production. They still need to be taken into account when optimising algae biomass production because this stage determines if the biomass contained in these products is lost or retained. Therefore, emission credits (avoided emissions) of the whole life cycle are displayed in Figure 5-6 and following corresponding figures.

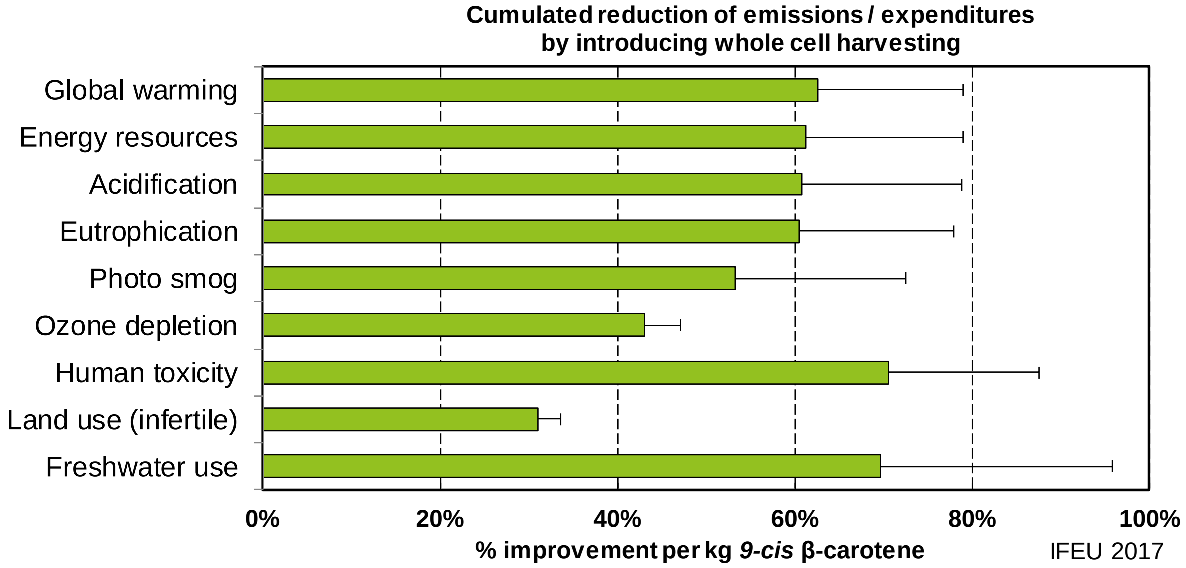

Figure 5-5: Reduction of emissions and expenditures of resources, respectively, of algae biomass production by introducing whole cell harvesting (scenario 1 "initial configuration" vs. scenario 3 "whole cell harvesting"). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

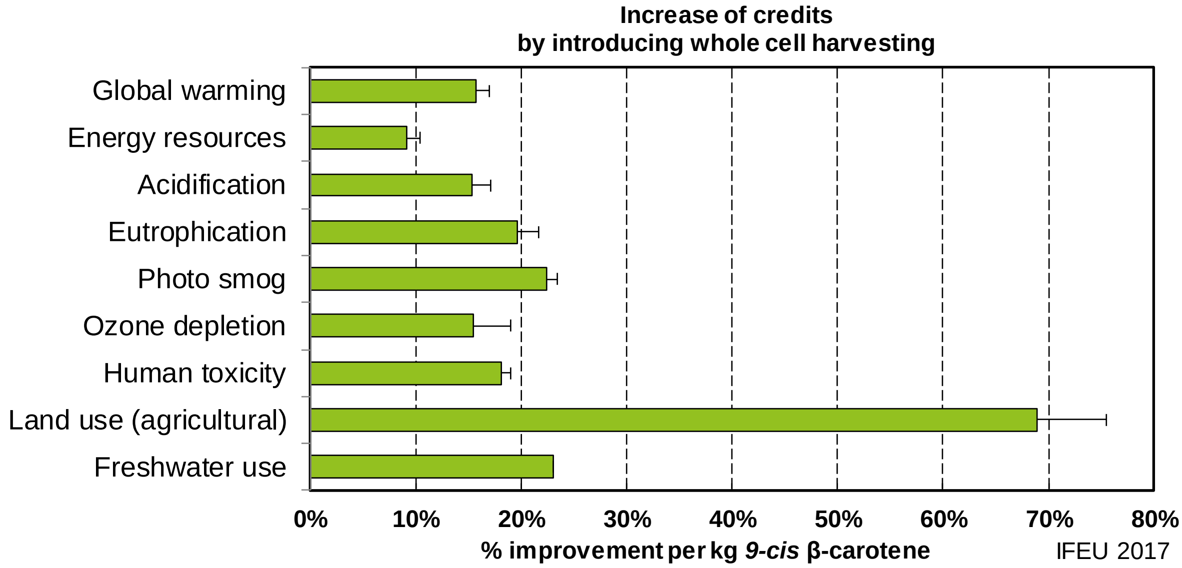

Figure 5-6: Increase of credits for avoided environmental burdens[3] by introducing whole cell harvesting (scenario 1 "initial configuration", which is in this aspect equivalent to scenario 2 "membrane pre-concentration", vs. scenario 3 "whole cell harvesting"). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

The full potential of whole cell harvesting is only used if most of the organic material that becomes available through this modification is used to create new products. Besides the use of proteins to be used as feed, which is already part of scenario 3 "whole cell harvesting", glycerol contained in the algae biomass can be used, too. This requires electrodialysis as a new processing step (Figure 5-7).

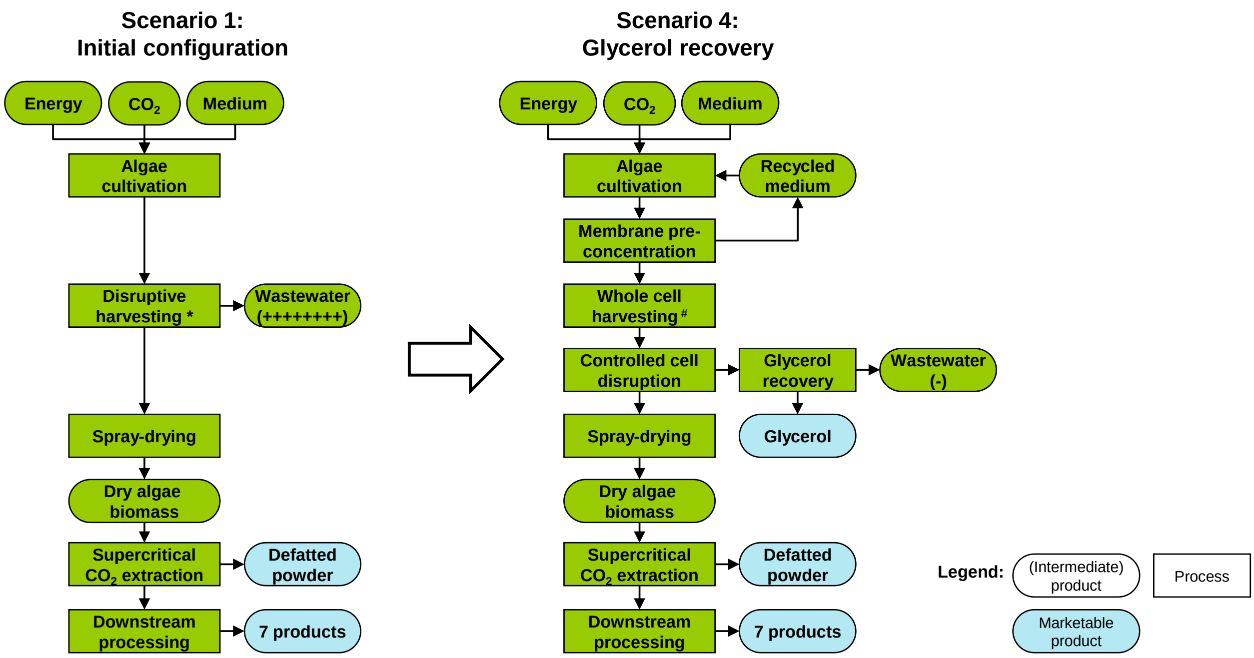

Figure 5-7: Simplified scheme of the optimisation steps from scenario 1 to scenario 4. *: By a disc-stack centrifuge, #: by an Evodos-type spiral-plate centrifuge. For a list of products please refer to Table 4-2 and for detailed process schemes please see the annex (chapter 8.3).

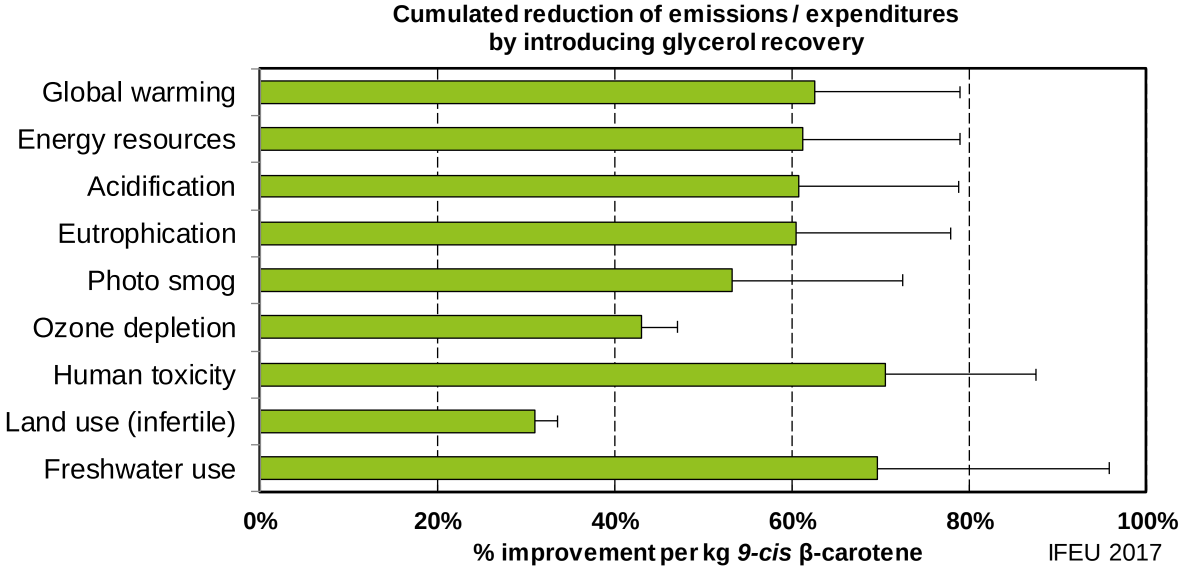

Figure 5-8: Reduction of emissions and expenditures of resources, respectively, of algae biomass production by introducing glycerol recovery (scenario 1 "initial configuration" vs. scenario 4 "glycerol recovery"). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

The introduction of glycerol recovery requires some energy. This compensates a small part of the emission reductions already achieved (Figure 5-8). However, increase in credits for the additional co-product glycerol (Figure 5-9) is higher than the disadvantages due to additional energy use. Thus, glycerol recovery improves the overall environmental impacts and should be established from an environmental standpoint.

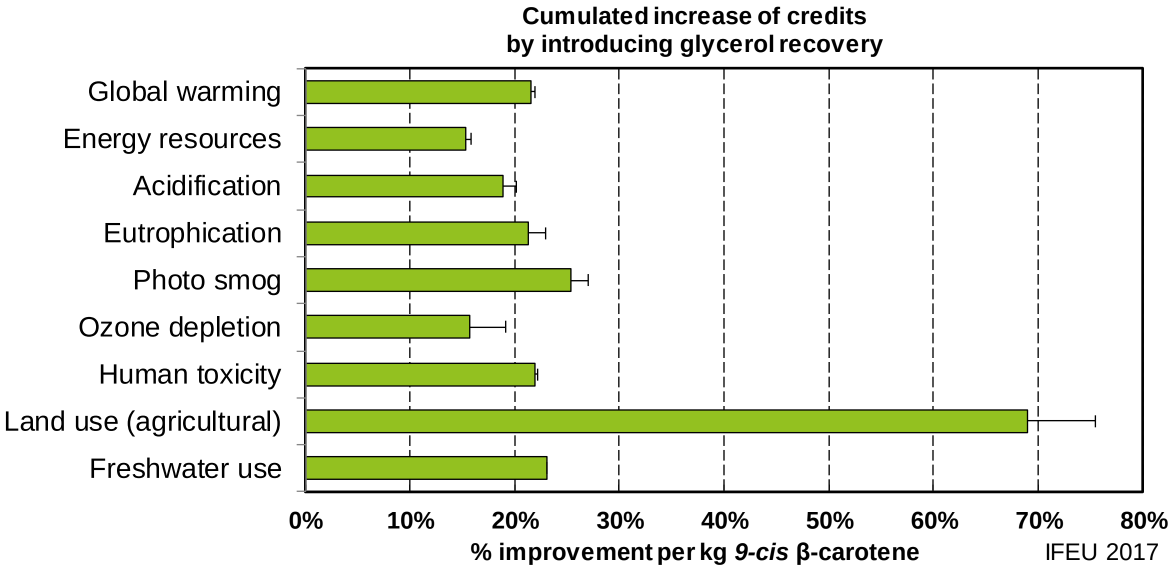

Figure 5-9: Increase of credits for avoided environmental burdens by introducing glycerol recovery (scenario 1 “initial configuration” vs. scenario 4 “glycerol recovery”). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

The analysis of optimisation options is not limited to the biorefinery processes themselves but also includes upstream and downstream processes in the life cycle. The most promising optimisations in these life cycle stages are alternative sources for electricity and brine.

If electric power is not taken from the grid but produced in an additional on-site photovoltaic installation, most environmental impacts can be reduced substantially (Figure 5-10). This is only possible at the expense of lower reductions in land use compared to the initial configuration. Nevertheless, solar power installations to provide about 80 % of the required electricity need less space than wastewater treatment in scenario 1 “initial configuration”. Supply and demand of solar power should be matching very well because most electricity demand that cannot be shifted in time stems from mixing of algae cultures. Its demand is highest when the sun is shining. For any concrete algae cultivation plant, the concrete savings have to be confirmed in a more detailed analysis of daily and seasonal load and supply of power. In any case, solar power can improve the environmental impacts and should be installed.

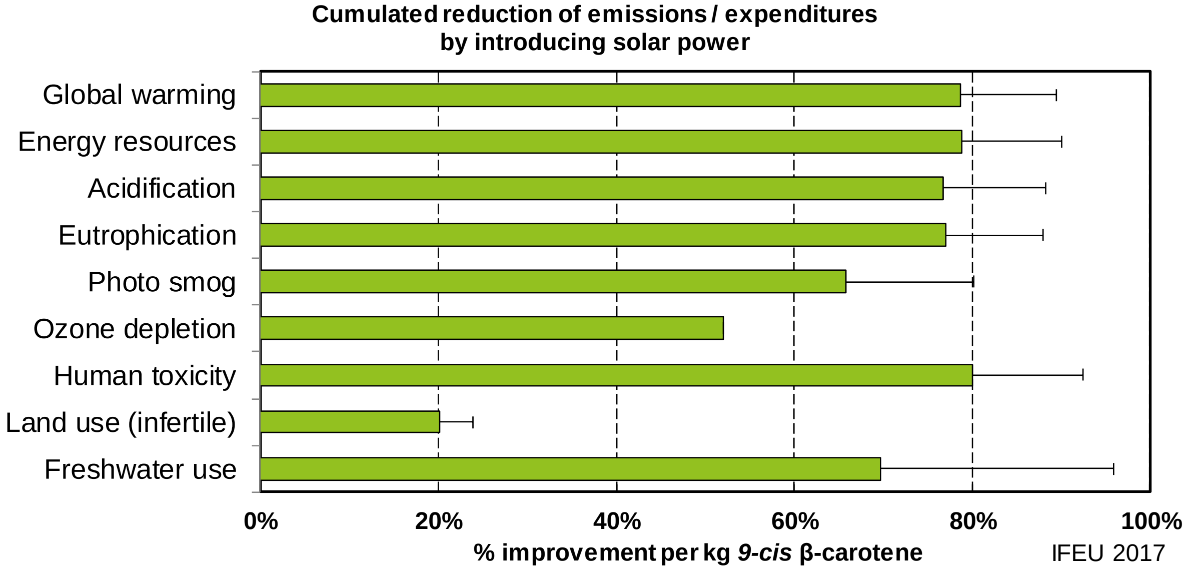

Figure 5-10: Reduction of emissions and expenditures of resources, respectively, of algae biomass production by introducing on-site solar power providing 80 % of the consumed electricity (scenario 1 "initial configuration" vs. scenario 4 "glycerol recovery" with 80 % solar power). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

A further reduction of environmental impacts can be achieved by choosing an optimal source of brine (Figure 5-11). This leads to substantial additional effects even in already highly optimised systems with high rates of medium recycling as analysed here. In this case, brine extracted from underground salt deposits is substituted by brine from existing seawater desalination plants for freshwater production. As for the introduction of solar power, credits for co-products are not affected.

Similar effects with more land use could be achieved by evaporating seawater in traditional sea salt evaporation ponds ("salt pans") until the salt concentration required for *Dunaliella salina* cultivation is reached. If recovered algae cultivation medium does not contain substantial amounts of valuable added components such as magnesium or nitrogen, or contaminants, then it may also be an option to establish a cascading use of brine instead of recycling it to cultivation ponds. In that case, brine would just be "borrowed" from e. g. a salt pan and fed beck to salt production after algae harvest. (Partial) cascading use may lead to lower overall environmental impacts depending on efforts required for reconditioning the medium in the recycling process. All integration options with existing sea salt operations have to be considered carefully: Such environments are always habitats for several organisms living in hypersaline water. They can be contaminants and predators for algae cultivation that may be hard to remove. This may partially neutralise the major advantage of *Dunaliella* cultivation in open raceways that hypersaline conditions are intolerable for most contaminating organisms.

This shows that the cultivation of hypersaline algae at low environmental impacts is only possible with recycling of salt within the system (e. g. via membrane pre-concentration, see also Figure 5-3) and/or cascading use of brine integrated with salt operations such as desalination or low-impact salt production. Such concepts have to be developed specifically for each potential site of an algae biorefinery according to the D-Factory concept.

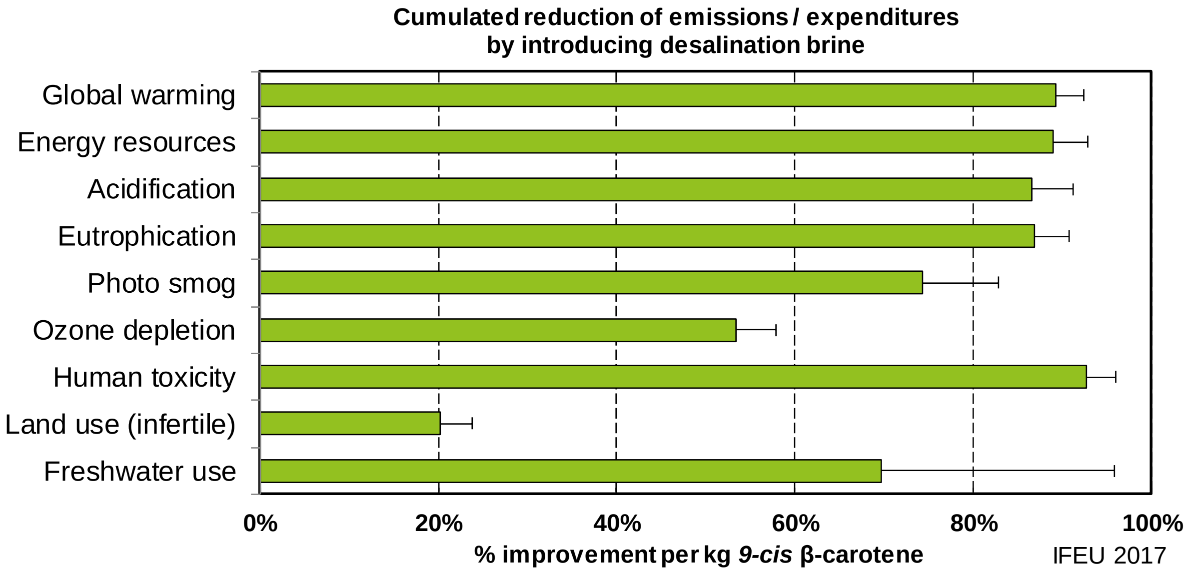

Figure 5-11: Reduction of emissions and expenditures of resources, respectively, of algae biomass production by introducing desalination brine (scenario 1 "initial configuration" vs. scenario 4 "glycerol recovery" with 80 % solar power and desalination brine use). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

5.2.2 Excursus: inoculum production with PBRs

In this project, inoculum production was studied using small raceways, green wall panels and multi-layer horizontal photobioreactors. The intention of using a closed cultivation system like green wall panels or photobioreactors was to protect the inoculum production from contaminations etc. This way, the main production in raceways can be restarted from many m³ instead of from the lab after a culture collapse e.g. due to predator contamination.

As Figure 5-12 shows, closed cultivation systems require in particular more energy for algae biomass production. Environmental burdens associated with infrastructure provision may be higher or lower but in any case less relevant. In total, the impact of closed cultivation systems for *Dunaliella* on global warming is twice to three times as high as that of raceways. Similar results were found for other impact categories. However, as inoculum production comprises only a very small fraction of the total algae cultivation, the influence on environmental impacts of algae-based products is small. If it could be achieved in practise to reduce downtimes of the facility, closed inoculum production systems may lead to an overall improvement of environmental performance. Thus, closed cultivation systems could be developed further as a protection against contaminants if contaminations should be frequent problems at a specific algae cultivation site.

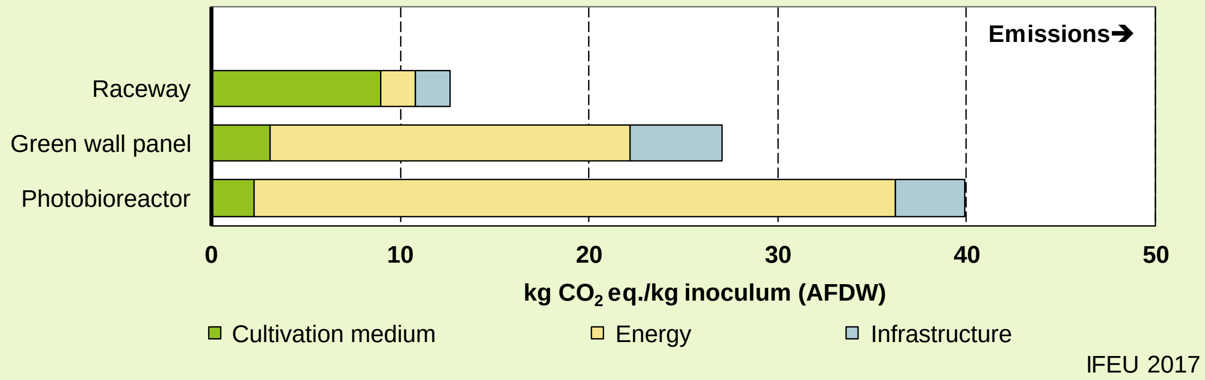

Figure 5-12: Carbon footprint of inoculum production by small raceways, green wall panels and multilayer horizontal photobioreactors. Power source: 80% on-site solar power.

5.2.3 Optimisation of algae biomass processing

A wide variety of options how to convert dried algae biomass into a diverse spectrum of products was studied within the D-Factory project. One exemplary possible configuration was modelled in detail for the purpose of sustainability assessment. It consists of an extraction with supercritical CO_2 ($scCO_2$) producing defatted powder and carotenoid extract. The extract is separated into up to 7 products by a sequence of processes including high-performance countercurrent chromatography (HPCCC) and preparative high-performance liquid chromatography (HPLC) (see Figure 5-13 for a simplified scheme and chapter 4.1 for a description). Especially HPCCC and HPLC technology were difficult to model quantitatively because important experience from operation at scale was not available. An analysis of the environmental impacts, however, clearly showed that the full sequence of downstream processing steps as modelled in scenario 3 causes enormous burdens (effect on global warming exemplarily displayed in Figure 5-14). Downstream processing dominates climate impacts of the whole life cycle by far. Largest emissions result from the last processing step. In that step, preparative HPLC is used to separate *9-cis* β-carotene from α-carotene.

As alternatives, shorter versions of the downstream processing were analysed (scenarios 5 and 6 in Figure 5-13). They save a lot of energy and solvents but produce less products, which leads to less credits for avoiding emissions elsewhere. Furthermore, the main product *9-cis* β-carotene is present in mixtures in products of scenarios 5 and 6, while being available as a pure substance from scenario 3. This analysis is based on the precondition that this does not limit the efficacy of *9-cis* β-carotene.

Leaving HPLC separation away (scenario 5) reduces impacts massively while hardly affecting credits for products (Figure 5-14). Likewise, the results for scenario 6 show that the greenhouse gas emissions avoided by additional products do not offset the emissions caused by the assessed versions of downstream processing. Similar results are found for all other environmental impact categories except for freshwater use and land use (see also Figure 5-15). Regarding these impacts, scenario 6 however still achieves largely neutral to slightly positive results, respectively, considering uncertainties.

From an environmental standpoint, the carotenoid extract should thus be sold as product without further purifications unless evidence is found that *9-cis* β-carotene needs to be pure to be effective or unless redesigned downstream processing can be achieved with much lower environmental impacts. Latest research by project partner Dynamic Extractions Ltd., UK, led to the very promising results that this could be achieved by a newly developed efficient and resource-saving modular HPCCC concept

[DeAmicis et al. 2017; Sutherland et al. 2013]. This remains to be analysed in more detail in a follow-up environmental assessment.

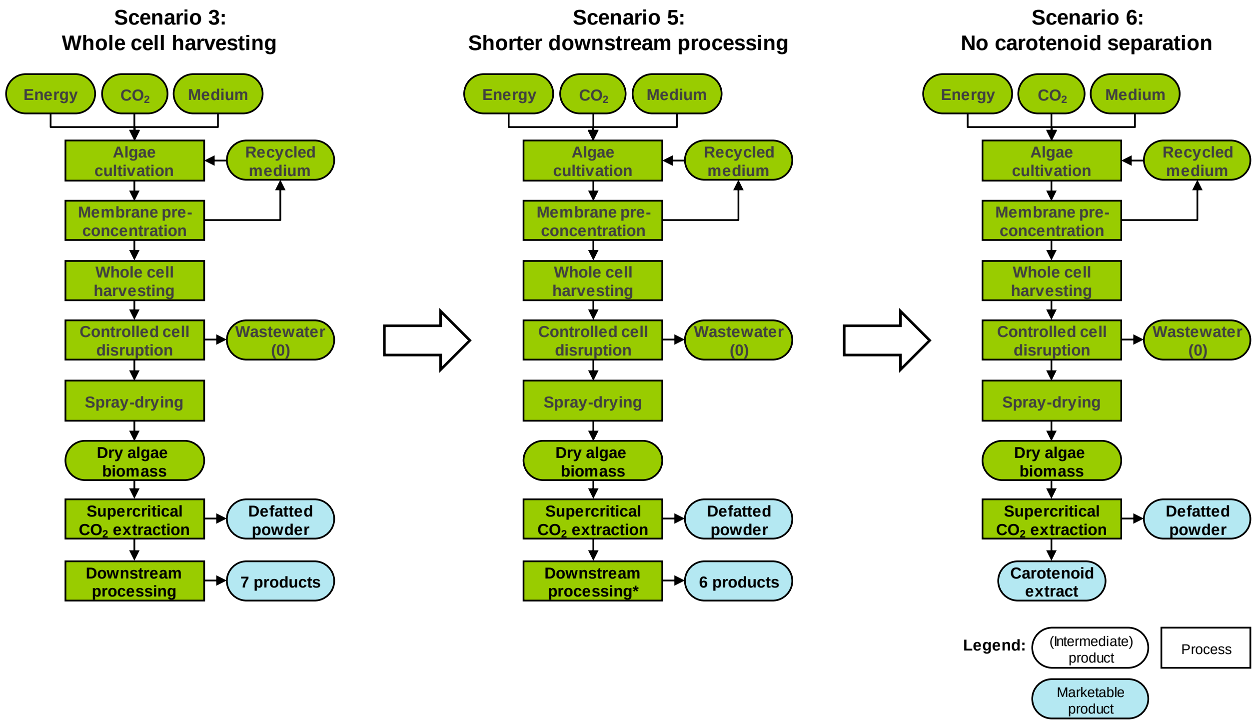

Figure 5-13: Simplified scheme of the variations from scenario 3 to scenarios 5 and 6. *: The shortened downstream processing producing only 6 products lacks a preparative HPLC process. For a list of products please refer to Table 4-2 and for detailed process schemes please see the annex (chapter 8.3). Note: The recovery of glycerol introduced in scenario 4 was omitted in this analysis for clarity.

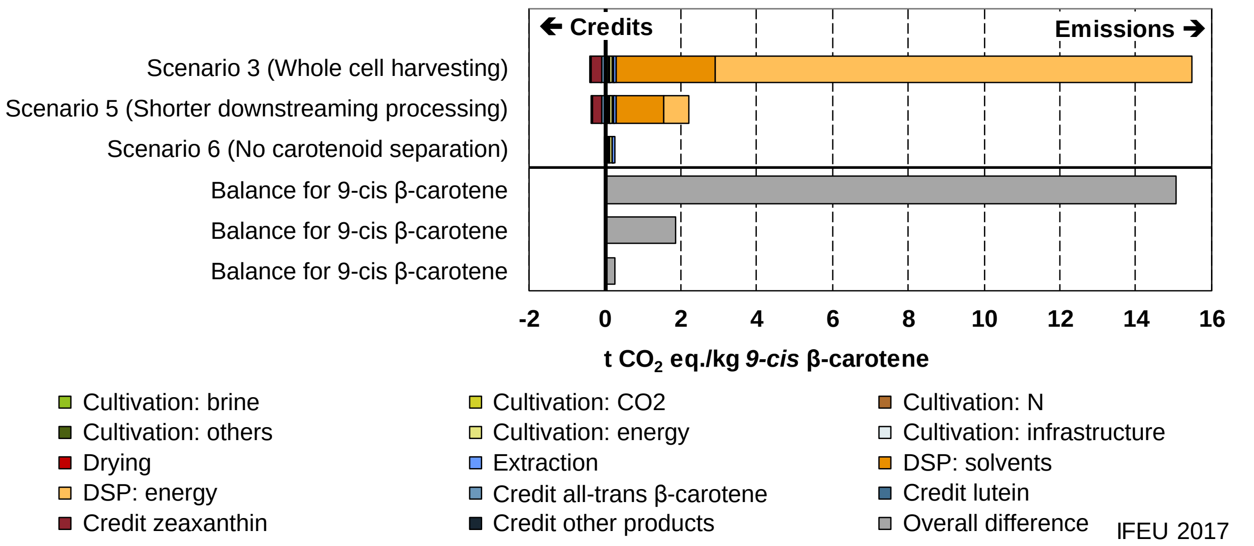

Figure 5-14: Improvement of the carbon footprint per kg *9-cis* β-carotene by shortening downstream processing (DSP) based on scenario 3 “whole cell harvesting”. Boundary conditions: Optimistic performance, solar power for algae cultivation. Please note that only scenario 3 produces pure *9-cis* β-carotene, while this compound is present in mixtures in products of scenarios 5 and 6.

5.2.4 Excursus: optimisation potentials by further products

Many more products have been studied in the D-Factory project than those that could be quantitatively assessed in this environmental assessment. This includes a higher value use of algae proteins than just for feed but e. g. as active enzymes or food such as sausages fortified with algae components. There is also initial evidence that *Dunaliella* components could have anti-diabetic activity. All these products could further improve a next generation of algae biorefineries. This would in most cases require the availability of sufficient amounts of certain biomass fractions and further research. Such work could build on a first implementation of a D-Factory algae biorefinery that could provide the required biomass. In any case, it is not granted that further products improve the overall environmental impacts (see also Figure 5-14). Additional emissions and resource expenditures for the extraction process need to be lower than the emissions that could be avoided elsewhere by replacing equivalent conventional products. This has to be ensured in a comprehensive life cycle assessment.

5.3 Overall global/regional environmental impacts

The optimisations of algae biomass production analysed in chapter 5.2 lead to a reduction of emissions by up to 90 % in most environmental impact categories (Figure 5-11) and to an increase of credited avoided emissions (Figure 5-9). The analysis of downstream processing clearly identified bottlenecks and showed that the modelled version of the process chain for product separation is not environmentally viable and should rather be omitted or redesigned (Figure 5-14).

This results in a range of overall environmental impacts per kg of *9-cis* β-carotene displayed Figure 5-15. Depicted ranges of results reflect varying boundary conditions and uncertainty about technical performance as well as potential effects of many decisions still to be taken during implementation. Paradoxical results can be seen for scenarios 3 and 4: Improvements in algae biomass production lead to more biomass reaching downstream processing and to more product. However, increased credits for more product are overcompensated by a slight relative increase in the high energy demand of downstream processing. If downstream processing was to be redesigned to be more energy and resource efficient, scenarios 3 and 4 are expected to perform clearly better than scenarios 1 and 2.

Remarkable results can be observed for the overall land use of *9-cis* β-carotene production (Figure 5-16): Co-products of the biorefinery set free a lot of land because conventional production of equivalent products can be avoided. In all assessed scenarios, the area set free is bigger than the one needed for algae cultivation itself. Even more, the conventional production requires fertile agricultural land while algae cultivation is possible on infertile land. This advantage is higher in all scenarios using whole cell harvesting with a spiral-plate centrifuge because more products, in particular protein-rich feed, are generated. Avoided marigold cultivation for lutein and zeaxanthin, avoided soy and cereal cultivation for feed and avoided rapeseed cultivation for lipids contribute substantially but in varying shares depending on the scenario.

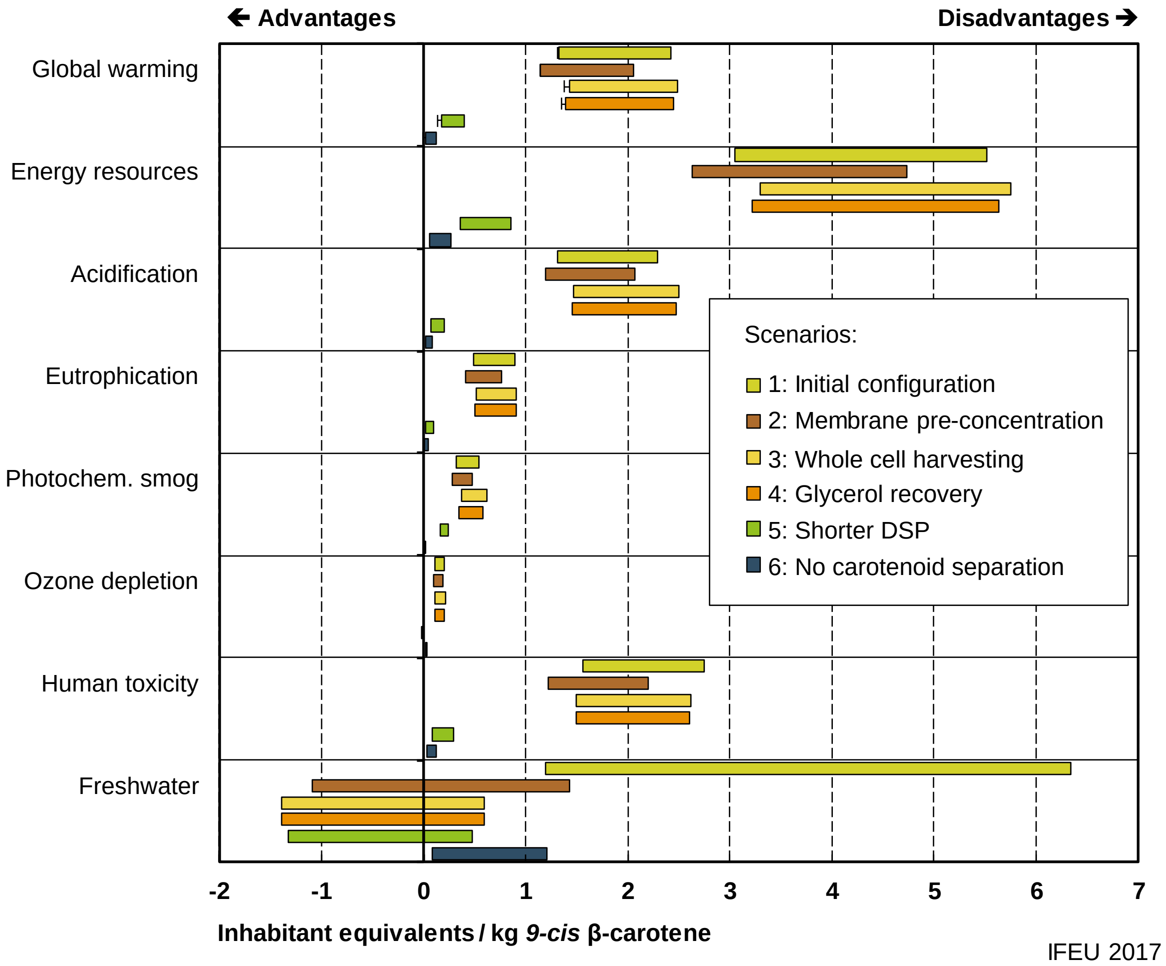

Figure 5-15: Ranges of environmental impacts of *9-cis* β-carotene production in all analysed D-Factory scenarios. Avoided environmental impacts of co-products were credited to the main product. Results are expressed in inhabitant equivalents[4]. Thin lines represent maximal potential impacts of avoided land use change on global warming through indirect effects.

How to read the first bar of Figure 5-15:

The production and use of 1 kg *9-cis* β-carotene in the Initial configuration scenario can cause a range of global warming impacts. The amount of greenhouse gas emissions ranges from as much as 1.3 inhabitants of Europe are causing on average in one year to emissions of about 2.4 inhabitants.

[4] A comparison of the magnitude – not the severity – of different environmental impacts can be done on the basis of inhabitant equivalents. In this case, the impacts caused by a certain scenario are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region, in this case the EU 28. Thus one inhabitant equivalent corresponds to the annual emissions in that impact category for one average EU inhabitant.

Avoided use of agricultural land also mitigates pressure to convert more and more (semi-)natural areas into cropland, which is known as indirect land use change. Land use changes can in the worst case mean cutting down rainforests, which is a realistic scenario for generating new area for soybean cultivation. This has impacts on climate change, biodiversity (keyword: “Orangutans are threatened with extinction”) and social disruptions (keyword: “land grabbing”). As soybean cultivation can be avoided by producing feed as algae-based co-product, avoided land use change and the related mitigation of climate change is advantageous for algae cultivation. In the analysed scenarios, this effect is however negligible (see thin lines in Figure 5-15 extending the result ranges for global warming).

Another aspect of avoiding the cultivation of partially irrigated crops is that it can also lead to net freshwater savings in some scenarios[5] (last bars in Figure 5-15). This shows that efficient recycling of algae cultivation medium and the efficient conversion of big shares of algae biomass into (co-)products can be more relevant than the production of the medium itself. This can even apply if (top-off) brine is even produced from freshwater for several technical reasons. Still, net freshwater savings are possible. Contrary to frequent arguments, these results also demonstrates that it can be less important for the environment whether algae are cultivated in freshwater, seawater or even brine if medium recycling and biomass use are efficient.

Net freshwater use is, however, only one aspect because local water availability or scarcity heavily affects the environmental impacts of water use. Therefore, local water availability needs to be ensured at the location of algae cultivation despite possible net freshwater savings (see also chapter 6 on local environmental impacts).

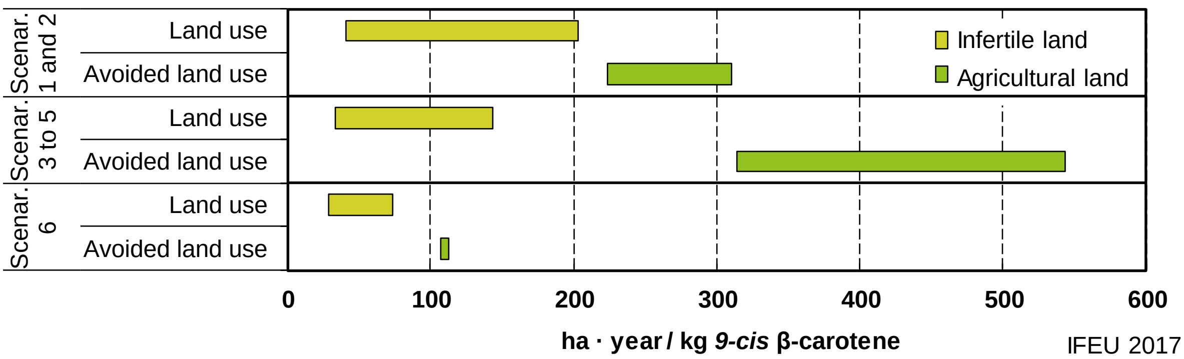

Figure 5-16: Ranges of land use impacts of *9-cis* β-carotene production in all analysed D-Factory scenarios. Infertile land is used and agricultural land use is avoided by co-product utilisation. Impacts of land use cannot be directly compared to impacts of avoided land use (as done by subtraction in Figure 5-15) because the type of land is different.

[5] Both water lost during harvesting and evaporated water contribute to freshwater use. Evaporation is highly dependent on local conditions and may be higher than the values used for conservative scenarios in very dry and windy areas. Conversely, freshwater use can also be reduced to zero if seawater is available and used instead following an appropriate overall concept (basis for optimistic scenarios).

Whether the substantial impacts in most environmental impact categories are acceptable for producing the new drug *9-cis* β-carotene cannot be judged by any life cycle-based environmental (or sustainability) assessment methodology. The reason is that there is no suitable reference for a drug providing a benefit that was previously not available. This screening LCA can only support such a societal decision by identifying measures to reduce environmental impacts (chapter 5.2) and show how the remaining environmental impacts relate to impacts of other more or less similar substances of different function. In case *9-cis* β-carotene should not show novel health benefits in clinical trials, a different line of analysis would have to be followed as shown in an excursus in chapter 5.3.1.

Figure 5-17 shows that exemplary available carotenoids with different functions than *9-cis* β-carotene can have ranges of carbon footprints spanning orders of magnitude. The impacts of *9-cis* β-carotene can be within this range but can also exceed it severalfold. Similar findings can be made for other environmental impacts (not shown). As a conclusion from an environmental perspective, *9-cis* β-carotene should not be purified – at least not using the DSP methods analysed in this report – but carotenoid extracts should be given to patients as a whole if possible for medical reasons. Then the production of *9-cis* β-carotene is similarly acceptable from an environmental standpoint as the production of other resource-intensive natural carotenoids but can provide the exclusive benefit of a new health effect. At least in smaller scales as required for drug manufacturing, this seems to be overall acceptable by society. Nevertheless, the range of potential environmental impacts has to be addressed in further analyses. One very important aspect will be the redesign of downstream processing for example by using a newly developed efficient and resource-saving modular HPCCC concept by project partner Dynamic Extractions Ltd., UK [DeAmicis et al. 2017; Sutherland et al. 2013]. If such an algae biorefinery should be established, which is a decision largely dependent on expected health benefits, a follow-up LCA should accompany the concrete planning process to turn current uncertainty into optimisation potentials.

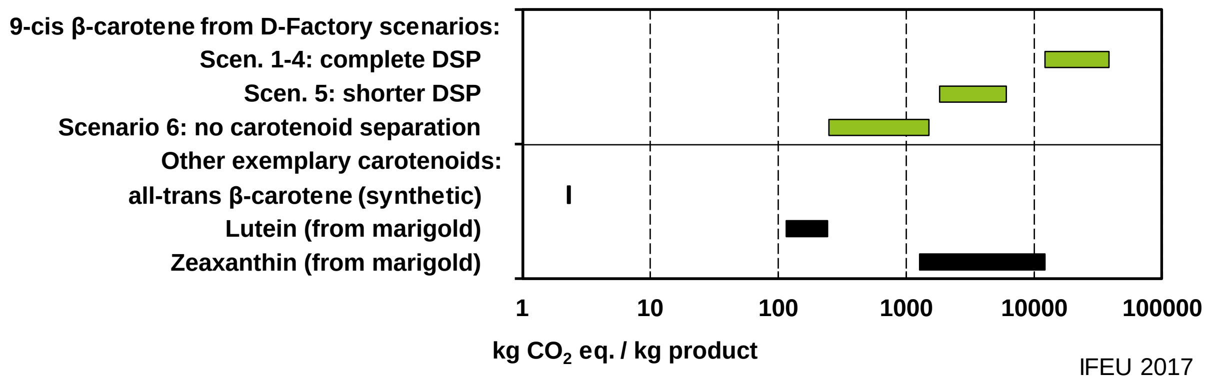

Figure 5-17: Relation of ranges of the carbon footprint of *9-cis* β-carotene production in selected D-Factory scenarios to carbon footprints of other carotenoids with different functions. Avoided environmental impacts of co-products were credited to the main product. Please note the logarithmic scale. DSP: downstream processing

5.3.1 Excursus: no novel health effect by 9-cis β-carotene

It could be that clinical trials result in no superior health effects of *9-cis* β-carotene over *all-trans* β-carotene. In that case, *9-cis* β-carotene would be evaluated just like *all-trans* β-carotene in terms of LCA. The algae biorefinery would have to be evaluated from an environmental standpoint as one of many options to use limited resources like land for mitigating environmental burdens. Figure 5-18 exemplarily displays the net environmental impacts of such a biorefinery per hectare and year of land use. There is no scenario that leads to relevant reductions of environmental burdens except for possible reductions of freshwater use. Additionally, suitable infertile land could be used better for the benefit of the environment by installing solar power (photovoltaics) plants, which for comparison saves about 50 inhabitant equivalents of emissions in the category global warming per hectare and year. Thus, such an algae biorefinery should not be supported from an environmental perspective using the technology underlying these scenarios.

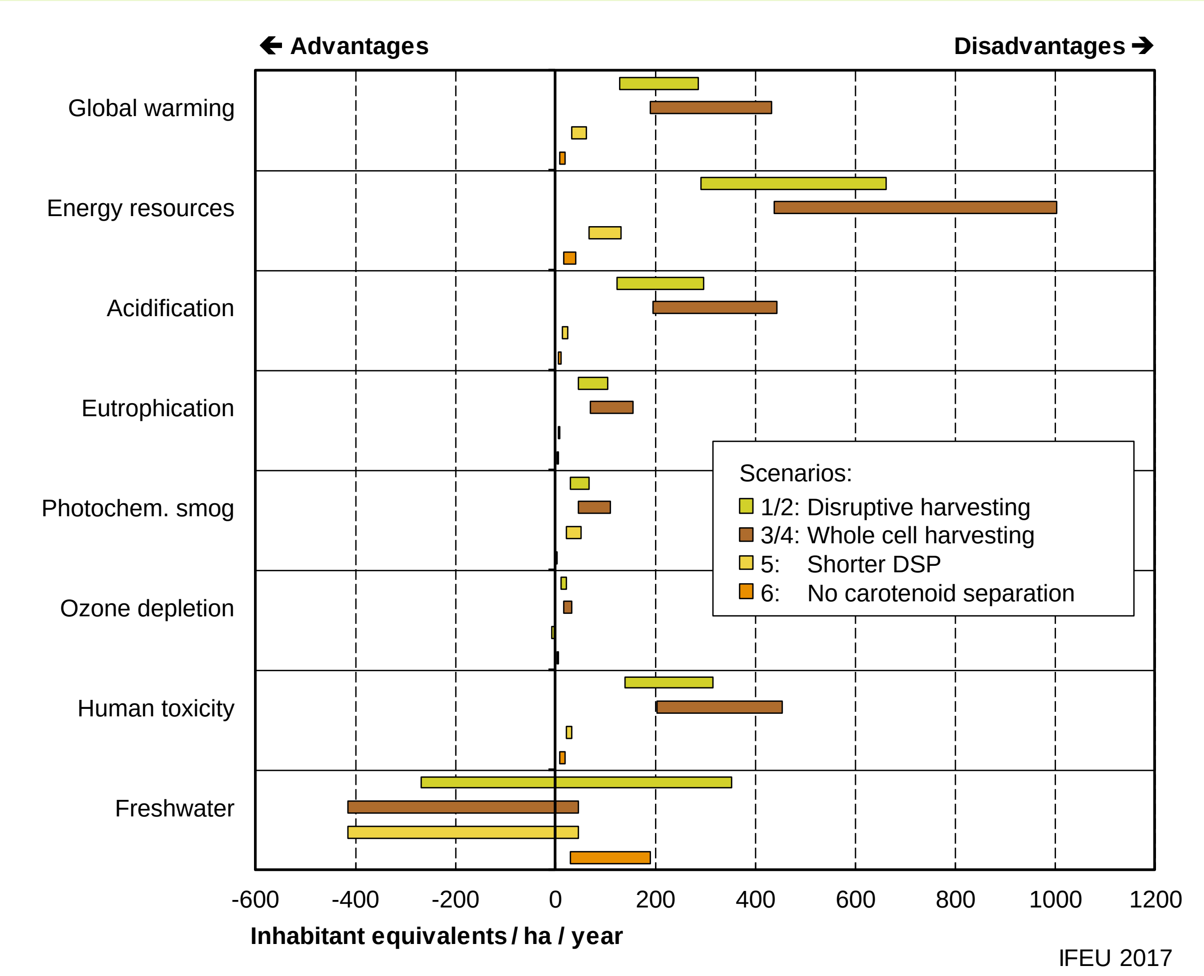

Figure 5-18: Ranges of environmental impacts of *9-cis* β-carotene production in all analysed D-Factory scenarios per hectare and year of land use. Avoided environmental impacts of co-products were credited to the main product. DSP: downstream processing

6 Results and conclusions: LC-EIA

Local environmental impacts associated with the D-Factory scenarios (see Table 4-1) and competing reference systems (see Table 4-2) were studied following the life cycle environmental impact assessment (LC-EIA) methodology (see chapter 3.3). A complementary analysis of global and regional environmental impacts can be found in chapter 5.

Chapter 6.1 focusses on the local environmental impacts of the D-Factory scenarios whereas chapter 6.2 presents the impacts associated with the competing reference systems. A comparison of all investigated systems is shown in chapter 6.3.

6.1 Local environmental impacts of the D-Factory systems

Following the system description in chapter 4, the D-Factory systems are divided into two consecutive steps. These are also referred to For the purpose of the LC-EIA:

- Dried algal biomass provision covering algae cultivation including upstream processes, harvest and algae biomass drying and
- Downstream processing covering algae oil extraction, processing, use phase and end of life.

Dried algal biomass provision takes place in one location and downstream processing is spatially separated. Thus, intermediate transport and logistics steps are required.

Dried algal biomass provision

Impacts from implementing an algae oil extraction and processing facility are expected from:

- the construction of the facility
- the facility itself: buildings, infrastructure and installations and
- operation of the facility

Impacts related with the construction of the facility are temporary and not considered to be significant.

Algae cultivation and processing facilities need buildings, infrastructure and installations (raceways, auxiliary facilities for harvest and algae biomass processing etc.), which usually goes along with sealing of soil. The associated impacts are related to the facility itself and are considered to be significant since both the raceways and the fairly large wastewater treatment lead to permanent soil sealing. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site:

- A greenfield site is land currently used for agriculture or (semi)natural ecosystems left to evolve naturally.
- A brownfield site is land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.

Impacts are of course much more pronounced if a greenfield site or a previously unsealed brownfield site are chosen for the construction of the algae cultivation facility.

Other impacts of the facility itself might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up facilities from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from the operation of the facility are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- disposal of wastes/residues
- risk of accidents, explosions, fires in the facility or storage areas

Significance of impacts might vary with the type of technology and the exact location of a potential facility. In addition to the choice between greenfield and brownfield sites, algae cultivation facilities can be built either in a "costal" or an "inland" location:

- Costal variant: brine from existing seawater desalination plants (co-product of freshwater production) is used. Hypersaline wastewater is treated by aerobic wastewater treatment on-site (to largely eliminate organic matter) and is then discharged to the sea following local regulation.
- Inland variant: brine is prepared by infusing freshwater through wells into underground salt deposits, which are relatively close to the surface. This brine has to be supplemented with magnesium to reach magnesium concentrations similar to seawater. Hypersaline wastewater is treated by aerobic wastewater treatment on-site (to largely eliminate organic matter) and is then injected into underground caverns left over after exploitation of salt deposits.

Potentially significant impacts on water and soil are expected for "inland" locations as a consequence of freshwater abstraction for brine preparation (especially in areas with water scarcity) and wastewater "dumping" in depleted caverns (especially if the fate of the organic matter load is unknown).

This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 3.3.1).

Transport and logistics

Transportation and distribution of dried algal biomass will mainly be based on trucks and railway/ships with need of roads and tracks/channels. Depending on the location of the algae oil extraction and processing facility, there might be impacts resulting from the implementation of additional transportation infrastructure. In order to minimise transportation, it could make sense from an economic point of view to build a plant close to dried algal biomass production. As far as it is necessary to build additional roads, environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species, disturbance by moving vehicles).

Storage facilities for dried algal biomass can either be constructed at the site of dried algal biomass provision and/or at the site of downstream processing. In any case, additional buildings cause sealing and compaction of soil, loss of habitats (plants, animals) and biodiversity as well as reduced groundwater infiltration.

Overall, the impacts associated with transportation and logistics are not expected to be significant.

Downstream processing (dried algal biomass conversion)

Impacts from implementing a dried algal biomass conversion facility are expected from:

- the construction of the facility
- the facility itself: buildings, infrastructure and installations and
- operation of the facility

Impacts related with the construction of the facility are temporary and not considered to be significant.

Downstream processing facilities need buildings, infrastructure and installations (processing facilities, energy generation, administration buildings, waste water treatment etc.), which usually goes along with sealing of soil. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site.

Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up facilities from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from the operation of the facility are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- risk of accidents, explosions, fires in the facility or storage areas

In summary, an algae biorefinery according to the D-Factory concept can have significant local impacts in particular on the environmental factors ABC. Significance of impacts might vary with the type of technology and the exact location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 3.3.1). The following measures should be considered when planning to build an algae biorefinery according to the D-Factory concept to minimise these impacts:

- Use land that is not suitable for agriculture (brownfield sites) and has been previously sealed wherever possible.
- Devise a concept for disposing wastewater with high salt contents without environmental damages. It is to be expected that this is easier in coastal locations.
- Devise a concept for minimising freshwater use. It is expected to be easier in coastal locations.

6.2 Local environmental impacts of the reference systems

A number of different products are manufactured in the D-Factory scenarios, each of which is compared to a reference product of equivalent function (see chapter 4.3). These reference products are partly bio-based, i.e. produced from agricultural raw materials, and partly fossil-based, i.e. produced from fossil raw materials. In the following sections, the local environmental impacts related to both (agricultural/fossil) raw material provision and downstream processing (raw material conversion) are described.

Agricultural raw material provision

The cultivation of dedicated crops includes both risks as well as opportunities, dependent on the type of crop. The assessment of crop-specific impacts primarily depends on the comparison with alternative land use, i.e. on the agricultural reference system.

Table 6-1 compares impacts from the provision of dedicated crops occurring in the reference systems to the land use reference system "idle land". This land use reference system covers degraded soils, degraded pastures or land that becomes free due to the intensification of existing land use. In this case, the difference in carbon stock between previous vegetation and crop cultivation is close to zero. Please note that the crops are cultivated in different agro-ecological zones. Direct comparisons are therefore not advisable. Detailed conflict matrices for these dedicated crops (compared to idle land) can be found in chapter 8.6.1 in the annex.

Table 6-1: Comparison of crop-specific impacts to the land use reference system idle land. Impacts are ranked in five categories; "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor

Feedstock	Marigold	Soybean	Wheat	Spinach	Rapeseed
Land use reference system	Idle land	Idle land	Idle land	Idle land	Idle land
Soil erosion	D	D	C	D	D
Soil compaction	D	D	C	D	D
Loss of soil organic matter	D	C	D	D	C
Soil chemistry/fertiliser	E	D	D	E	D
Eutrophication	E	D	D	E	D
Nutrient leaching	E	D	D	E	D
Water demand	E	D	C	E	D
Weed control/pesticides	E	E	E	E	E
Loss of landscape elements	D	E	C	D	C
Loss of habitat types	D	E	D	D	D
Loss of species	C	E	D	D	D

Fossil raw material provision

Fossil raw material provision is related with different types of risks causing potential impacts on the environment. Impacts of transportation are taken into consideration as well. Table 6-2 summarises major implications of fossil raw material provision in comparison with the no-action alternative. A detailed conflict matrix for crude oil provision can be found in chapter 8.6.2 in the annex.

Downstream processing (raw material conversion)

Agricultural raw materials are converted in a dedicated conversion facility (e.g. mill) depending on the crop. Fossil raw materials such as crude oil are converted in a conventional oil refinery.

Table 6-2: Potential impacts on the environment related to the provision of crude oil (reference system: no use). Impacts are ranked in five categories; “A” and “B“ are assigned to the best options concerning the factor (but not used in this case); “E” is assigned to unfavourable options concerning the factor

Feedstock	Crude oil
Prospection	C
Drilling/Mining	E
Waste	D
Demand of water (process water)	C/D
Emissions (exhaust fumes, dust, water, metal)	C/D
Land requirements	C/D
Demands of steel (tubes, equipment)	D
Transportation (carriers, pipelines)	D
Refining/processing/enrichment	D
Accidents (traffic, pipeline leakage)	E

Impacts from implementing a conversion facility are expected from:

- the construction of the facility
- the facility itself: buildings, infrastructure and installations and
- operation of the facility

Impacts related with the construction of the facility are temporary and not considered to be significant.

Fish oil extraction and processing facilities need buildings, infrastructure and installations (processing facilities, energy generation, administration buildings, waste water treatment etc.), which usually goes along with sealing of soil. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site.

Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up facilities from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from the operation of the facility are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- risk of accidents, explosions, fires in the facility or storage areas

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 3.3.1).

The alternative to D-Factory consists of a basket of bio-based and fossil resource-based products. Both have significant local environmental impacts:

- The bio-based products use a lot of land for intensive agriculture with particular impacts on the environmental factors soil, fauna and flora.
- The fossil resource-based products mainly cause irreversible impacts e. g. around oil wells.

These have to be considered in a comparison to D-Factory.

6.3 Comparison: D-Factory vs. its reference systems

Raw material provision

Compared to the no-action alternative, significant impacts of a D-Factory algae cultivation facility are expected on the environmental factors soil, water, fauna, flora, and landscape.

Potential impacts on the environmental factors climate/air quality, human health and biodiversity are not expected to be significant, based on the precondition that the facility will not be located in or in the vicinity of ecologically sensitive areas.

No significant impacts are expected to occur during the construction of the facility. If state-of-the-art technology is used, these impacts are temporary and restricted to the time of construction.

Likely significant impacts, indicated by solid borders in the lower part of Table 6-3, are expected to occur either from the facility itself and/or resulting from the operation of the facility. The following technology-related factor was identified as the main driver for significant impacts (on the environmental factors soil, water, flora, fauna, landscape, and biodiversity):

- drain on land resources due to soil sealing and compaction, leading to loss of habitats, species diversity and landscape elements.

However, facility-related impacts due to soil sealing and compaction are only considered to be significant in case the algae cultivation facility is being built on a greenfield site or if a previously unsealed brownfield site is being (partially) sealed.

Since the D-Factory product portfolio also contains products, for which otherwise dedicated crops would have to be cultivated, credits for avoided significant impacts could be obtained. Depending on the exact equivalence factors (today unknown), the corresponding cultivation areas could be freed up and left to evolve naturally. This indirect effect could 2 - 5 times over-compensate the direct impact on land resources related to the D-Factory facility. An objective weighting of the impacts of one against the other, however, is unfortunately not possible on the generic level, on which the LC-EIA is conducted.

In addition, there are **potentially significant impacts** resulting from the operation of the facility which depend on the exact location and local surrounding of the facility. This site-dependency is indicated by dashed borders in the lower part of Table 6-3. The following technology-related factors were identified:

- drain on water resources (site-specific ranking “C” or “E”)
- emission of nutrients (site-specific ranking “D” or “D/E”)
- disposal of wastes /residues.

Regions with water shortage in the warmer season as well as ecologically sensitive areas could be affected by freshwater abstraction. Moreover, the disposal of wastewater – which after treatment still contains high salt loads as well as an organic load – in underground caverns could potentially give rise to methane emissions and in case of leakage of the salt mine negatively affect groundwater resources. Therefore, a careful site-specific investigation has to be done in advance to exclude significant adverse impacts. In case mitigation should not be possible, other locations have to be taken into account.

Comparison of systems

Comparing only the four investigated D-Factory scenarios to each other, no differences are expected in terms of impacts related to the construction of the facility. However, there are enormous differences between the four investigated D-Factory scenarios regarding impacts from the facility itself as well as impacts related to the operation.

As compared to Scenarios 2 – 4, Scenario 1 is connected with a considerably higher drain on land resources, drain on water resources, emission of nutrients, and disposal of wastes/residues. Significance of impacts, however, depends on where exactly the algae cultivation facility is being built. In terms of drain on land resources, impacts due to soil sealing and compaction are only considered to be significant in case the algae cultivation facility is being built on a greenfield site or if a previously unsealed brownfield site is being (partially) sealed. Regarding water-related impacts, an inland location is connected with higher risks related to drain on freshwater resources as well as to the disposal of salt- and nutrient-rich wastewater, the former especially in areas with water-scarcity.

When comparing the D-Factory scenarios to the reference products, it becomes clear that the impacts of the latter are dominated by the cultivation of dedicated crops, i.e. by agricultural operations. Looking only at the direct land use impacts of each system, even the worst-case implementation of D-Factory, Scenario 1 – greenfield – inland, could be viewed as more favourable than the reference system. One could come to this view if one considers the impacts related to the sealing of former agricultural land to be less severe than the impacts related to the management on 2 times the agricultural land for crop cultivation. Such judgements, however, involve value choices and therefore cannot be scientifically objective. This is because objective criteria are missing that would allow a quantification and comparison of ecological value across different agro-ecological zones or between different types of land use. However, all implementations of D-Factory on previously sealed brownfield sites would definitely outperform the reference system independent of value-based choices.

On top of this, D-Factory would avoid the manufacture of fossil-based, non-renewable products, which are associated with mostly heavy, long-term impacts on the local environmental factors water, soil, flora, fauna and landscape e. g. around oil wells.

In conclusion, the local environmental impacts of the D-Factory scenarios can in general be considered to be less pronounced than the local environmental impacts of the reference systems. This is mainly due to the fact that D-Factory potentially frees up a land area which is up to 10 times as big as the area required for the production of agricultural raw materials for the reference products. Nevertheless, the D-Factory scenarios do cause likely significant impacts as well as potentially significant impacts on a number of environmental factors. Moreover, there are indeed enormous differences between the four investigated D-Factory scenarios. Mitigation measures (in order to minimise impacts) should target both the technical design as well as the location of the algae cultivation facility: Scenarios with extensive medium recycling are definitely to be preferred and a costal (previously sealed) brownfield site is considered to be connected with fewer risks than an inland greenfield site.

Conversion/downstream processing

Compared to the no-action alternative, significant impacts of an industrial facility are expected on the environmental factors soil, water, fauna, flora, landscape, and biodiversity.

Potential impacts on the environmental factors climate/air quality, human health and biodiversity are not expected to be significant. Precondition is that the facility will not be located in or in the vicinity of ecologically sensitive areas.

No significant impacts are expected to occur during the construction of the facility. If state-of-the-art technology is used, these impacts are temporary and restricted to the time of construction.

Likely significant impacts, indicated by solid borders in the lower part of Table 6-3, are expected to occur from the operation of the facility. The following technology-related factor was identified as the main driver for significant impacts (on the environmental factors soil, water, flora, fauna, landscape, and biodiversity):

- risk of accidents, explosions, fires.

In addition, there are **potentially significant impacts** from the facility itself (i.e. buildings, infrastructure and installations) as well as from the operation of the facility which depend on the exact location and local surrounding of the facility. This site-dependency is indicated by dashed borders in the lower part of Table 6-3.

The facility itself potentially causes significant impacts on the environmental factors soil, water, flora, fauna, landscape, and biodiversity due to the following technology-related factor:

- drain on land resources due to soil sealing and compaction, leading to loss of habitats, species diversity and landscape elements.

However, facility-related impacts due to soil sealing and compaction are only considered to be significant in case the facility is being built on a greenfield site or if a previously unsealed brownfield site is being (partially) sealed.

Furthermore, the operation of the facility might lead to potentially significant impacts on the environmental factor water by:

- drain on water resources for production (site-specific ranking “C” or “E”)
- emission of nutrients (site-specific ranking “D” or “D/E”).

Regions with water shortage in the warmer season as well as ecologically sensitive areas could be affected. A careful site-specific investigation has to be done in advance to exclude significant adverse impacts. In case mitigation should not be possible, other locations have to be taken into account.

Comparison of systems

Overall, the differences between the D-Factory scenarios and their competing reference systems are expected to be relatively small. Impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible.

In conclusion, the downstream processing facility should ideally be built on a (previously sealed) brownfield site in an area without water scarcity.

Table 6-3: Technology-related impacts expected from the implementation of the D-Factory system and its competing reference systems, respectively. Impacts are ranked in five comparative categories; "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Mari-gold	Soy-bean	Wheat	Spinach	Rape-seed
(Algal) biomass provision									
Impacts resulting from construction									
Construction works	C	C	C	C	C	C	C	C	C
Impacts related to the facility itself (F) and/or from operation (O)									
Soil sealing	E	D/E	D/E	D/E	n.a.	n.a.	n.a.	n.a.	n.a.
Soil erosion	n.a.	n.a.	n.a.	n.a.	D	D	C	D	D
Soil compaction	E	D/E	D/E	D/E	D	D	C	D	D
Loss of soil organic matter	n.a.	n.a.	n.a.	n.a.	D	C	D	D	C
Soil chemistry/fertiliser	n.a.	n.a.	n.a.	n.a.	E	D	D	E	D
Weed control/pesticides	n.a.	n.a.	n.a.	n.a.	E	E	E	E	E
Loss of habitat types	E	D/E	D/E	D/E	D	E	D	D	D
Loss of species	E	D/E	D/E	D/E	C	E	D	D	D
Barrier for migratory animals	E	E	E	E	n.a.	n.a.	n.a.	n.a.	n.a.
Loss of landscape elements	D	D	D	D	D	E	C	D	C
Risk for iLUC	C/E	C/E	C/E	C/E	D	E	D	D	D
Drain on water resources	E	D/E	D/E	D/E	E	D	C	E	D
Emission of nutrients (to water)	E	D/E	D	D	E	D	D	E	D
Emission of gases/fine dust (to air)	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Traffic (collision risk, emissions)	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Disposal of wastes/residues	D	C/D	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Accidents, explosions, fires, GMO	C	C	C	C	n.a.	E	n.a.	n.a.	n.a.
Downstream processing									
Impacts resulting from construction									
Construction works	C	C	C	C	C	C	C	C	C
Impacts related to the facility itself									
Buildings, infrastruct. & installations	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E
Impacts resulting from operation									
Drain on water resources	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E
Emission of nutrients (to water)	D	D	D	D	D	D	D	D	D
Emission of gases/fine dust (to air)	C	C	C	C	C	C	C	C	C
Traffic (collision risk, emissions)	C	C	C	C	C	C	C	C	C
Disposal of wastes/residues	C	C	C	C	C	C	C	C	C
Accidents, explosions, fires, GMO	C	C	C	C	C	C	C	C	C

Potential impacts

Likely significant impacts

Potentially significant impacts depending on the exact location and local surrounding of the facility

7 Recommendations

Based on the conclusions drawn in chapters 5 and 6, the following recommendations can be made to businesses, science, policymakers and consumers from an environmental perspective:

To businesses

Dunaliella salina-based algae biorefineries following the concept developed in this project can be set up in the near future. Depending on how much is invested in further optimisation and whether algae extracts are separated into several products or sold as such, environmental impacts can be very high or low. From an environmental perspective, the following recommendations should be considered to reduce impacts to adequate levels. Here, product use must be differentiated: if clinical studies demonstrate that *9-cis* β-carotene has novel medical value, i.e. it is a new medicine with no alternative, different environmental demands must be placed on the product than if 'only' nutraceuticals were produced, independent of the medicinal value of *9-cis* β-carotene. In the former case, it would be sufficient to reduce the environmental burdens as far as possible, in the second case more stringent requirements apply in order actually generate environmental benefits:

- **If a *Dunaliella* biorefinery is built, because clinical studies demonstrate a novel benefit of *9-cis* β-carotene,** include the following points in your **biorefinery concept design** to limit the environmental burdens to an acceptable level:
  - **Only split up the carotenoid extract into its components instead of selling *9-cis* β-carotene as part of this mixture, if required for medical reasons or if new purification methods are confirmed to be sufficiently efficient.**
    If initial indications are confirmed that *9-cis* ß-carotene in extracts displays similar efficacy to the pure substance, the carotenoid extract does not need to be fractionated. It is only advantageous from an environmental standpoint if burdens that may be saved thanks to additional co-products are higher than burdens caused by required additional downstream processing. This is not the case for modelled versions of these processes. Therefore, first, the efficacy of the extract should be compared to that of the pure substance in the clinical trials still to be performed. Second, newly developed more environmentally friendly downstream processing methods using modular high performance countercurrent chromatography (HPCCC) should be investigated in more detail.
  - **Select a site that facilitates the integration with existing facilities for producing salt products or seawater desalination facilities.** In particular, this is necessary to minimise the environmental burdens of energy and material use, impacts on local freshwater availability and of the disposal of saltwater. The following measures can contribute to this:

    

    - Develop concepts for internal recycling of the medium and/or a cascading use of brine in the participating facilities. Select the concept that leads to the lowest overall environmental impacts considering the availability of the medium, medium reconditioning, wastewater treatment and downtime due to contamination. A screening LCA of selected aspects may support this selection process.

- Guarantee sufficient availability of freshwater, in particular at inland sites in semi-arid and arid regions, but also in the Mediterranean region. Existing water uses in the respective catchment area must be taken into consideration. The use of fossil groundwater is not sustainable.
- Devise a concept for disposing of the remaining wastewater with a high salt load without causing ecological harm. It is expected that this will be easier in coastal locations.

Regardless of where a facility is eventually built, a specific environmental impact assessment must be performed compliant with Directive 2014/52/EU.

- **Wherever possible, select a site that cannot be used agriculturally (*brownfield site*) and was previously sealed.** If this is not feasible, sealing agricultural land can be acceptable under two conditions: (1) Lower value biomass streams are converted into co-products such as feed or fatty acids for oleochemistry in substantial quantities and high quality. In this way, other agricultural products can be substituted to reduce the overall demand for agricultural land. (2) Ecological compensation areas must be created according to the results of a site-specific environmental impact assessment. Whatever the case, avoid particularly ecologically valuable areas.

- **Install photovoltaic systems** to produce as much of the required electricity on site as possible. One option is to install only limited capacity at the outset and to set aside land for an extension once more data from actual operations allow for analysing and adjusting load and demand profiles. Additional modules could be financed from the first revenues. A second option would be to install sufficient solar power capacity from the outset and to feed excess power into the grid.

- If you are planning to build a *Dunaliella* algae biorefinery to supply **natural and environmentally friendly nutraceuticals independent of the medicinal value of *9-cis* β-carotene**, you should ensure that the biorefinery truly contributes to mitigating environmental burdens. This is not possible with exactly those processes that are described in the analysed scenarios. Therefore, the following improvements have to be implemented before:
  - **Confirm that new downstream processing technologies** meet expectations to sufficiently decrease energy and material consumption.

  Once this is achieved, the following measures have to be adopted in addition:
  - **Strictly limit the land used to unused infertile land** without ecologically particularly valuable areas.
  - **Optimise the whole process** so that efficiencies close to what is depicted in the scenarios under optimistic conditions are achieved.

  - **Ensure that lower value biomass streams are converted into co-products** such as feed or fatty acids for oleochemistry **in substantial quantities and high quality**.
  - Conduct a **comprehensive life cycle assessment** once concrete concepts or plans are available, to verify the intended environmental benefits. In addition, a specific environmental impact assessment must be performed for the planned site compliant with Directive 2014/52/EU.

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To science

The most important contribution of science to an environmentally friendly *Dunaliella* biorefinery is to **gather knowledge for process optimisation**. This should aim at reducing the current high uncertainty with regard to the performance of the whole process chain. In this way, concrete optimisation measures can be identified to reduce environmental impacts to an absolute minimum.

- **Verify the novel medicinal value of *9-cis* β-carotene as a pure substance and in mixtures in an adequate clinical trial**.
- Continue the **development of an efficient process chain in downstream processing of carotenoid extracts** based on a new concept. Using the modular high-performance countercurrent chromatography (HPCCC) system newly devised within this project, possibly integrated with membrane technology in a compact system, is expected to be the most promising approach for this.
- Study the **conversion of lower value biomass streams into co-products** such as feed or fatty acids for oleochemistry in more detail once substantial amounts of these biomass fractions are available.
- Further develop **ideas for high-value products** such as anti-diabetic pharmaceuticals, specialty food ingredients, etc., which came up during this project, into **concrete process designs**. Based on a sustainability assessment, it can then be assessed whether they should be integrated in the biorefinery concept.
- **Collect and publish existing biotechnological knowledge on efficient *Dunaliella salina* cultivation** and possible disturbances that can cause the collapse of cultures and production downtimes.

To consumers

- **Carotenoids should only be taken as dietary supplements if there are health indications for this.**
  
  The consumption of dietary supplements is a lifestyle trend often encouraged by the media and the advertising industry based on somewhat dubious science. In many cases, however, dietary supplements do promote the health of certain groups, e.g. people with pre-existing conditions. Production of high-quality natural carotenoids, in particular zeaxanthin and lutein, is not currently feasible without substantial environmental burdens. Carotenoids should therefore only be consumed as dietary supplements by people who need them for health reasons [MedlinePlus n.d.]. In addition, a nature-identical synthetic alternative, which causes much lower environmental impacts, is available for (*all-trans*) β-carotene. Although many studies on animal establish that natural *9-cis* β-carotene from algae is better for health than *all-trans* β-carotene from other sources (e.g. [Ben-Amotz et al. 1989]), there is no accepted proof that the natural algae alternative is more effective in humans [European Commission & European Food Safety Authority (EFSA) n.d.]. Therefore, the nature-identical alternative should be preferred as long as no further evidence arises.
- **Be prepared to spend more money for healthy, sustainable nutrition.**
  

  Sustainable production of foodstuffs and dietary supplements is generally associated with higher costs than production based on resource exploitation. This applies to all foodstuffs, including algae-based products, in particular. If nature-identical synthetic products like (*all-trans*) β-carotene are available, they can however be significantly cheaper and better for the environment as to be seen in this case.

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To policymakers

Algae cultivation has raised high hopes for environmentally friendly production of various bio-based products. Using the example of a *Dunaliella* biorefinery, this study has shown that algae-based products are not necessarily environmentally friendly. **Certain boundary conditions need to be in place and efficiency still needs to increase to reach this goal.** Politics can support both by the following measures:

- Algae cultivation and use needs experience in large demonstration or small industrial scale facilities over several seasons in continuous operation to advance. The current limit of knowledge is reflected in the large uncertainty with regard to the anticipated environmental impacts. *Dunaliella salina*-based algae biorefineries following the D-Factory concept could provide an additional module to fill this gap. If such projects are publicly supported, the following should be taken into account:
  - **Sufficient time should be allowed** for all necessary components to reach maturity. As also documented in this study, great improvements have been made, but the further optimisation potential still appears large.

  - After the improvement of central components mainly targeted in current approaches, **whole life cycles must be integrated and optimised** to achieve low environmental impacts. In this algae utilisation concept the focus is to be placed on substantially evolving or even redesigning downstream processing. Additionally, the following aspects should now be elaborated in more detail after the main processes of algae cultivation are set:
    - medium recycling concepts
    - the use of lower value biomass streams
    - the integration of heat and cooling (where applicable)
    - LCAs and analyses of local environmental impacts should accompany such processes to guide optimisation.
- Concepts for future algae cultivation and use perspectives need to be integrated into **overall European land use and decarbonisation concepts**. In particular, the following aspects should be taken into account:
  - Establish **land use plans for land that is not suitable for agriculture**, but which may be suited to photovoltaics and/or algae cultivation, to both avoid conflicts among these land use options and remove particularly ecologically valuable land from use.
  - Note **that the use of CO_2 by algae**, which is a variant of what is known as carbon capture and use (CCU), **does not intrinsically lead to any environmental benefits**. From a methodological perspective, CO_2 uptake and emission accounting for algae is no different to that for energy or industrial crops, which also initially take up a certain amount of CO_2. However, this is then emitted again, generally with a short delay, either during use or on disposal of the bio-based products. In contrast to the land-based crops, which take up CO_2 from the surrounding atmosphere, in algae cultivation CO_2 is generally used that is separated with energy input, and if necessary concentrated, from the exhaust gas streams of large emitters such as power stations, steelworks, cement works or chemicals industry facilities. Some of this CO_2 is emitted during algae production and some is incorporated as carbon in algae-based products. However, this 'interim storage' is only short-term and at the end of the life cycle of the algae-based products exactly the same quantity of CO_2, which would otherwise have been directly emitted by the industrial facility, is emitted again with minor delay. This is similar to most crops, which however capture CO_2 from air instead of flue gas. Shifting of CO_2 emissions using algae does not help the environment. If any kind of bonus or incentive would be available for such shifting, it may

Images from top to bottom: © luise/pixelio.de; Marco Barnebeck/pixelio.de even be counter-productive if it leads to a longer service life for the industrial facility. Additionally, care must be taken in CO_2 accounting that this fossil CO_2 either appears in the accounts of the large emitter or is passed on to the algae cultivation operator in the form of a CO_2 backpack. From the life cycle assessment perspective, only the first approach makes sense given the questions that currently have to be answered. For this reason, we have used it in our accounting and thus only attributed the additional expenditure for CO_2 separation (carbon capture) to algae cultivation. Against the backdrop of these deliberations, care must therefore be taken when developing accounting rules in directives, laws and regulations that the fossil CO_2 emissions do not remain disregarded twice. That is, the forwarded CO_2 may not be subtracted while at the same time the CO_2 emissions from use or disposal of the CCU products are set to zero.

- **Plans are required for synchronising the decarbonising processes and technologies based on CO_2 as an input substance, which will continue to grow in the future**, such as algae cultivation, power-to-X or carbon capture and storage (CCS). If the decarbonisation policy direction initiated today is successfully implemented in the coming decades, increasingly few CO_2 sources such as coal fired power stations will be available for CO_2 utilisation from exhaust gases in the future. Establish plans to synchronise the decarbonisation process and upcoming CO_2-based technologies, including algae cultivation, power-to-X and carbon capture and storage (CCS) to avoid misallocation of money and resources or unjustified delays in decarbonisation.

- **Focus development support for the algae industry on producing high-value, low-volume main products**. In this way, industrial production can be tested on a relatively small scale. This can then deliver insights into technological, practical and environmental aspects to adjust future plans.

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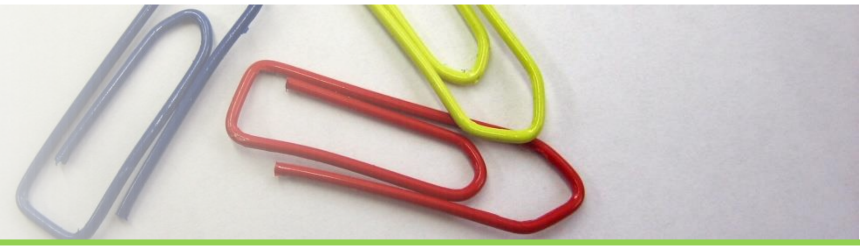

8 Annex

The annex provides the following additional information:

- Glossary and abbreviations (chapter 8.1)
- References (chapter 8.2)
- Detailed scenario schemes (chapter 8.3)
- Summary of quantitative input data (chapter 8.4)
- Further methodological aspects (chapter 8.5)
- Additional LC-EIA results: detailed conflict matrices (chapter 8.6)

8.1 Glossary and abbreviations

Agricultural land	Agricultural land is defined as land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.
Brownfield site	Land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.
CCS	Carbon capture and storage is the process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, and depositing it in e. g. underground geological formations.
CCU	Carbon capture and use summarises various process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, to use it for producing products (see also “algae cultivation” and “PtX”).
CO_2	Carbon dioxide
Disc-stack centrifuge	Conventional centrifuge using series of conical discs typically to remove small amounts of particles from large volumes of liquids in continuous operation. Also known as disc bowl centrifuge or conical plate centrifuge.
D-Factory	Project acronym, “*The Micro Algae Biorefinery*”
EIA	Environmental impact assessment
Freshwater	Freshwater refers to so called “blue water” used e.g. for algae cultivation or irrigation, which includes tap water, water from wells, rivers or lakes but not rainwater.
GMO	Genetically modified organism
Greenfield site	Land currently used for agriculture or (semi)natural ecosystems left to evolve naturally

HPCCC	High-performance countercurrent chromatography
HPLC	High performance liquid chromatography
IE	Inhabitant equivalent, A comparison of the magnitude – of different environmental impacts can be done on the basis of inhabitant equivalents. In this case, the impacts caused by a certain scenario are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region, in this case the EU 28. Thus one inhabitant equivalent corresponds to the annual emissions in that impact category for one average EU inhabitant.
ILCD	International Reference Life Cycle Data System
ILCSA	Integrated life cycle sustainability assessment is a methodology for comprehensive sustainability assessment of products. see also [Keller et al. 2015]
iLUC	Indirect land use change
LC-EIA	Life cycle environmental assessment is a methodology for the assessment of local environmental impacts that cannot (yet) be adequately covered by LCA.
LCA	Life cycle assessment
LCI	Life cycle inventory, its creation is part of an LCA study
LCIA	Life cycle impact assessment, part of an LCA study
N_2O	Nitrous oxide
PBR	Photobioreactor, a closed system of transparent tubes or other containers for algae cultivation using sunlight.
Photoautotrophic	Photoautotrophic microorganisms use sunlight as their energy source.
PtX	Power-to-X is used to summarise processes that use excess electric power, which is supposed to come from renewable sources in the future, to synthesise chemicals from substances such as water and CO_2.
PV	Photovoltaic
$scCO_2$	Supercritical carbon dioxide, can be used as solvent for extraction processes.
SEA	Strategic environmental assessment
Spiral-plate centrifuge	Innovative centrifuge using spiral plates. In this project a model from project partner Evodos replaces conventional disc-stack centrifuges.

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8.3 Detailed scenario schemes

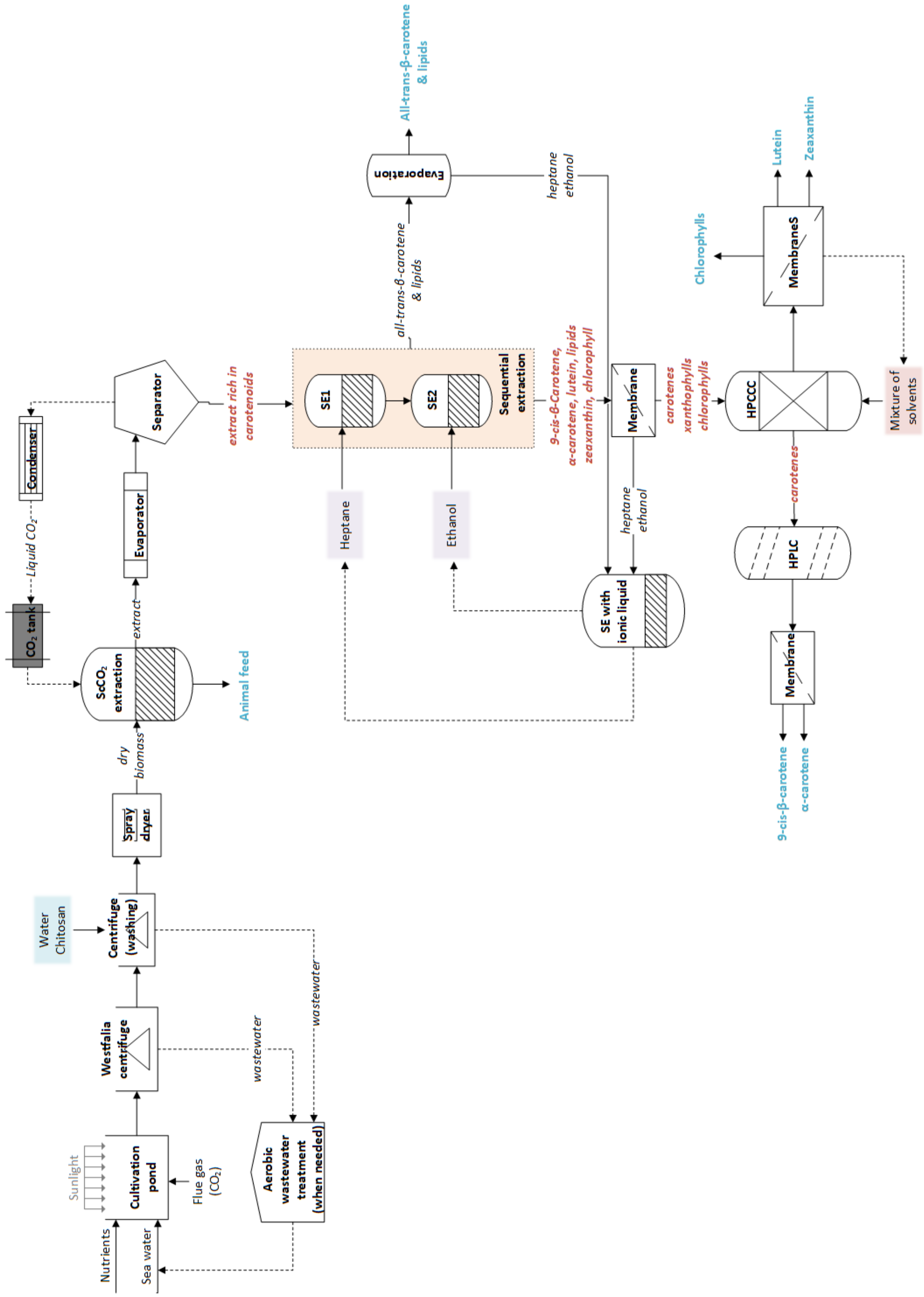

Figure 8-1: Detailed scheme of scenario 1, see chapter 4.2 for a description

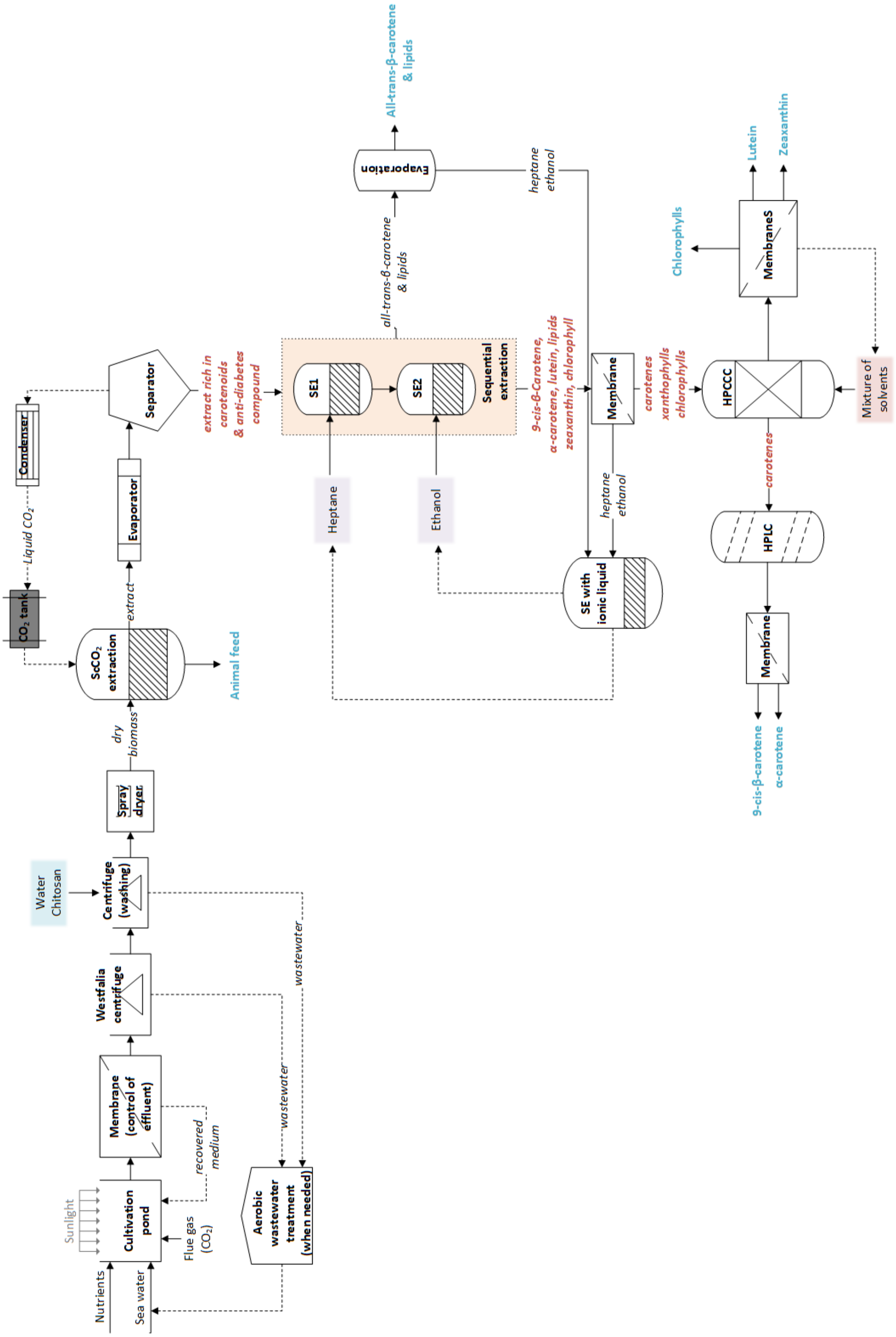

Figure 8-2: Detailed scheme of scenario 2, see chapter 4.2 for a description

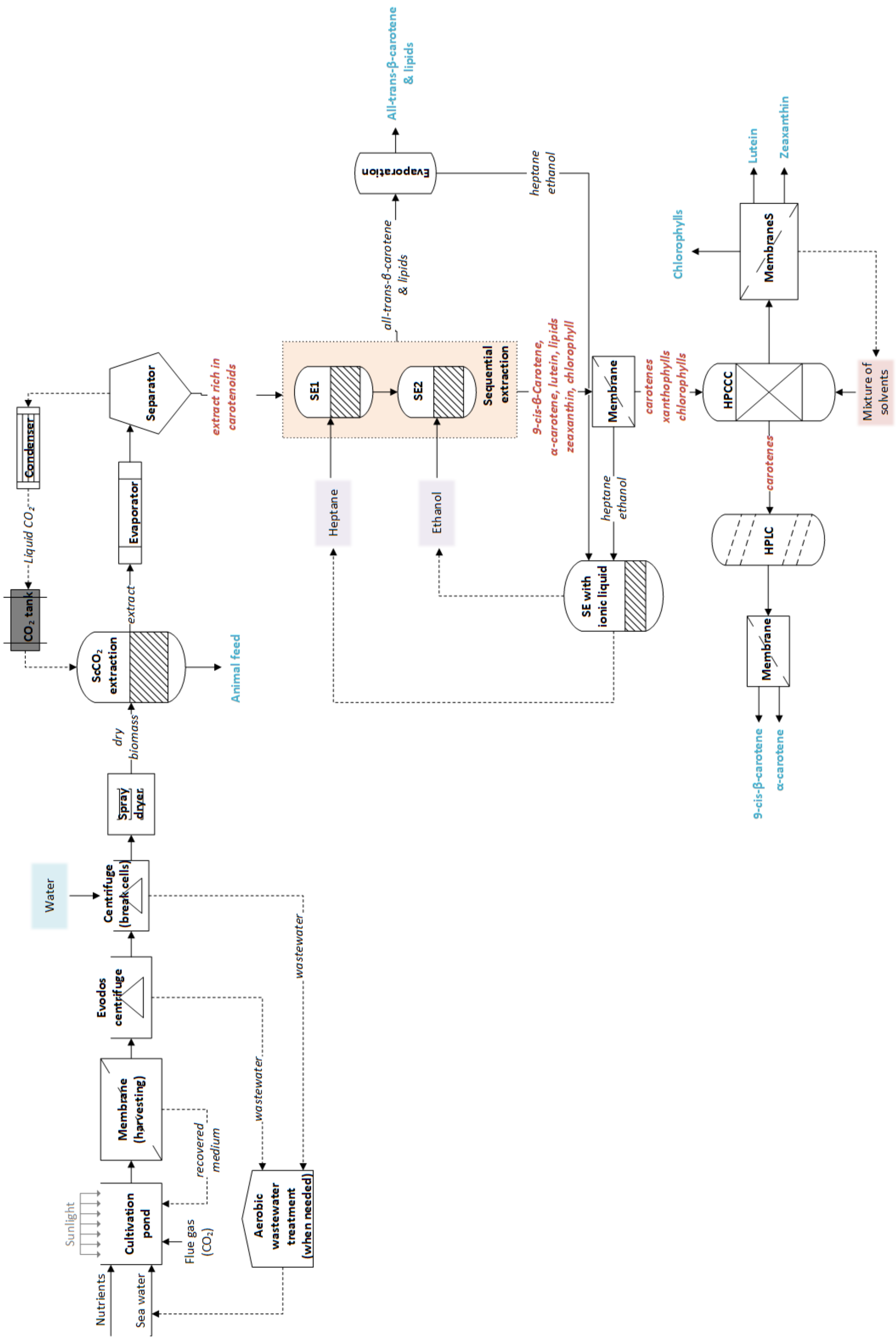

Figure 8-3: Detailed scheme of scenario 3 (whole cell harvest), see chapter 4.2 for a description. Scenario 5 and 6 are truncated versions of scenario 3 ending with the intermediates 'carotenes' and 'extract rich in carotenoids', respectively.

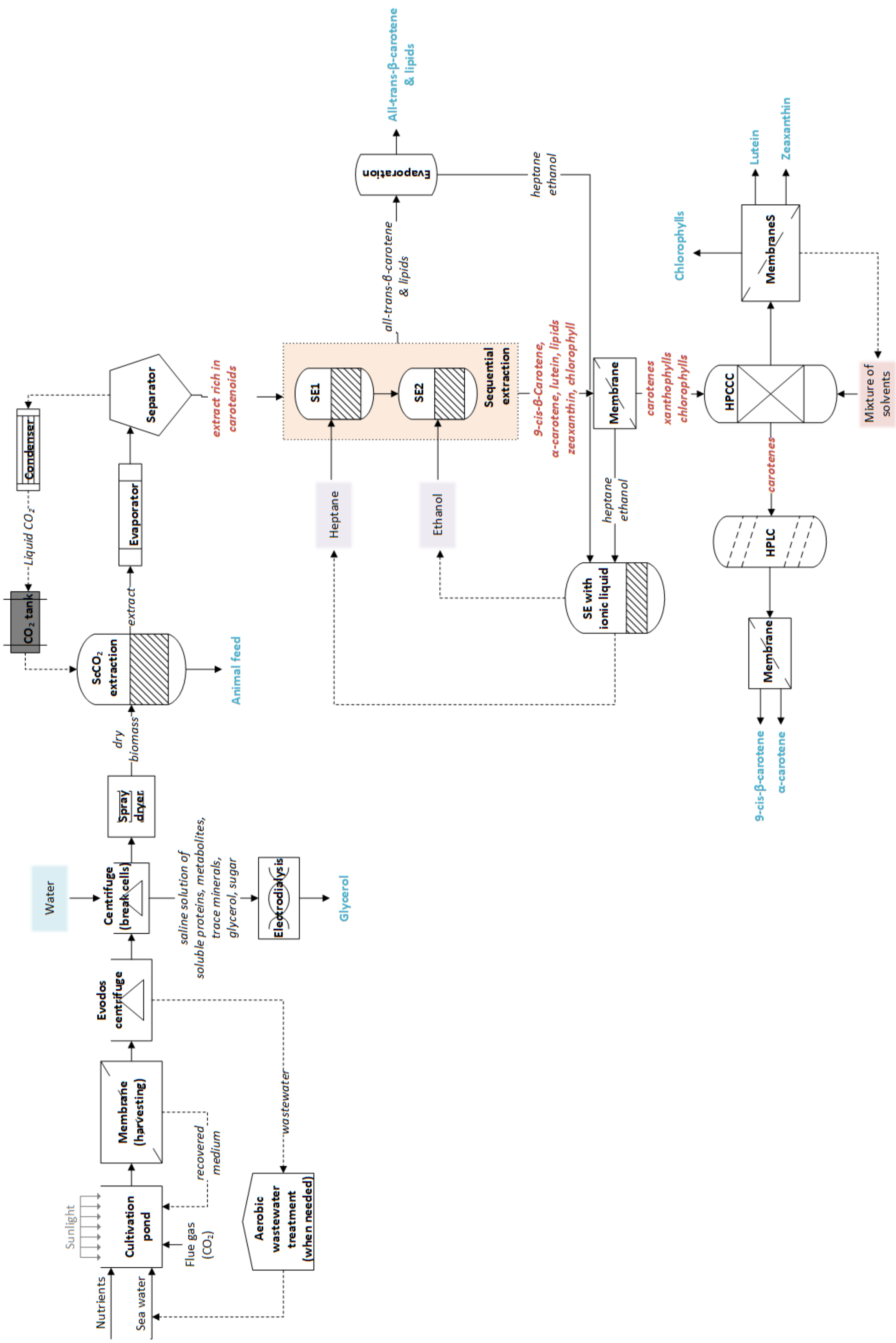

Figure 8-4: Detailed scheme of scenario 4, see chapter 4.2 for a description

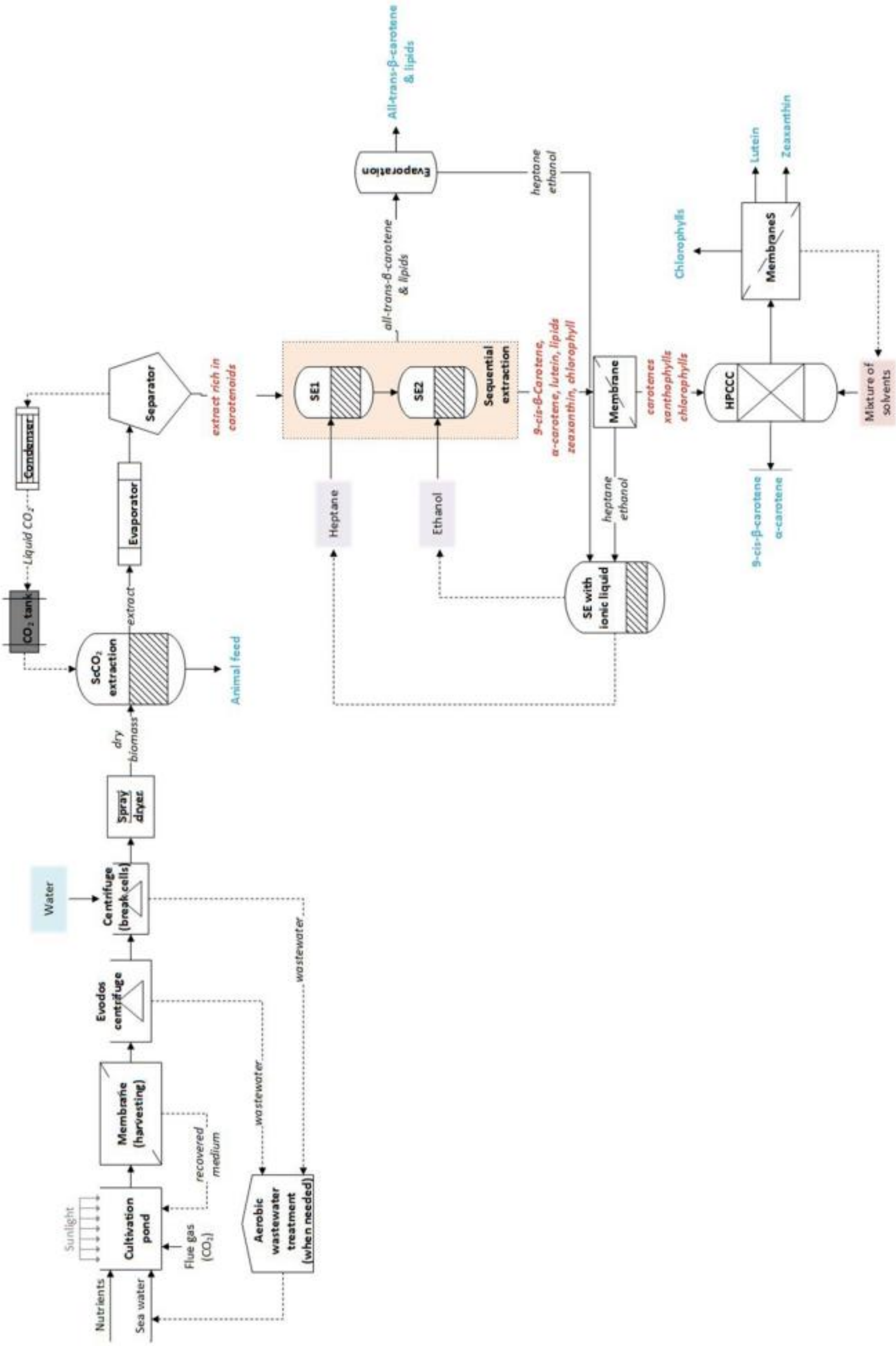

Figure 8-5: Detailed scheme of scenario 5, see chapter 4.2 for a description

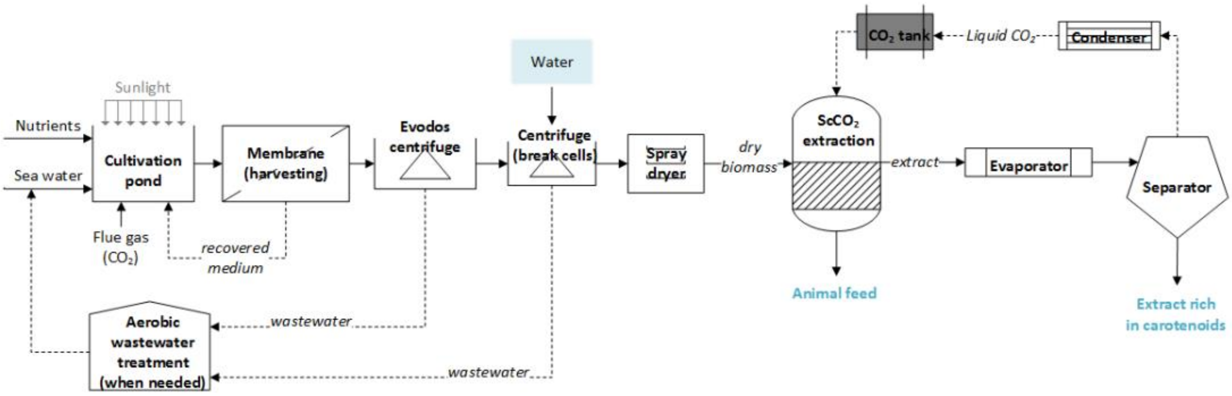

Figure 8-6: Detailed scheme of scenario 6, see chapter 4.2 for a description

8.4 Summary of quantitative input data

Input data for the LCA calculations are summarised in this chapter.

8.4.1 Algae cultivation and processing

All scenarios described in chapter 4.2 were analysed based on a quantitative model. The most important data resulting from this model are summarised in Table 8-1 and Table 8-2.

Potential direct emissions from algae cultivation and wastewater treatment ponds in particular of N_2O and dimethyl sulphide were taken into account [Alcántara et al. 2015; Fagerstone et al. 2011; McCoy et al. 2015; Mezzari et al. 2013; Myhre et al. 2013]. However, they were found to be irrelevant for the results of this study.

Table 8-1: Summary of most important energy and material inputs and outputs, part 1: scenarios 1 – 3. All data refers to 1 year of facility operation.

		1 Initial Configuration		2 Membrane pre-concentration		3 Whole cell harvesting	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
CULTIVATION, HARVESTING AND WASHING							
Inputs							
Brine	m³	729 000	662 000	36 000	132 000	36 000	132 000
Fresh water	m³	364 000	331 000	18 000	66 000	18 000	66 000
KNO_3	kg N content	7 600	3 800	7 600	3 800	7 600	3 800
H_3PO_4	kg	7 600	3 800	7 600	3 800	7 600	3 800
$MgSO_4$	kg	12 200 000	6 000 000	600 000	1 200 000	600 000	1 200 000
CO_2	t	430	210	430	210	640	320
Further information							
Total Land area	ha	20	20	16	17	16	17
Production pond surface area	ha	14	14	14	14	14	14
Days of operation per year	d	330	300	330	300	330	300
GLYCEROL RECOVERY							
(Inputs contained in overall energy demand)							
Outputs							
Product: glycerol	t	0	0	0	0	0	0
DRYING							
Input							
Natural gas	t	20	25	20	25	20	25
$scCO_2$ EXTRACTION							
Input							
CO_2 (from bottles)	t	110	230	110	230	170	340
Output							
Product: Feed	t AFDW	120	60	120	60	170	90

		1 Initial Configuration		2 Membrane pre-concentration		3 Whole cell harvesting	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
HEPTANE/ETHANOL EXTRACTION							
Input							
Heptane	kg	460 000	210 000	460 000	210 000	690 000	310 000
Ethanol	kg	640 000	290 000	640000	290000	950 000	430 000
Ionic liquid	kg	270 000	120 000	270000	120000	400 000	180 000
Output							
Pure all-trans beta carotene	t BC	5.5	2.2	5.5	2.2	6.4	2.5
Pure lipids	t	12	5	12	5	37	15
HPCCC							
Input							
		Confidential					
Output							
Product: Pure chlo-rophylls	t	0.7	0.2	0.7	0.2	1.0	0.3
Product: Pure lutein	t	0.3	0.1	0.3	0.1	0.4	0.1
Product: Pure ze-axanthin	t	0.1	0.0	0.1	0.0	0.2	0.1
HPLC							
Input							
Solvents - methanol	kg	380 000	170 000	380 000	170 000	570 000	260 000
Output							
Product: *9-cis* beta carotene (pure or in mixtures)	t	4.0	1.1	4.0	1.1	4.8	1.4
Product: Pure α-carotene	t	0.9	0.2	0.9	0.2	1.3	0.4
OVERALL ENERGY DEMAND							
Power	kWh	55 000 000	26 000 000	54 000 000	26 000 000	80 000 000	38 000 000
Heat	MJ	3 300 000	1 800 000	3 300 000	1 800 000	4 900 000	2 700 000

Table 8-2: Summary of most important energy and material inputs and outputs, part 2: scenarios 4 – 6. All data refers to 1 year of facility operation.

		4 Glycerol recovery		5 Shorter downstream processing		6 No carotenoid separation	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
CULTIVATION, HARVESTING AND WASHING							
Inputs							
Brine	m^3	36 000	132 000	36 000	132 000	36 000	132 000
Fresh water	m^3	18 000	66 000	18 000	66 000	18 000	66 000
KNO_3	kg N content	7 600	3 800	7 600	3 800	7 600	3 800
H_3PO_4	kg	7 600	3 800	7 600	3 800	7 600	3 800
$MgSO_4$	kg	600 000	1 200 000	600 000	1 200 000	600 000	1 200 000
CO_2	t	640	320	640	320	640	320
Further information							
Total Land area	ha	16	17	16	17	16	17
Production pond surface area	ha	14	14	14	14	14	14
Days of operation per year	d	330	300	330	300	330	300
GLYCEROL RECOVERY							
(Inputs contained in overall energy demand)							
Outputs							
Product: glycerol	t	14	6	0	0	0	0
DRYING							
Input							
Natural gas	t	20	25	20	25	20	25
$scCO_2$ EXTRACTION							
Input							
CO_2 (from bottles)	t	170	340	170	340	170	340
Output							
Product: Feed	t AFDW	170	90	170	90	170	90
HEPTANE/ETHANOL EXTRACTION							
Input							
Heptane	kg	690 000	310 000	690 000	310 000	0	0
Ethanol	kg	950 000	430 000	950 000	430 000	0	0
Ionic liquid	kg	400 000	180 000	0	0	0	0
Output							
Pure all-trans beta carotene	t BC	6.4	2.5	6.4	2.5	0.0	0.0
Pure lipids	t	37	15	21	8	0	0

		4 Glycerol recovery		5 Shorter downstream processing		6 No carotenoid separation	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
HPCCC							
Input							
				Confidential			
Output							
Product: Pure chlorophylls	t	1.0	0.3	1.0	0.3	0.0	0.0
Product: Pure lutein	t	0.4	0.1	0.4	0.1	0.0	0.0
Product: Pure zeaxanthin	t	0.2	0.1	0.2	0.1	0.0	0.0
HPLC							
Input							
Solvents - methanol	kg	570 000	260 000	0	0	0	0
Output							
Product: *9-cis* beta carotene (pure or in mixtures)	t	4.8	1.4	5.1	1.7	5.6	2.7
Product: Pure α-carotene	t	1.3	0.4	0.0	0.0	0.0	0.0
OVERALL ENERGY DEMAND							
Power	kWh	80 000 000	38 000 000	6 300 000	4 300 000	2 200 000	2 400 000
Heat	MJ	4 900 000	2 700 000	4 900 000	2 700 000	1 600 000	1 200 000

8.4.2 Normalisation factors

The factors used to normalise the environmental impacts are:

Table 8-3: EU 25+3 inhabitant equivalents (IE) for the year 2000 [CML 2016; Eurostat 2007; Ravishankara et al. 2009]

Impact category	Inhabitant equivalent	
Global warming	10 581	kg/yr
Ozone depletion *	0.07	kg/yr
Photochemical smog	20	kg/yr
Human toxicity (respiratory inorganics)	40	kg/yr
Acidification	70	kg/yr
Eutrophication	5.8	kg/yr
Resource depletion: Non-renewable energy *	82.09	GJ/yr

*: As described in chapter 3.2.2, these indicators deviate from the CML methodology and thus adapted normalisation factors were used.

Due to the uncertainty related to future emissions of various substances, the IE are calculated based on the latest available emission data (CML: base year 2000). These values are subsequently used to normalise data which are calculated for 2025. To ensure comparability, results for the Indian case studies are also normalised using the EU inhabitant equivalents for EU27.

8.5 Further methodological aspects

According to chapter 3.2.1, consequential modelling is applied in this screening LCA. This includes the evaluation of consequences an additional use of limited resources can have. The newly established system can e. g. cause the displacement of another user of this resource. Therefore, it has to be analysed, which resources used by algae production may be limited. This is discussed here for CO_2 and infertile land.

8.5.1 CO_2 as potentially limited resource of the future

Many national and international decarbonisation strategies aim at reducing CO_2 emissions by ¾ or more in the coming decades. This implies that all avoidable sources of CO_2 such as fossil fuel power plants will have to be shut down. Furthermore, CO_2 from left over point sources like cement factories, ammonia plants or bioenergy plants will not be a largely unused resource any more but become limited. Depending on the decarbonisation strategy, this CO_2 could either be captured and stored (CCS) or used (CCU). In particular, various Power-to-X technologies may compete for CO_2 from point sources. Algae cultivation may thus compete with CCS and/or power-to-X (PtX) for the same CO_2 resources. This may lead to less CCS, installation of CO_2 capture from air or even a later shut-down of fossil fuel power plants. In all cases, the environmental burdens of CO_2 use are likely to increase along with the progress in decarbonisation within a few decades. This has to be taken into account for the evaluation of future perspectives of algae cultivation. However, concentrated sources of CO_2 will still be abundant in 2025, the reference year of this study. Therefore, scenarios do not contain the displacement of other CO_2 users.

8.5.2 Infertile land as potentially limited resource of the future

Even the use of infertile land may compete with other uses such as the installation of solar power/photovoltaic (PV) systems as these use options may favour similar types of locations with high solar irradiation and certain infrastructure. This competition is expected to increase as the use of solar power is a central element of future energy concepts. Nevertheless, substantial competition, which would also be visible as rise in prices for infertile land, is not expected by 2025. Therefore, scenarios do not contain the displacement of PV installations if infertile land is used.

8.6 Additional LC-EIA results: detailed conflict matrices

8.6.1 Agricultural raw materials

In this chapter, detailed information and impact matrices for dedicated crops can be found which in chapter 6.2 were only presented in an aggregated table.

Soybean

Based on the high content of oil and protein soy is one of the dominant plants in global agriculture. In 2010 about 260 million tons of soy was produced according to the Food and Agriculture Organisation of the United Nations [FAOSTAT 2017].

Soy is an annual crop usually grown on loose soils which are easily warmed up and provide a high water capacity. Due to high demands on temperature and climate it is basically grown in warmer regions/countries out of Europe such as USA, Brazil and Argentina.

Especially during the last years, genetically modified soy seeds resistant against Glyphosate ("round up") were used allowing airborne application of fertiliser and pesticides on a large scale. As a consequence health problems in the vicinity of treated fields as well as the explosion of Glyphosate-resistant "super-weeds" were observed [Antoniou et al. 2010]. Table 8-4 summarises the risks associated with cultivation of soybean on the environmental factors.

Table 8-4: Risks associated with the cultivation of soybean compared to the reference system idle land.

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants/ Biotopes	Animals	Climate/Air	Landscape	Human health and recreation	Bio-diversity
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative	negative	negative				neutral
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching	negative	negative							
Water demand		negative	negative	neutral	neutral				neutral
Weed control / pesticides		negative	negative	negative	negative			negative	negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral	neutral				neutral
Loss of species				neutral	neutral				neutral

Rapeseed

Rapeseed is generally grown on deep loamy grounds and requires adequate lime content and constant water supply. On heavy soils the production requires good nutrient supply with homogeneous precipitation. Both shallow and sandy soils lead to minor yields as rapeseed needs a high rooting depth. High efforts in weed/pest control is necessary as rapeseed is sensitive against diseases (e.g. fungi) and certain vermin beetles (e.g. cabbage stem flea beetle *Psylliodes chrysocephala* and cabbage stem weevil *Ceutorhynchus napi*). Furthermore rapeseed needs high doses of nitrogen (110-220 kg/ha) with an increased danger of nutrient leaching and eutrophication especially on groundwater. With a fruit to straw ratio of about 1:2,9 [Kaltschmitt et al. 2009] ploughing of straw after harvesting e.g. in case of biodiesel production can contribute to soil balance although the residues provide high nitrogen doses in the soil thus enhancing the risk of nutrient leaching.

Potential impacts on soil fertility can be minimised with rotational cropping e.g. using rapeseed as a winter crop. Due to its intensive rooting and a dense coverage it is often used as a starter crop for early wheat seeds. Although rapeseed is cultivated in monocultures thus affecting the biodiversity of epigeous fauna the blossoms attract flower-visiting insects with a promoting effect on animals and biodiversity. Table 8-5 summarises the risks associated with cultivation of rapeseed on the environmental factors.

Table 8-5: Risks associated with the cultivation of rapeseed compared to the reference system idle land.

Type of risk	Affected environmental factors								
	Soil	**Ground water**	**Surface water**	**Plants/ Biotopes**	**Animals**	**Climate/ Air**	**Landscape**	**Human health and recreation**	**Bio-diversity**
Soil erosion	neutral/ negative[1]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral/ negative[1,2]			neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1]
Soil chemistry / fertiliser	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative	negative/ positive[2]				negative/ positive[2]
Loss of species				neutral/ negative	negative/ positive[2]				negative/ positive[2]

1: Negative impact can be minimised in case of double cropping, if used as a starter crop

2: Negative because of low biodiversity due to monoculture but increased number of blossom visiting insects during flowering period

Cereals

Cereals do not differ in the requirements for soil quality. They are grown on deep, heavy and nutrient-rich high quality soils. Intensive agricultural use primarily leads to negative impacts on soil. Prevention from diseases, weed and pest control is obligatory, increasing the risk of soil compaction, which is usually linked to negative aspects on the diversity of arable flora and epigeous fauna as well as the recharge rate of groundwater. Erosion effects due to lacking soil coverage can be minimised after harvesting with succeeding crops (e.g. sorghum). Especially the young plants require a dressing of nitrogen fertiliser (approx. 150 kg/ha) which increases the risk of nutrient leaching and eutrophication. The demand for lignocellulosic material might lead to the cultivation of high stem varieties, as they offer a higher yield of feedstock. This could lower the use of herbicides as long stem varieties are competitive against the arable flora. Depending on the type of landscape used for the cultivation, the impacts are variable. Barley plantations in potato regions would slightly increase habitat variety mitigating the adverse effects on animals, plants and biodiversity. Table 8-6 summarises the risks associated with cultivation of cereals on the environmental factors.

Table 8-6: Risks associated with the cultivation of cereals compared to the reference system idle land.

Type of risk	Affected environmental factors								
	Soil	**Ground water**	**Surface water**	**Plants/ Biotopes**	**Animals**	**Climate/ Air**	**Land-scape**	**Human health and recreation**	**Bio-diversity**
Soil erosion	neutral/ negative[2]		negative						
Soil compaction	neutral/ negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative[2]	negative[2]				negative
Soil chemistry / fertiliser	negative	negative							
Eutrophi cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative							
Water demand		negative		negative	negative				neutral
Weed control / pesticides		neutral/ negative[1,2]	neutral/ negative[1,2]	neutral/ negative[1,2]	neutral/ negative[12]				neutral/ negative[1,2]
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]
Loss of species				neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]

1: Negative in case of short-stalked varieties; long-stalked varieties afford less weed control

2: Negative impact can be minimised by crop rotation; e.g. winter wheat and/or double cropping

Spinach

Spinach (*Spinacia oleracea* L.) is an edible flowering plant in the family Amaranthaceae native to central and western Asia. Since its leaves are eaten as a vegetable, it belongs to the leaf vegetables. Spinach is also used for extraction of chlorophyll which is registered as a food additive/colorant (E140). In 2014, the world total production of spinach was 24.3 million tonnes, with China alone accounting for about 90 % of this quantity [FAOSTAT 2017]. The annual average production of spinach is around 10-30 tonnes/ ha, depending on the region (EU: ~20 tonnes $ha^{-1}yr^{-1}$).Cultivation of spinach quite intensive, involving both high fertilizer input and heavy pesticide use. Due to the latter, the Environmental Working Group ranks spinach second on the Dirty Dozen™ list of fruits and vegetables with the most pesticides, including the insecticide permethrin which is was found in 75 % of the samples and which is not permitted to be used on food crops in the EU [ewg.org 2017]. For this reason, the risks associated with nutrient input and pesticide use are especially pronounced. Table 8-7 summarises the risks associated with cultivation of spinach on the environmental factors.

Table 8-7: Risks associated with the cultivation of spinach compared to the reference system idle land.

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants/ Biotopes	Animals	Climate/ Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative						
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative	negative	negative					negative
Weed control / pesticides		negative	negative	negative	negative			negative	negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative	neutral/ negative				neutral/ negative
Loss of species				neutral/ negative	neutral/ negative				neutral/ negative

Marigold

Marigold (*Tagetes erecta* L.) is a flowering plant in the family Asteraceae native to the Americas. Despite its New World origin, it is often called African marigold. Apart from being used as an ornamental plant, marigold is cultivated commercially to extract lutein, a common yellow/orange food colour (E161b). The main cultivation areas are China (about 50 % of the world market), India (about 25 %), Thailand, Latin America and Africa. Marigold blooms annually from July to October, depending on the region. Fresh flowers, which are the raw material for lutein, are harvested manually and sent to processing factories. The annual average production of fresh flowers is 30-60 tonnes/ha. In China, farmers nurture marigold in greenhouses in mid-March and transplant the plants into fields after one month. Cultivation of marigold is quite intensive, involving both irrigation (5,000-10,000 m^3/ha, depending on irrigation method) and high fertilizer input, which typically amounts to 200–400 kg N, 150–300 kg P_2O_5 and 200–400 kg K_2O per hectare. Therefore, the risks associated with high water demand and nutrient leaching are especially pronounced. Although marigold is cultivated in monocultures thus affecting the biodiversity of epigeous fauna the blossoms attract flower-visiting insects with a promoting effect on animals and biodiversity. Table 8-8 summarises the risks associated with cultivation of marigold on the environmental factors.

Table 8-8: Risks associated with the cultivation of marigold compared to the reference system idle land.

Type of risk	Affected environmental factors							
	Soil	**Ground water**	**Surface water**	**Plants/ Biotopes**	**Animals**	**Climate/ Air**	**Land-scape**	**Human health and recreation**	**Bio-diversity**
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative						
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative	negative	negative					negative
Weed control / pesticides		negative	negative	negative	negative			negative	negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative	negative/ positive[1]				negative/ positive[1]
Loss of species				neutral/ negative	negative/ positive[1]				negative/ positive[1]

1: Negative because of low biodiversity due to monoculture but increased number of blossom visiting insects during flowering period

8.6.2 Fossil raw materials

Crude oil

Impacts of crude oil provision are expected to affect all environmental factors. The impacts are classified as unfavourable for the environment. Drilling processes especially in combination with the production of oil and water based mud and the huge demand of water [Ziegler 2011] bear significant risks for the environment. Further significant impacts are expected from transportation especially the implementation of pipelines.

The value chain includes high risks of environmental impacts due to accidental and operational discharges from provision, transport and use [GPA n.d.]. Basically the environmental factors soil, water, plants/biotopes, animals and biodiversity are affected. Table 8-9 summarises potential impacts on environmental factors on the value chains for both crude oil provision and gas provision as exploitation and refining are very often done simultaneously.

Table 8-9: Impacts on environmental factors related with the value chain of crude provision, compared to the reference system "no use". Potentially significant impacts are indicated by bold solid borders

Technological factor	**Affected environmental factors**								
	Soil	**Ground water**	**Surface water**	**Plants/ Biotopes**	**Animals**	**Climate/ Air**	**Land-scape**	**Human health and recreation**	**Bio-diversity**
Prospection	negative			**negative**	**negative**				negative
Drilling/ mining	negative	negative	negative	negative	negative		**negative**		**negative**
Waste (oil based and water based mud)	**negative**	**negative**	**negative**	**negative**	**negative**				negative
Demand of water (process water)		**negative**	**negative**	**negative**	negative		**negative**		**negative**
Emissions (exhaust fumes, water, metal)		negative	negative	negative	negative	negative		negative	
Land requirements	negative	negative	negative	negative	negative	negative	negative		negative
Demands of steel (tubes, equipment)	negative			negative	negative		negative		
Transportation (carriers, pipelines)	**negative**	negative	negative	**negative**	**negative**	negative	**negative**	negative	**negative**
Refining/ processing	negative	negative	negative	negative	negative		negative	negative	negative
Accidents (traffic, pipeline leakage)	**negative**	**negative**	**negative**	**negative**	**negative**		**negative**	**negative**	negative

Bold print and solid borders: Likely significant impacts

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