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Integrated sustainability assessment of algae-based polyunsaturated fatty acid production

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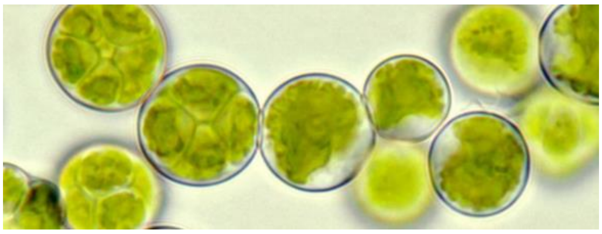

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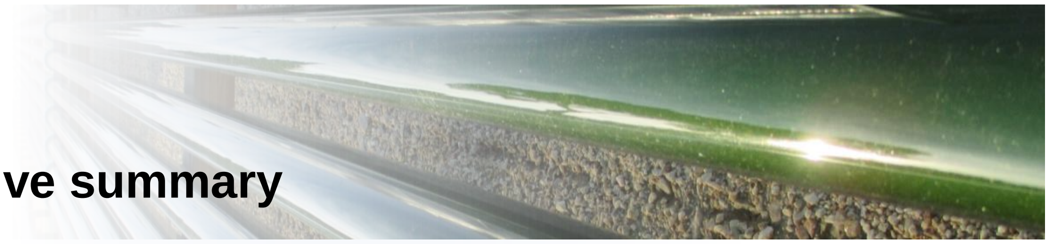


Executive summary

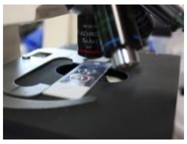
Polyunsaturated fatty acids (PUFAs), especially omega-3 fatty acids such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA) are very important constituents of a healthy human diet. 39Until today, certain wild-caught marine fish are the only major direct source in the human diet for these substances. However, marine resources are declining while the demand is increasing. The EU funded project "*The Value Chain from Microalgae to polyunsaturated fatty acids"* investigates new processes with algae to produce PUFAs using sunlight as energy source and CO_2 as carbon source.

An integrated sustainability assessment led by IFEU – Institute for Energy and Environmental Research Heidelberg, Germany, analyses the sustainability impacts of the newly devised processes (see chapter 2 for a description). It joins detailed analyses of technological, environmental and socio-economic aspects (see chapters 4.1 – 4.3 for summaries) into an overall picture and derives common conclusions and recommendations (chapters 4.4 and 5).

To this end, algae-based PUFA production was compared to alternatives for meeting additional PUFA demand using fish cuttings, by-catch or by means of fermentation. The aim is to arrive at conclusions on how and under what conditions algae-based biorefineries should be developed in line with the PUFAChain concept. The systems were therefore compared on the basis of scenarios modelling future, industrial-scale, mature processes.

Key insights are summarised below:

Potentials and need for optimisation



Enormous technological, environmental and socio-economic improvements to algae-based PUFA production were achieved in the course of this project. For example, environmental burdens per tonne of PUFAs can be reduced by up to 80–90% following the analysed scenarios and the costs can be reduced to 50% of the costs of competing PUFA production in the best case. A wide range of technical measures along the entire value-added chain were optimised in detail to achieve this. They include, for example, the use of new algae strains, optimisation of seasonality, site selection criteria, integration of renewable energy generated on site, such as solar electricity, with algae cultivation and many more. In addition, numerous other promising technologies not yet quantitatively modelled in the context of large-scale facilities were investigated in the project. They comprise extraction by means of propane or novel oleochemical purification processes for the extracted oils, for example. It should therefore be anticipated that dynamic technological developments will continue. This means that in the coming years additional breakthroughs, and therefore substantial improvements in technological, environmental and socio-economic sustainability, can be anticipated.

Advantages and disadvantages compared to alternatives

Analysis of the scenarios investigated in this project revealed that, in the coming years, PUFA production employing the PUFAChain concept will probably continue to result in

Images from top to bottom: © A4F – algae for future, Lisbon, Portugal; Martin Gapa/pixelio.de

greater global and regional environmental burdens such as acidification, eutrophication, ozone depletion or the use of non-renewable energy resources than competing systems. Impacts on climate change are also greater, but may be indirectly compensated if co-products can displace feeds particularly harmful to the climate from the market. However, it cannot be said with sufficient reliability whether this will actually be the case. From today's perspective, extracting PUFAs from the existing by-products of other processes such as fish cuttings and by-catch therefore tends to be more environmentally friendly.

With regard to other sustainability aspects, benefits result for PUFAs from algae[1] compared to competing systems. They are less dependent on limited resources such as fish cuttings, by-catch or arable land to produce sugar, which is required for fermentation. This can lead to lesser local environmental harm to flora, fauna, soils, etc. Moreover, no genetically modified organisms are used, which is often the case in fermentation. Under certain conditions, costs can even be pushed lower than those of the analysed competing products.

Perspectives

Whatever the case, it is better to produce PUFAs such as EPA and DHA, which cannot be extracted from the limited volume of fish cuttings or by-catch, using algae instead of relying on increased fishing to service the growing demand. Here, value-added chains adopting the biorefinery concept developed in this project have enormous potential if the technology and overall utilisation concept continue to be consistently developed. Here, one of the strengths of the concept is that primarily high value–low volume products are addressed and simultaneously large volumes of high quality feeds can be produced. This reduces the danger of future competition for sites and resources such as suitable CO_2 sources. In general, algae harbour great potential as a healthy and sustainable alternative in the food sector. This potential should be developed further, supported by comprehensive sustainability analyses, e.g. by means of integrated life cycle sustainability assessments (ILCSA).

Concrete recommendations to algae community in business and science, to policymakers and to consumers were derived from these conclusions which short, medium and long term action should be taken to improve the sustainability of algae-based PUFA production and which lessons can be learned for algae production and use in general. Besides further recommendations in chapter 5, these include in particular:

- Choose the site of a facility carefully because it can crucially influence profitability, environmental and social impacts. (to businesses and science).
- Use as much of your own renewable energy, in particular photovoltaics, as possible to run algae cultivation. (to businesses and science).

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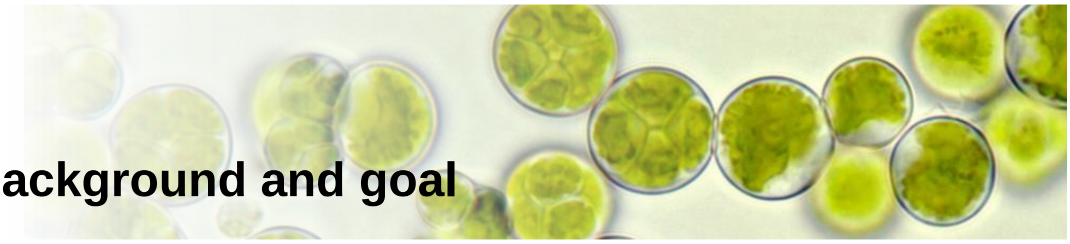
[1] In this report, ‘algae’ only refers to photoautotrophic (micro-)organisms, i.e. microorganisms that use light as an energy source. Heterotrophic microorganisms used in competing fermentation processes are often also termed ‘heterotrophic algae’, which is in conflict with current scientific consensus. Thus, 'algae cultivation' is used for the cultivation of photoautotrophic algae, while 'fermentation' refers to processes using heterotrophic microorganisms.

Image at top: © Rike/pixelio.de; image at bottom: © Jürgen Frey/pixelio.de

- Supplying the population with PUFAs such as EPA and DHA can initially be improved by promoting the use of fish residues and by-catch (to policymakers).
- Examine which regulatory requirements can be softened without sacrificing safety or support approvals financially in case of societal benefits. (to policymakers).
- Only take PUFAs as dietary supplements if this is beneficial for your personal health. (to consumers).
- Be open for new vegetable foodstuffs, e.g. from algae (to consumers).

These and other conclusions and recommendations are aimed at pointing the way to a concrete route for turning algae cultivation, in particular to produce high value food ingredients, into a future component of Europe's bioeconomy.



1 Background and goal

1.1 Background of the project

Polyunsaturated fatty acids (PUFAs), especially omega-3 fatty acids such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA) are very important constituents of human diet. An increasing number of connections between low PUFA diets and conditions such as cardiac diseases or attention deficit hyperactivity disorder is found and being researched. This increasing awareness and also the growing world population lead to an increasing demand for PUFAs. Until today, certain wild-caught marine fish are the only major direct source in the human diet for these substances. However, marine resources are declining while the demand is increasing. As a substitute, dietary supplements containing EPA and DHA are available on the market for which demand is growing. Nevertheless, also for capsules or functional food enriched with EPA and DHA, the fishing industry with its by-catch or fish scraps is the main natural source - but also this source is diminishing.

Microalgae are important primary producers of EPA and DHA and pass them on to shellfish, fish, and finally humans within the food web. Thus, they are a valuable alternative source, also because they can be produced in photobioreactors under controlled conditions and thus, free from pollutants. In the frame of the PUFAChain project (The Value Chain from Microalgae to PUFA), the feasibility of such a process is investigated. It is supported by the EU (GA number: 613303). For more information see www.pufachain.eu. The project partners cover all relevant steps along the value chain and investigate the process from finish to start: The rising demand of highly purified EPA and DHA for food and pharmaceutical applications primarily defines the quality of all downstream processes such as algal harvest, cell disruption, extraction and purification of the desired fatty acids.

1.2 Goal of this integrated sustainability assessment

The main motivation for this project is to provide DHA and EPA because it becomes increasingly difficult to sustainably satisfy the demand from the main conventional source, which is marine fish oil. However, a novel approach for DHA and/or EPA production via algae doesn’t automatically imply better sustainability performance. Therefore, it needs to be assessed for its sustainability, too. Furthermore, it has to be compared to other options of providing equivalent products to establish whether or under which conditions the approach followed in PUFAChain is more sustainable.

The overall sustainability assessment in PUFAChain is based on a life cycle approach. It takes into account the entire life cycle from “cradle” (= algae cultivation) to “grave” (e.g. end-of-life treatment) including the use of co-products (Fig. 1-1). The analysis of the life cycles within PUFAChain follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015]. The methodology builds upon and extends existing frameworks and standards [Andrews et al. 2009; ISO 2006a; b; JRC-IES 2012; Swarr et al.

Image: © SAG Culture Collection of Algae at Göttingen University, Göttingen, Germany

2011] (see chapter 2 for details). This report joins the detailed analyses of environmental, socio-economic and technological aspects [Keller et al. 2017; Reyer et al. 2017; van der Voort et al. 2017] (see chapters 4.1 – 4.3 for summaries) into an overall picture (chapter 4.4).

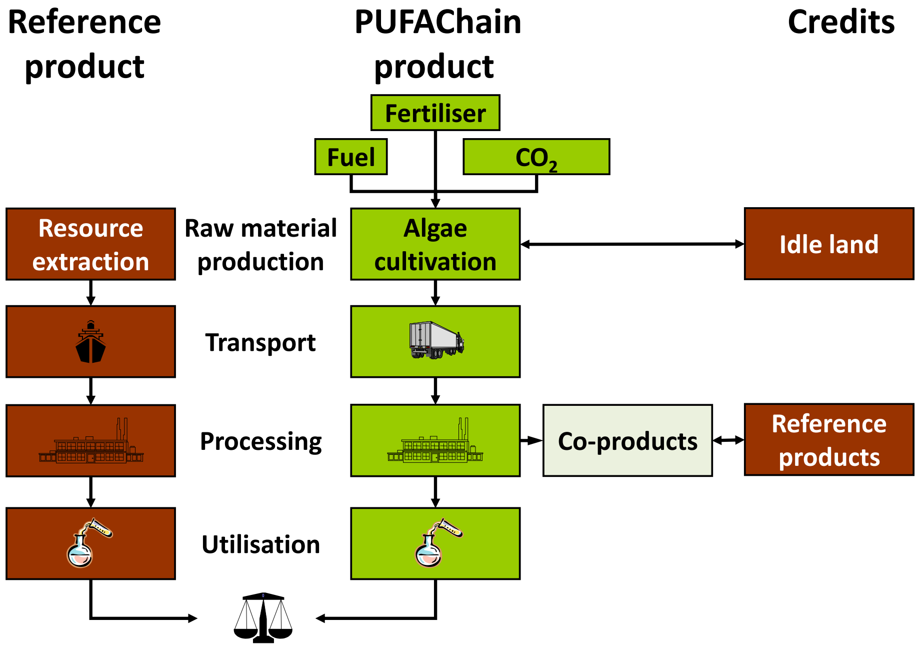


Fig. 1-1 Sustainability assessment in PUFAChain: The concept of life cycle sustainability assessment, which compares the whole life cycles of two products

2 Methodology and settings

The sustainability analysis in PUFAChain 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 chapters 2.1 and 2.3. Specific definitions and settings that are only relevant for the technological, environmental or socio-economic assessment as well as details on individual methodologies are described in the respective reports [Keller et al. 2017; Reyer et al. 2017; van der Voort et al. 2017].

2.1 Goal & scope questions

The integrated assessment of sustainability aims at answering a number of key questions, which have been defined and agreed on by the PUFAChain consortium. In the following, the list of key questions is given.

How and under which conditions can EPA and/or DHA production from algae cultures contribute to ensuring a sustainable supply of the world population with health-promoting omega-3 fatty acids?

This main question leads to the following sub-questions:

- Which EPA and/or DHA production concept from algae is best from a sustainability point of view?
  - Which product portfolio including co-products shows the highest sustainability?
  - How do the specific results for the different perspectives on sustainability (such as environmental, economic, social) differ from each other?
  - Which are the best algae cultivation conditions?
  - Which extraction and separation processes should follow the algae harvesting?
  - What is the influence of different co-product uses and co-product accounting methods?
- Which unit processes determine the results significantly and what are the optimisation potentials?
- Which technological, political or other barriers may hinder the large-scale implementation or continuous operation of plants according to the PUFAChain concept? Is there a risk that such barriers require changes to the concept that affect sustainability?
- How does the PUFAChain concept perform compared to alternative options of meeting the increasing demand of PUFAs?

Image: © Thomas Leya for Fraunhofer IZI-BB, Potsdam, Germany

2.2 Methodological approach

The analysis of the life cycles within PUFAChain follows the integrated life cycle sustainability assessment (ILCSA) methodology (Fig. 2-1). The methodology builds upon existing frameworks. 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]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. This includes a benchmarking procedure in which all scenarios are compared to a selected benchmark scenario. It is adapted to each decision context. See chapter 4.4.2 for details on the procedure selected in this study.

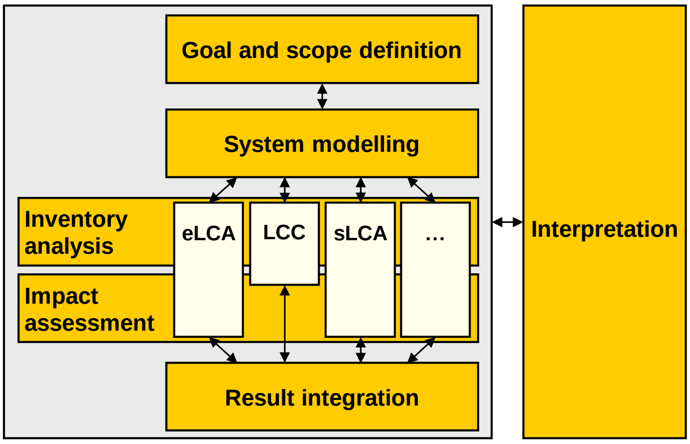


Fig. 2-1 Schematic workflow of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015]. It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

2.3 Common definitions and settings

All parts of the integrated sustainability assessment are based on the same common definitions and settings. These are summarised in the following. For additional specific definitions, settings and methodological aspects of the assessments of environmental, socio-economic and technological aspects please refer to the respective detailed reports [Keller et al. 2017; Reyer et al. 2017; van der Voort et al. 2017].

System boundaries

System boundaries specify which unit processes are part of the product system and thus included into the assessment.

The sustainability assessment of the PUFAChain system takes the entire value chain (life cycle) from cradle to grave into account, i.e. from algae cultivation to the distribution and usage of final products including land use change effects. The main focus is on the provision of EPA and DHA. All further products are considered as co-products.

Technical reference

The technical reference describes the technology to be assessed in terms of plant capacity and development status/maturity.

PUFAChain systems is assessed as mature, industrial-scale technology (often termed “nth plant”) on a scale of 10 to 100 hectares of photosynthetic area (any processing equipment, labs and infrastructure such as drive ways add to this area). It is essential to know how future production according to this concept performs as compared to established alternatives, which are operated at industrial scale. This way, it can be evaluated whether the PUFAChain concept of algae-based EPA and DHA production is worth being further developed/supported.

Timeframe

The PUFAChain system must be described not only in space but also in time. The timeframe of the assessment determines e.g. the development status of used technology or burdens associated with inputs such as acquired electricity.

The PUFAChain project delivers an algae-based PUFA production concept at its end in 2017. A mature, industrial-scale plant will not be the first one to be built based on this concept. Instead, building and routine operation of a smaller plant will contribute to technological learning and improve maturity. Thus, it seems realistic that a mature, industrial-scale plant will become operational only after 2020. Since data availability is much better for years divisible by 5, the time frame is set to 2025.

Geographical coverage

Geography can play a crucial role in many sustainability assessments, determining e.g. productivity of algae cultivation, transport systems and electricity generation. The PUFAChain project focuses on the EU as a geographical region. Two regions are assessed for algae cultivation to cover the range of technically possible locations for cultivating algae and of cultivation conditions such as temperature, light intensity, etc. in Europe and one location is assessed in an excursus:

- Southern Europe (prototypical location: region around Lisbon, around 40° N)
- Central Europe (prototypical location: region around Munich, around 50° N)
- Excursus: Northern Europe (prototypical location: region around Oslo, around 60° N)

Cultivation conditions such as temperature, light intensity, etc. and possible plant configurations are defined for these two regions and suitable algae strains are selected accordingly. In order to answer further questions related to the sustainability performance of the envisioned pathways, prototypical locations and related parameters have been selected more detailed, e.g. to assess the influence of electricity generation or wages.

The choice of the prototypical locations was considering several regions according to annual solar irradiation and annual temperature. Besides that, Lisbon and Munich areas are good locations due to other reasons, such as:

- Proximity to technology and logistics for microalgae production and biorefining;
- Easy access to the most relevant raw materials and utilities;
- Easy access to all transportation systems;
- Availability of workforce and a local talent pool;
- Well-known political strategies;
- Close to the potential final consumer.

Infrastructure

A biased comparison can 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 if photobioreactors are involved.

Therefore, infrastructure is taken into account. Yet, only relevant infrastructure specific for the assessed 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 is similar for the assessed scenarios and conventional reference systems (e.g. office buildings) is not assessed explicitly if the impact on the final results is negligible.

Functional unit

The functional unit is a key element of life cycle based sustainability assessment. It is a reference to which the environmental, social and economic effects of the studied system are related, and is typically a measure for the function of the studied system. Consequently, it is the basis for the comparison of different systems.

In this case, PUFA content is the most suitable single measure because it reflects the utility of the main product better than e.g. the whole product mass. Therefore, the *provision of 1 tonne of DHA and EPA equivalents contained in the product* is selected as primary functional unit. In scenarios where stearidonic acid (SDA, a precursor of EPA and DHA) is additionally present in the PUFA mixtures, its amount is converted into EPA and DHA equivalents with a factor based on metabolic conversion rates.

Independent of the functional unit, results may be displayed related to e.g. biomass input or used land for answering specific questions.

Data sources

PUFAChain 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 PUFAChain partners. Quantitative data comprises mass and energy balances as well as parameters on infrastructure. The underlying data from PUFAChain 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.

Secondary data:

Background data e.g. on provision of non-biomass material inputs or on prices was supplemented separately for environmental, socio-economic and technological assessment.

A summary of and more detailed remarks on used data can be found in the detailed reports on environmental, socio-economic and technological assessment [Keller et al. 2017; Reyer et al. 2017; van der Voort et al. 2017].

3 System description

Within this chapter, the systems are described that are analysed in the sustainability assessment. The set of scenarios describing the PUFAChain concept is presented in chapter 3.1. Main scenarios are assessed for environmental, socio-economic and technological aspects. Sub-scenarios are only addressed where a substantial deviation of the respective sustainability impact is expected. Its processes are described in detail in chapter 3.2 and competing alternatives, the reference systems, are summarised in chapter 3.3.

3.1 Overview and PUFAChain scenarios

The PUFAChain system primarily aims at providing valuable polyunsaturated fatty acids (PUFAs) for health-related applications from algal biomass to overcome shortages of conventional sources such as small fish from marine fishing. In particular, PUFAChain focusses on omega-3 fatty acids such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA), which have been found to show the highest health benefits of all PUFAs regarding the intended applications [Burdge et al. 2003; Stark et al. 2008].

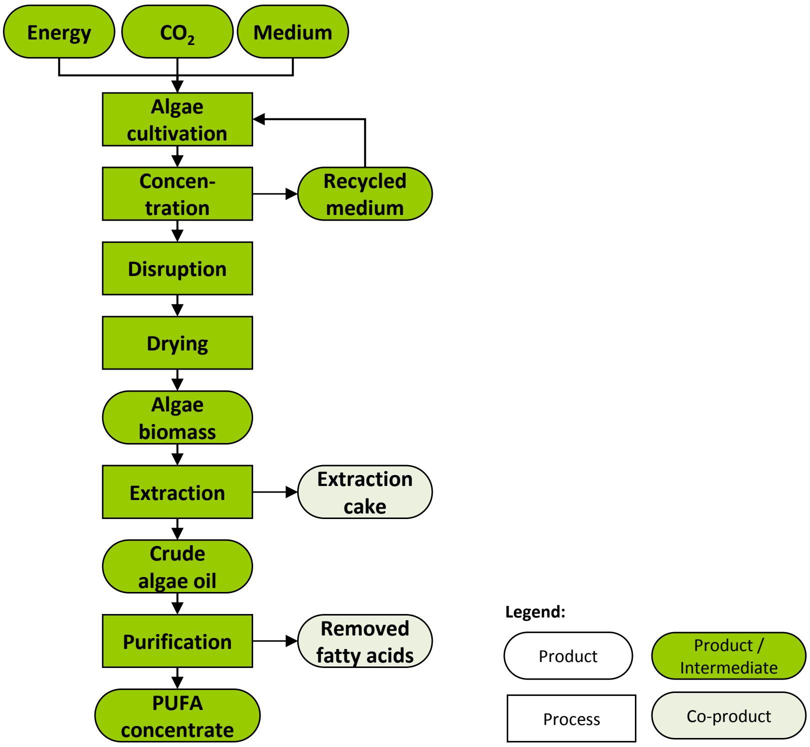


Fig. 3-1 Overview of life cycle stages depicted in the assessed scenarios for the PUFAChain system.

Image: © Thomas Leya for Fraunhofer IZI-BB, Potsdam, Germany

Fig. 3-1 gives a general overview of the PUFAChain system. Amongst the dozens of possible options which algae to cultivate for which product portfolio, the general scenarios listed in Table 3-1 were chosen as the most promising to follow up on. All scenarios generally refer to two sets of processes and conditions comprising a bandwidth of potential future implementations in 2025:

- Conservative: on a 10 ha scale with efficiencies etc. that could be reached by 2025 with existing processes properly implemented on that scale.
- Optimistic: on a 100 ha scale with highest efficiencies etc. that could plausibly be reached by 2025.

For some processing steps, variations of processes and conditions are studied in sub-scenarios as described in the following chapters.

Table 3-1 Investigated general scenarios of algae production and use.

Scenario	Algae	Season	Main products	Water type	Proto-typical location *
Combined PUFA production, Southern Europe	*Prorocentrum*	All year (330 days)	EPA, DHA & SDA	Saltwater	Lisbon
Combined PUFA production, Central Europe	*Prorocentrum*	All year (330 days)	EPA, DHA & SDA	Saltwater	Munich
Initial combined PUFA production, Southern Europe	*Thalassiosira*	All year (330 days)	EPA & DHA	Saltwater	Lisbon
Initial combined PUFA production, Central Europe	*Thalassiosira*	All year (330 days)	EPA & DHA	Saltwater	Munich
EPA plant, Southern Europe	*Chloridella*	Summer (240 days)	EPA	Freshwater	Lisbon
	Raphidonema	Winter (90 days)	EPA	Freshwater	
EPA plant, Central Europe	*Chloridella*	Summer (140 days)	EPA	Freshwater	Munich
	Raphidonema	Winter (190 days)	EPA	Freshwater	
EPA plant, Northern Europe	*Chloridella*	Summer (80 days)	EPA	Freshwater	Oslo
	Raphidonema	Winter (250 days)	EPA	Freshwater	

Bold print: main scenarios. * : The prototypical locations refer to the region around the respective city.

All scenarios generally refer to a single set of processes and conditions. For some processing steps, variations of processes and conditions are studied in sub-scenarios. Additional options, which are not the aim of the PUFAChain project, are analysed for reference to demonstrate the sustainability advantages of the progress made in this project. All sub-scenarios listed in the following overview are explained in more detail in chapter 3.2 to 3.2.2.

Sub-scenarios on algae cultivation:

Spray cooling (standard scenario); electricity powered heat exchanger cooling system (sub-scenario)

Sub-scenarios on drying:

Spray drying with electricity (standard scenario) or with natural gas

Sub-scenarios on seasonality:

Cultivation all year around (standard scenario) or winter break without cultivation depending on location.

Sub-scenarios on location:

Some sustainability impacts are dependent on the exact location or type of location chosen for algae cultivation. In standard scenarios, a greenfield site[2] in the vicinity of a larger city is selected. Alternatively, a brownfield site[3] or a location in more communities are assessed.

3.2 Detailed process descriptions for the PUFAChain system

3.2.1 Algae cultivation, harvesting and biomass processing

Algae strains and crop rotation

The PUFAChain system is based on the photoautotrophic cultivation of microalgae that grow in seawater or freshwater. Genetically modified algae strains are excluded from the assessment because no such candidate strains are screened within the project. Within the PUFAChain project multiple algae strains are investigated. One major goal is to achieve high yields in EPA and DHA.

The cultivation conditions such as temperature, light intensity, etc. under which the algae strains are suitable for mass production vary for each strain. Some strains show promising results for warm climate zones/warm climatic conditions, others are suitable for temperate or cold climate zones/climatic conditions. Considering all options, either a cultivation of one strain all year around or an algae crop rotation with one strain in warmer and another strain in colder times of the year was chosen (see Table 3-1).

As summarised in section 0, conditions for cultivation vary strongly across Europe. For the sustainability assessment of algae cultivation the two regions “Southern Europe” and “Central Europe” are defined. Additionally, algae crop rotation in Northern Europe is assessed in a sensitivity analysis.

Regarding cultivation, a focus is on closed system unilayer horizontal tubular photobioreactors (UHT-PBRs). They have a wide application range in algae cultivation for DHA and EPA production because they represent a controllable environment with a low contamination risk. Green wall flat panels are assessed for inoculation.

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[2] A greenfield site is land currently used for agriculture or (semi)natural ecosystems left to evolve naturally.

[3] 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.

Algae cultivation process

The algae cultivation process in UHT-PBRs consists of the following steps:

- Culture medium preparation from freshwater, recycled medium (recovered after harvest), nutrients and salt (for saltwater strain). A high recycling rate of medium of 90% is set for these scenarios.
- Inoculation of small flasks with LED lighting with algae from live or frozen stocks (up to few litres of culture volume).
- Transfer of inoculum to “green wall panels”, which are single-use plastic bags supported by racks in a particularly controlled environment (up to few m³).
- Transfer of small volume cultures to big UHT-PBRs (many m³).
- Semi-continuous cultivation with periodic partial harvests, corresponding medium replacement and online tube surface cleaning.
- Occasional complete harvests depending on biological parameters followed by thorough offline cleaning and restart of the culture with new batches.
- In some scenarios: Switching of cultivation strains according to crop rotation principle.

For their operation, UHT-PBRs need inputs such as water in different qualities, CO_2, energy or nutrients (Fig. 3-2). Additionally, non-potable process water may be needed for spray cooling, cleaning etc. UHT-PBRs represent an intensive and particularly controlled option for algae cultivation. They require substantial infrastructure such as tubes, racks, tanks or pumps (Fig. 3-2). Depending on the geographical location, temperature needs to be managed with suitable devices such as cooling systems for hot weather or heating for cold weather. Cooling may be achieved either with external spray cooling with process water or internal heat exchangers.

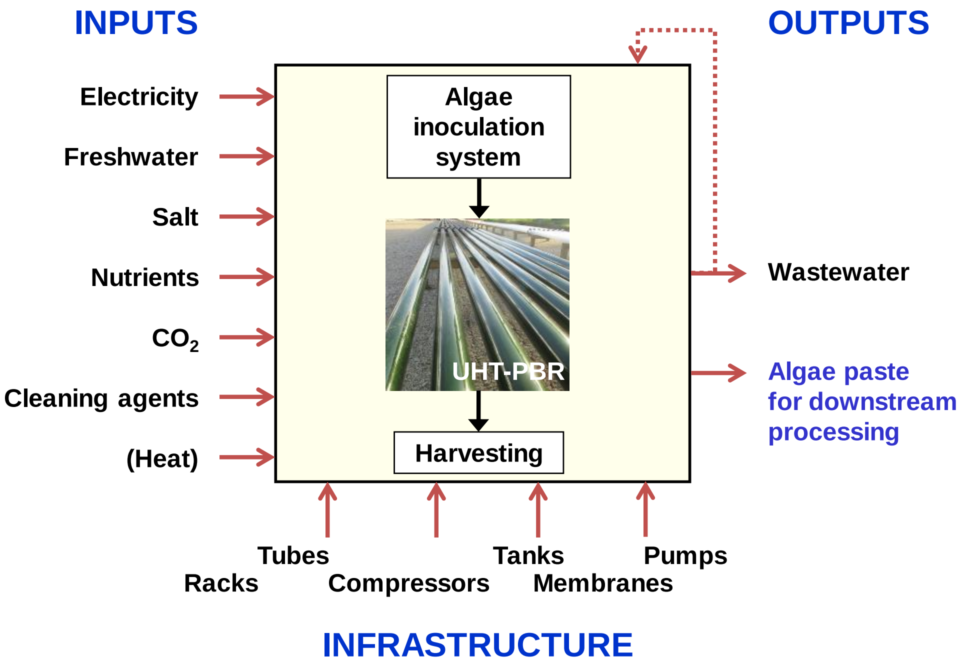

Fig. 3-2 Schematic input/output diagram for algae cultivation in photobioreactors (UHT-PBRs).

Image: © A4F – algae for future, Lisbon, Portugal

Algae harvesting and medium recycling

Algae harvesting is of central importance to PUFAChain and is achieved via membrane concentration. The conditions determine energy demands and may influence the recyclability of the culture medium. The more dilute the algae culture is, the more important energy demands and medium recycling become. Additionally, salt concentrations have to be reduced as far as possible for all strains grown in saltwater. This is achieved by washing and diafiltration steps. With this process, the following can be achieved: (1) enrich the product on biomass (because salt is removed), and therefore, on PUFAs content and (2) simplify the consequent extraction process since less product has to be manipulated and this product has higher content of PUFA. This leads to higher extraction yields of PUFAs.

Utility provision and wastewater treatment

In standard scenarios, power is provided from the grid and heat (if required) by natural gas boilers. In sub-scenarios, on-site photovoltaic systems provide power to all processes at the algae cultivation site.

Wastewater is reduced as far as possible by internal recycling of algae cultivation medium. Remaining wastewater is treated in municipal wastewater treatment expecting that concentrations of substances such as salt are low enough to allow such a treatment.

Disruption

Harvested algae have to be made available for algae oil extraction. Each strain is disrupted with the method that has been found most suitable in the course of this project. In case advanced disruption processes cannot be quantified yet, bead milling is assessed as a worst case option. For the assessed strains, the following processes were selected:

Table 3-2 Disruption methods for each assessed algae strain.

Algae	Water type	Disruption method
Prorocentrum	Saltwater	Osmotic shock
Thalassiosira	Saltwater	Osmotic shock
Chloridella	Freshwater	Bead milling
Raphidonema	Freshwater	Bead milling

Drying

Spray drying is selected as preferred drying method. Subsequent pelleting is necessary for availability to supercritical CO_2 extraction.

Transportation

Dry biomass is transported and oil extraction is performed in a central plant. Extracted algae oil is transported to a central oil processing facility (see chapter 3.2.2 for details). This ensures best use of extraction and processing facilities.

3.2.2 Algae oil extraction and processing

Processes required for algae oil extraction and processing can be divided into five different groups:

- Crude algae oil extraction
- PUFA concentration and separation
- Downstream processing
- Co-product utilisation
- Utility provision (power, steam, cooling) from biomass residues and/or external energy carriers including wastewater treatment

One idea behind PUFAChain is to combine the production of low volume – high value products (PUFAs) with medium volume – medium value products to improve the performance. The latter are protein containing extraction cake and non-PUFA fatty acids. Any potential industrial scale PUFAChain process produces one PUFA-containing main product and up to three co-products (Fig. 3-3, see also Table 3-3).

Crude algae oil extraction

PUFAs are extracted by supercritical CO_2 ($scCO_2$). This requires dried algal biomass. Any extraction yields extraction cake as a co-product. The method influences its further use options.

Crude algae oil extraction takes place in a separate plant because the dried feedstock can be transported and the $scCO_2$ extraction plant is very capital intensive. For these reasons, transportation to a central facility that processes algae biomass amongst other feedstocks in campaign mode is modelled.

PUFA concentration

PUFAs in the crude algae oil fraction are concentrated after extraction to increase their value. This takes place in existing integrated facilities in the oleochemical industry. Many strategies have been researched within the project and several routes are possible. It depends on exact biomass properties etc. which of these performs best. Two different strategies have been found most useful depending on the algae oil and are analysed in detail in this study:

Prorocentrum:

This algae oil contains EPA, DHA and the additional valuable PUFA stearidonic acid (SDA) in such high fractions that a further enrichment (removal of undesired fatty acids) is not necessary. Only impurities such as pigments or degraded biomass need to be removed. The removed impurities contain harmless biomass and are treated as normal waste. They also contain pigments that may be valorised at a later stage. This is not included in the scenarios assessed here because of lacking data. PUFAs are converted into magnesium soaps because this form can have a better bioavailability than conventional PUFA ethyl esters. In standard scenarios, equal bioavailability is set for all PUFA forms. In a sensitivity analysis, potentially different bioavailability is taken into account.

All other algae (Chloridella, Raphidonema, Thalassiosira):

For these algae, a more standard approach is followed. Fatty acids in the algae oil are converted into ethyl esters. This allows a separation of undesired fatty acids by short path distillation. The resulting product contains PUFA ethyl esters. Mixtures of other removed fatty acids and glycerol are obtained as co-products.

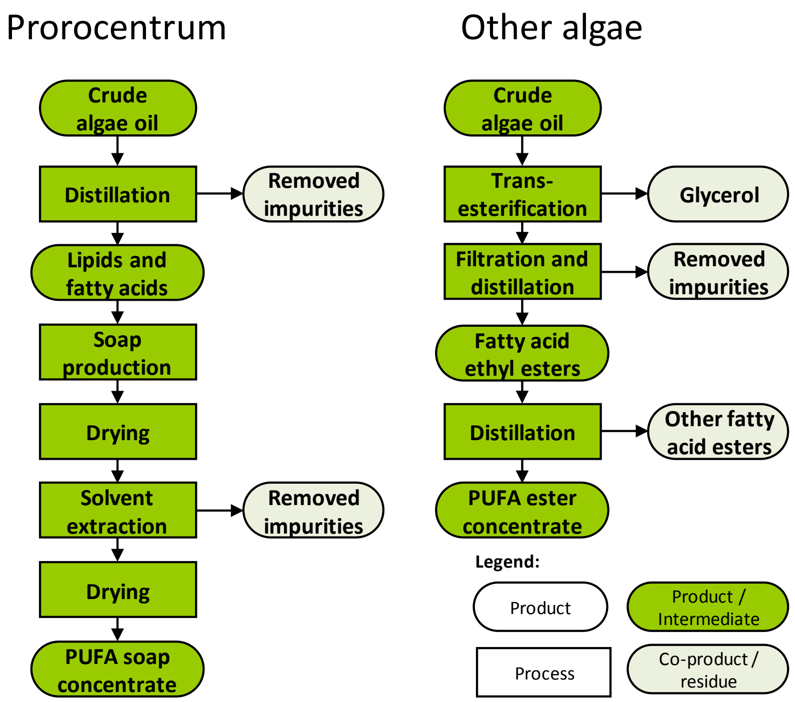

Fig. 3-3 Schematic diagram for algae oil purification.

Formulation

Formulation serves the purpose of converting biomass fractions into marketable products. This includes blending to fulfil certain specifications and/or formulation to stabilise the product. PUFA capsules also require additives. Furthermore, products have to be packaged. However, screening analyses revealed that impacts on sustainability are expected to be low and similar for products and reference products. Therefore, formulation is not assessed explicitly in this assessment but set to be equal for product and replaced reference product.

Products

For the investigated main scenarios, the main products of the PUFAChain system are EPA or a mixture of EPA and DHA. The content of EPA and DHA depends on the cultivated algae strain (see Table 3-1). In some scenarios, the PUFA stearidonic acid (SDA), which is a precursor of EPA/DHA, is present in the product, too, as a valuable component. Furthermore, the concentration of EPA and DHA can be increased in the concentration step, such that a range of main products containing different concentrations of EPA/DHA is available. PUFA mixtures are used in nutraceutical applications, which requires certain EPA + DHA (+ SDA) contents and fulfilling certain further criteria. They are packaged into capsules. Due to its high PUFA concentration, the product has a high market value.

Co-product utilisation

Several material side streams can be produced depending on the process configuration. This assessment in particular addresses extraction cake (from PUFA extraction), removed fatty acid (from PUFA concentration) and glycerol (from PUFA transesterification). Scenarios are used to explore the possible uses of co-products and determine the sustainability of further conversion steps into the following products:

- Extraction cake (probably protein-rich): Conversion into livestock feed, fish feed or biogas
- Removed fatty acids: Use in oleochemistry, maybe requiring upgrading/downstream processing
- Glycerol: Use in various products of the pharmaceutical, cosmetics or chemical industry.

To increase the total product value, material side streams have been evaluated for many more valuable components. They are not evaluated in the standard scenarios of the sustainability assessment but the exploitation potential of the most promising compounds is addressed in the technological assessment.

Utility provision and wastewater treatment

In standard scenarios, power is provided from the grid and heat by natural gas boilers.

Summary of assessed biomass processing systems

Potential configurations of biomass processing systems with their main products and co-products are listed in Table 3-3.

Table 3-3 Scenarios of the PUFAChain value chain selected from all options discussed in chapter 3.2.

Scenario	Algae strains	Product
Combined PUFA production	Option 1: Prorocentrum	PUFA concentrate containing magnesium soaps of EPA, DHA and SDA
	Option 2: Thalassiosira	PUFA concentrate containing ethyl esters of EPA and DHA
Dedicated EPA production	Chloridella (summer) + Raphidonema (winter)	PUFA concentrate containing ethyl esters of EPA

3.2.3 Use phase and end of life

The use phases of most PUFAChain products and equivalent conventional products are expected to be very similar. Only those differences in the use phase that are due to diverging product properties are explicitly assessed.

All PUFAChain products and co-products are consumed during the use phase (human consumption, feeding, combustion for energy recovery, fertiliser application). Thus, a separate end of life treatment such as recycling, disposal etc. does not take place (except for waste streams from the infrastructure installations). Nevertheless, this life cycle step is assessed when applicable.

3.3 Alternatives to the PUFAChain system

This chapter describes systems competing with PUFAChain. They produce products of equivalent utility (reference products, see also Fig. 1-1).

General approach regarding reference products

In the case of PUFAChain, it is challenging to find suitable product reference systems because the aim of the project is to supply a product, for which conventional sources are increasingly limited. These conventional sources are wild-caught marine fish with a major share of anchovy. Many studies agree that their catch at least cannot be extended substantially any more without endangering fish populations thus being unsustainable. Furthermore, the increasing awareness for health benefits provided by PUFAs and also the growing world population lead to an increasing demand for PUFAs. Together, these developments have triggered the exploration of alternative sources. One of these options, PUFA provision from autotrophic microalgae cultivation, is subject of this project.

Wild-caught fish such as anchovy etc.[4] or tuna etc.[5] and wild-caught krill are not assessed as reference systems. These fisheries cannot be sustainably extended to a substantial degree according to all sources we currently know of. In this case, an unsustainable expansion would not only mean damages to environment, economy and society in general, which is commonly measured by sustainability assessments. It would also directly cause a decline in future levels of PUFA provision from these sources. Thus, a long-term expansion of these fisheries beyond a certain threshold is simply impossible and therefore cannot be assessed with these methodologies. This requires a verbal discussion of this aspect of sustainability outside of the methodological framework. Thus, they are listed as conventional sources and a literature overview on the potential developments of their populations and catch volumes is given.

Proposals for life cycle comparisons of products and reference products assessed within PUFAChain are summarised in Fig. 3-4 and described in detail below.

Most of these products are PUFAs from other more or less innovative sources that are still to be established. They are compared based on their content of DHA and EPA. SDA is converted into EPA/DHA equivalents based on the metabolic conversion rate of 0.3 g EPA per g SDA [James et al. 2003].

Detailed reference product descriptions

Depending on the product and its use, there may also be several options for a reference product. In the following, they are described and assigned to the respective PUFAChain products.

PUFAs from fermentation

Fermentation for PUFA production is expanding and can be expanded further. It uses heterotrophic microorganisms such as fungi and other protists. Some of these

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[4] Whole fish, which are commonly sold for industrial applications such as fish meal production

[5] Whole fish, which are commonly sold for direct human consumption

microorganisms are often termed algae although they are not classified into this group according to current scientific consensus. The carbon source for these organisms is glucose or similar medium components, which have to be supplied from agricultural production. Thus, arable land use has to be taken into account for fermentation.

PUFAs from unused fish cuttings or by-catch

There is a certain potential to use previously discarded fish cuttings from fish processing plants or by-catch for the extraction of PUFAs. In particular, changes to EU fishery policies are expected to increase the amount of by-catch that is landed instead of being discarded to the sea. However, the volume is limited because both resources are by-products.

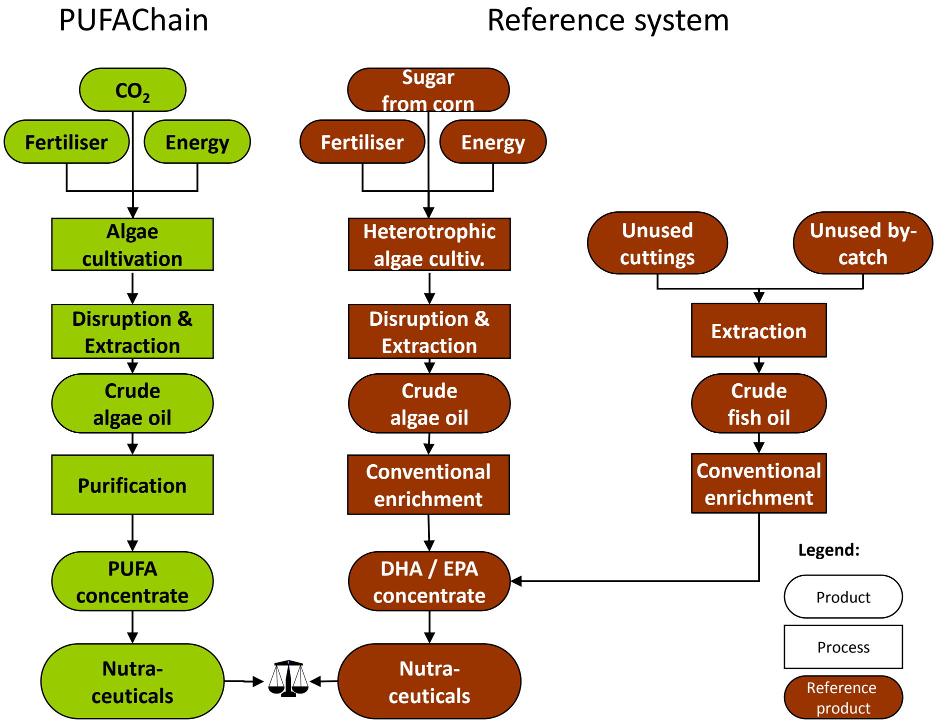

Fig. 3-4 Life cycle comparison scheme for PUFAChain products.

Bioavailability

All standard scenarios are based on the setting that the bioavailability of PUFAs in their various chemical forms is identical. In a sensitivity analysis, current knowledge, which is not yet robust scientific consensus, is taken into account [Dyerberg et al. 2010]. The following factors are applied:

PUFAs in natural oils: 100%

Free fatty acids/soaps: 91%

Ethyl esters: 73%

Reference products for co-products

The extraction cake resulting from PUFA extraction from algae biomass has a high protein content of around 45%. It is used as livestock or fish feed. It is compared to other feed sources based on its protein content (Fig. 3-5).

Removed fatty acids from PUFA enrichment (gained from for all value chains except for the one using *Prorocentrum*) are used in oleochemistry e.g. for cosmetics, technical applications or animal feed instead of other oils with similar fatty acids. As an example, high erucic acid rapeseed oil is assessed as a reference product because its fatty acid profile is probably most comparable.

Glycerol from transesterification (in all value chains except for the one using *Prorocentrum*) is used in various industries including cosmetics or pharma as ingredient for formulations. It replaces a range of chemically different but functionally equivalent basic chemicals.

Potential reference systems that are not assessed

- DHA produced in genetically modified plants such as canola because market perspectives for nutritional products from genetically modified organisms (GMOs) do not seem promising in the EU.
- Synthetic DHA because, to our knowledge, there is no synthetic DHA on the market.
- Alpha-linolenic acid from plants such as flax. Alpha-linolenic acid is much less efficiently converted into EPA/DHA than SDA and the conversion is even more dependent on various other parameters such as the nutritional status of the person. Thus is not suitable to be delivered reliably and in relevant amounts via capsules.

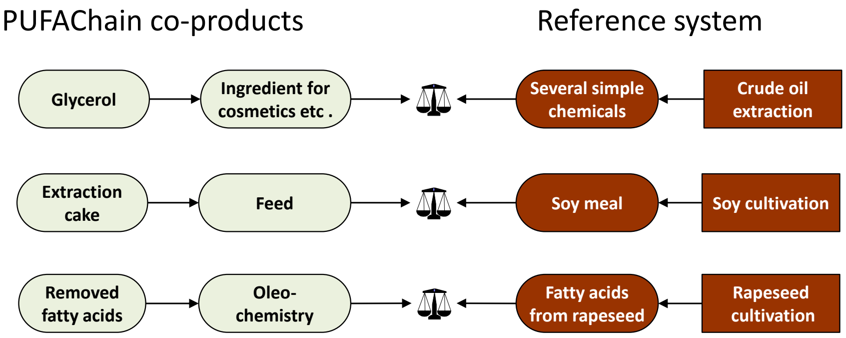

Fig. 3-5 Life cycle comparison scheme for PUFAChain co-products.

Land use reference system

Each form of algae cultivation requires land, which could also be used otherwise in most cases. This land does not need to be arable land (as for cultivation of higher plants), but depending on the location, the use of agricultural land[6] may be an attractive option.

Conversion of most kinds of land into algae farms may come along with impacts such as clearing of vegetation or sealing of soils. Even desert-like land may have a high ecological value, which is lost if algae farms are built. Additionally to direct land use change effects,

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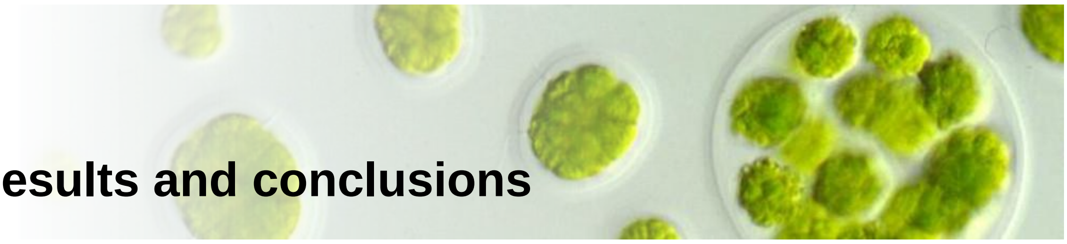
[6] Agricultural land is defined as the land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.

indirect effects may arise if agricultural land is converted into algae farms and thus the global agricultural area decreases. Assuming that the demand for agricultural products remains constant, then their production is displaced to another area, which may cause unfavourable land use changes, i.e. the conversion of (semi-)natural ecosystems might occur. This phenomenon of indirect land use changes is also called leakage effect or displacement. Both direct and indirect land use changes can lead to changes in the carbon stock of above- and below-ground biomass [Brandão et al. 2011]. Depending on the previous land use and on the land use to be established, these changes can be neutral, positive or negative. The respective impacts of land use changes are taken into account for both PUFAChain systems and alternative reference systems, where applicable.



4 Results and conclusions

As a basis for further analyses, this chapter contains summaries of the assessments of individual sustainability aspects (chapter 4.1-4.3). The results from these individual assessments are combined, extended and jointly assessed in the results chapter on the integrated assessment (chapter 4.4). For methodological details and settings see chapter 2.

4.1 Summary: technological assessment

This assessment by the project partner IOI Oleo GmbH analysed all technological aspects that could have an impact on sustainability. For details and further results please refer to the original technological assessment report [Reyer et al. 2017].

4.1.1 Potential barriers

The following aspects were identified as potential barriers that could prevent or limit a realisation of the analysed scenarios:

Maturity

The maturity of the present technology for microalgae omega-3 fatty acids production is basically operational. Crude oil with the target molecules DHA and EPA were derived from the different microalgae species.

However, the quantitative cell disruption is still very challenging. The best results were obtained by the extraction of dry biomass by supercritical CO_2. Also a second extraction technology was performed. Extraction of wet biomass by liquid propane showed similar or even worse results compared with the performance of the extraction of dry biomass by supercritical CO_2.

Additional effort will be required to optimize cell disruption and crude oil extraction to gain an economic attractive production process for industry.

Availability of infrastructure

The infrastructure in EU for the production of microalgae high value material was found to be challenging. Due to the fact that microalgae products did not reach the broad consumer markets, fatty acids derived from GMO free microalgae material is still an innovative pre-industrial application.

4.1.2 Potential risks

The following aspects were identified as potential technological risks that are associated with the analysed scenarios:

Image: © SAG Culture Collection of Algae at Göttingen University, Göttingen, Germany

Toxicity risk

The toxicity risk of microalgae production and the obtained omega-3 fatty acids is low or very low. Taste and door of the microalgae and crude oil is not attractive for human consumption.

However, the primary and even more important the secondary metabolism of these algae makes the presence of toxic molecules in an appropriate concentration unlikely. Extraction media (mainly CO_2) were removed from extraction material quantitatively.

Risk of explosion and fire

The risk of an explosion is found to be “medium” risk for the extraction of dry biomass by supercritical CO_2. This process needs >500 bar for supercritical condition. However, the equipment was built following the current regulations for high pressure units. CO_2 exhibits a very low risk for fire and deflagration.

4.1.3 Conclusion

PUFAChain

The cultivation and extraction of microalgae are showing very promising results for the sustainable production of omega-3 fatty acids. These plants have a high value for the health of human and mammalians.

Today, the extraction of crude algae oil is possible but challenging. Besides the supercritical CO_2-extraction analysed in these scenarios, propane extraction may offer the benefit of extracting wet biomass in the future to save energy of drying. However, this technology still needs development for its maturation. Novel results of this study indicating that beside DHA and EPA more economic interesting molecules are synthesized in the metabolism of microalgae. Stearidonic acid (SDA) a health fatty acid promoting precursor molecule of omega-3 fatty acids and phytosterols were found. Basic research on microalgae metabolism is required to gain more information about these molecules.

Alternatives to PUFAChain

The traditional source of omega-3 fatty acids (DHA/EPA) for health promotion in humans and mammalians is fish oil. This oil could be derived from water farming or fishing. In the last years fish oil made of by-catch fish getting more and more economic interesting e.g. cephalopodae. The last innovation regarding the harvest/production of DHA /EPA is a gene modified alga (GMO alga) which produces these fatty acids in a very efficient manner.

However, to overcome the destruction of our maritime fauna and flora by industrial overfishing, these processes are not suitable to solve the problem of omega-3 fatty acids supply for humans in the future.

GMO could be an effective alternative to the PUFA chain approach, having in mind that the gene modification of organisms and the risk of consuming GMO derived material over a long time period and the risk for our environment is yet not totally understood.

4.2 Summary: environmental assessment

This assessment by the project partner IFEU - Institute for Energy and Environmental Research Heidelberg analysed all environmental implications of the scenarios described in chapter 2. For details and further results please refer to the original environmental assessment report [Keller et al. 2017].

The most important results and insights are summarised in the following.

4.2.1 Optimisation of environmental impacts

Tremendous improvements have been achieved within the project in reducing resource consumption and environmental impacts.

Early in the project, the energy demand for cultivation and for drying the algae biomass primarily caused the greatest environmental burdens (Fig. 4-1). By optimisation focussing on these inputs, both the consumption of non-renewable energy resources and the environmental burdens per tonne of PUFAs were reduced by up to 80–90%, depending on the environmental impact (Fig. 4-2). In future, numerous additional contributions, for example the use of nutrients such as nitrogen or expenditures for downstream processing, which cause a substantial proportion of the remaining environmental burdens, need to be addressed.

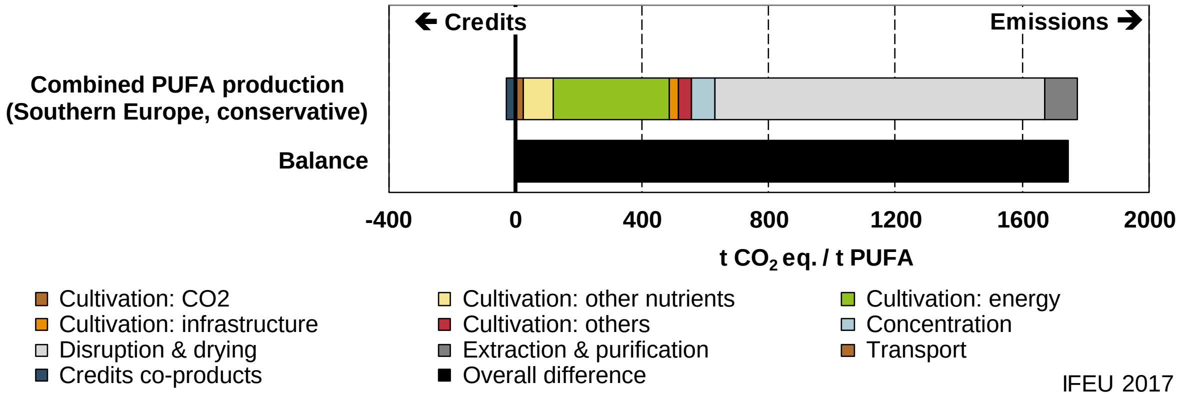


Fig. 4-1 Contribution of life cycle stages to the environmental impact category global warming potential for one exemplary scenario.

The greatest environmental improvements can be achieved by using improved algae strains, renewable energy sources such as an on-site solar power supply and optimised algae biomass drying strategies.

In addition, strategies for reducing heating energy requirements in regions with cold winters are needed. In addition to a variety of technical measures, this can also be achieved in principle using algae crop rotation, by cultivating suitably cold-tolerant algae in winter. However, the strains newly identified in this project for this purpose are not yet productive enough to achieve reductions in the majority of environmental burdens.

These, and other, optimisation strategies were investigated in the project and adopted for planning optimised facilities (Fig. 4-2). Because the full potential of these strategies can only be exploited given sufficient experience, additional long-term tests in demonstration facilities should nevertheless be carried out.

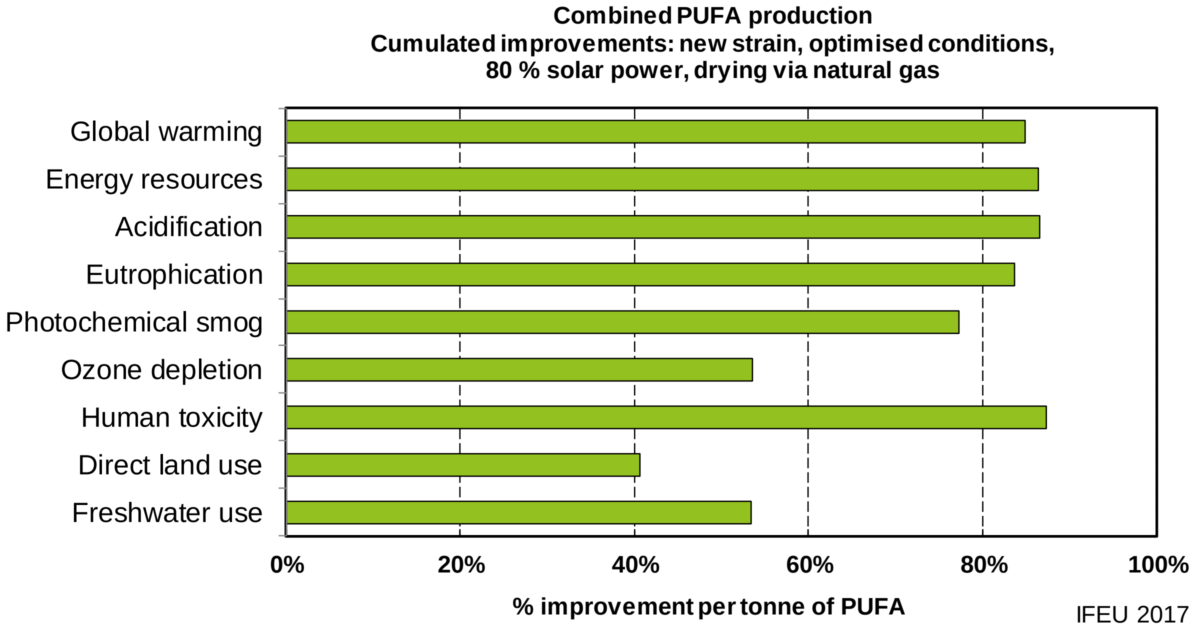


Fig. 4-2 Cumulated reduction of environmental impacts by several optimisation measures (Combined PUFA production with Prorocentrum under optimistic conditions with 80% PV and optimised drying by natural gas in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

Local environmental impacts can be minimised in particular by developing disused industrial sites, optimising ecological value by e.g. creating meadows beneath photobioreactors as well as by choosing sites with sufficient and sustainable freshwater supply.

Significant local environmental impacts can be associated with algae cultivation – in particular on the environmental factors fresh-water use, land use, soil and biodiversity. However, algae cultivation does not require fertile land. If brownfield sites[7] are used instead of greenfield sites[8], it may even be possible to enhance areas if their design is ecologically optimised (Table 4-1). This can include the creation of meadow instead of gravel fill beneath photobioreactors or planting hedges. Irrespective of this, sufficient (blue) water availability must be guaranteed in order to implement the PUFAChain system at the planned site. Existing water uses in a catchment area, also referred to as environmental flow requirements, must be taken into consideration here.

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[7] Land previously used for industrial, commercial or military purposes (often with known or suspected contamination) that is not currently used.

[8] Land currently used for agriculture or (semi-)natural ecosystems left to evolve naturally.

Table 4-1 Technology-related impacts expected from the implementation of the PUFAChain 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

	PUFAChain				Fer-mentation	Cut-tings	By-catch	Soy-bean	Rape-seed
Algal/fish biomass (1-7) or biomass (8+9) provision	**Brown field eco**	**Brown field gravel**	**Green field eco**	**Green field gravel**					
Impacts resulting from construction phase									
Construction works	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Impacts related to the facility itself (F) or resulting from operation phase (O)									
Soil sealing	A	C	C	D	n.a.	n.a.	n.a.	n.a.	n.a.
Soil erosion	A	n.a.	A	n.a.	D	n.a.	n.a.	D	D
Soil compaction	B	D	B	D	D	n.a.	n.a.	D	D
Loss of soil organic matter	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	C	C
Soil chemistry/fertiliser	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	D	D
Weed control/pesticides	n.a.	n.a.	n.a.	n.a.	E	n.a.	n.a.	E	E
Loss of habitat types	A	C	C/D	E	D	n.a.	n.a.	E	D
Loss of species	A	C	C/D	E	D	n.a.	n.a.	E	D
Barrier for migratory animals	C/D	D	C/D	D	n.a.	n.a.	n.a.	n.a.	n.a.
Loss of landscape elements	A	B	C	D	C	n.a.	n.a.	E	C
Risk for iLUC	A/B	A/B	E	E	E	n.a.	n.a.	E	D
Drain on water resources	C/E	C/E	C/E	C/E	D	n.a.	n.a.	D	D
Emission of nutrients (to water)	D	D	D	D	D	n.a.	n.a.	D	D
Emission of gases and fine dust (to air)	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Electromagnetic emissions	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	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Accidents, explosions, fires, GMO release	C	C	C	C	n.a.	n.a.	n.a.	E	n.a.
PUFA provision									
Impacts resulting from construction phase									
Construction works	C	C	C	C	C	C	C	n.a.	n.a.
Impacts related to the facility itself									
Buildings, infrastructure and installations	C/E	C/E	C/E	C/E	C/E	C/E	C/E	n.a.	n.a.
Impacts resulting from operation phase									
Drain on water resources for production	C/E	C/E	C/E	C/E	C/E	C/E	C/E	n.a.	n.a.
Emission of nutrients (to water)	D	D	D	D	D	D/E	D/E	n.a.	n.a.
Emission of gases and fine dust (to air)	C	C	C	C	C	C	C	n.a.	n.a.
Traffic (collision risk, emissions)	C	C	C	C	C/D	C	C	n.a.	n.a.
Disposal of wastes/residues	C	C	C	C	C	C	C	n.a.	n.a.
Accidents, explosions, fires, GMO release	C	C	C	C	D	C	C	n.a.	n.a.

🟨 Potential impacts

▣ Likely significant impacts

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

Current technological improvements are so ground-breaking that it cannot be conclusively estimated what mature algae cultivation processes will look like.

Currently, the environmental burdens associated with PUFA production in any future large-scale facility from 2025 onwards cannot be conclusively estimated. On one side, the scenarios anticipate improvements that are yet to be realised. On the other side, given the current dynamic developments it is very probable that further technological breakthroughs can be achieved in the coming years. These, however, cannot yet be foreseen and therefore cannot be incorporated in the scenarios. Whether a facility could be built in 2025 that would subsequently be regarded as generally mature, or developments continue to advance dynamically, cannot be foreseen at this time. Research and funding concepts should therefore be regularly adapted to reflect the state of the art every few years.

4.2.2 Evaluation of optimised systems

Algae cultivation and processing require substantial resources in addition to sunlight and CO_2 and are therefore not intrinsically environmentally friendly.

Converting abundantly available CO_2 into valuable substances with the aid of algae and sunlight is a highly promising concept. However, if algae are to be cultivated and harvested in sufficient concentrations, substantial energy and material inputs will be needed. Overall, algae cultivation – similar to traditional agriculture – is not possible without the input of limited resources and without significant environmental burdens (Fig. 4-3). Algae-based products are therefore not intrinsically environmentally friendly, nor do they necessarily contribute to mitigating climate change just because algae consume CO_2.

Based on currently foreseeable technological developments, algae-based PUFA production is likely to continue to cause greater environmental impacts than PUFAs from fish cuttings or from fermentation processes – probably for several years to come.

In a detailed comparison, the reference systems should be differentiated:

- By comparison, the **fermentation processes** generally perform better in the majority of global environmental impacts such as acidification, eutrophication, ozone depletion or the depletion of non-renewable energy resources (Fig. 4-4).
  However, in terms of water consumption and land use, as well as the associated local environmental impacts, fermentation presents no benefits. PUFAs from algae and fermentation can cause similarly high freshwater use unless sugar from irrigated agriculture is excluded from use in fermentation. In addition, PUFAs produced by fermentation require up to 7 times as much land (Fig. 4-5). This is primarily because the use of algae co-products means that land used for soy and rapeseed cultivation can be indirectly saved. While sugar production for fermenters demands generally limited arable land, algae cultivation ideally requires nothing but infertile land. If algae cultivation does not lead to additional sealing of fertile arable land, benefits result in terms of the impacts on the environmental factors land, soil and biodiversity.

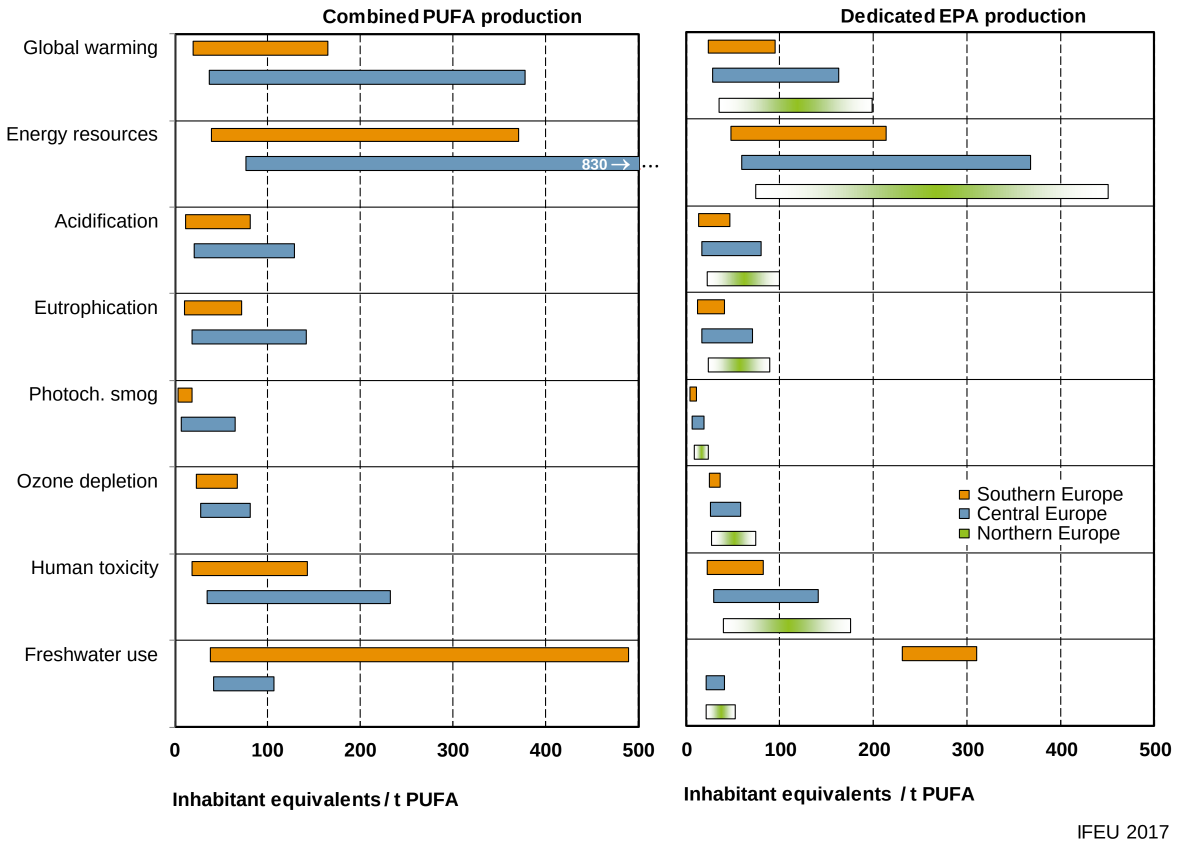

Fig. 4-3 Ranges of results for analysed scenarios of PUFA production. Results are expressed in inhabitant equivalents (IE)[9]. Avoided impacts due to the use of co-products were credited.

- **PUFAs from fish cuttings and by-catch** generally cause considerably lower global and regional environmental burdens (Fig. 4-4), because here a previously underused but available resource can be utilised with relatively little effort (Fig. 4-4). This option will hardly provide as much sustainable feedstuff as PUFA production from algae and thus not achieve similar indirect environmental benefits. This is however no primary aim of this project and can also be achieved otherwise. PUFAs from fish residues cuttings and by-catch should therefore be given priority. However, given increasing global PUFA demand, the potential will sooner or later be exhausted. Besides, it should be analysed how far this option can also contribute to an additional feed production like algae cultivation does, to achieve positive environmental impacts via avoided land use.

Overall, at least as far as the production of PUFAs is concerned, no industrial-scale algae cultivation facilities should be funded until the technology has been tested in detail and optimised. Experience gained in several years of operating a demonstration facility covering

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[9] 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.

a few hectares will probably be necessary to achieve this. If optimised systems become ready for operation in the future, their implementation should remain limited to infertile land.

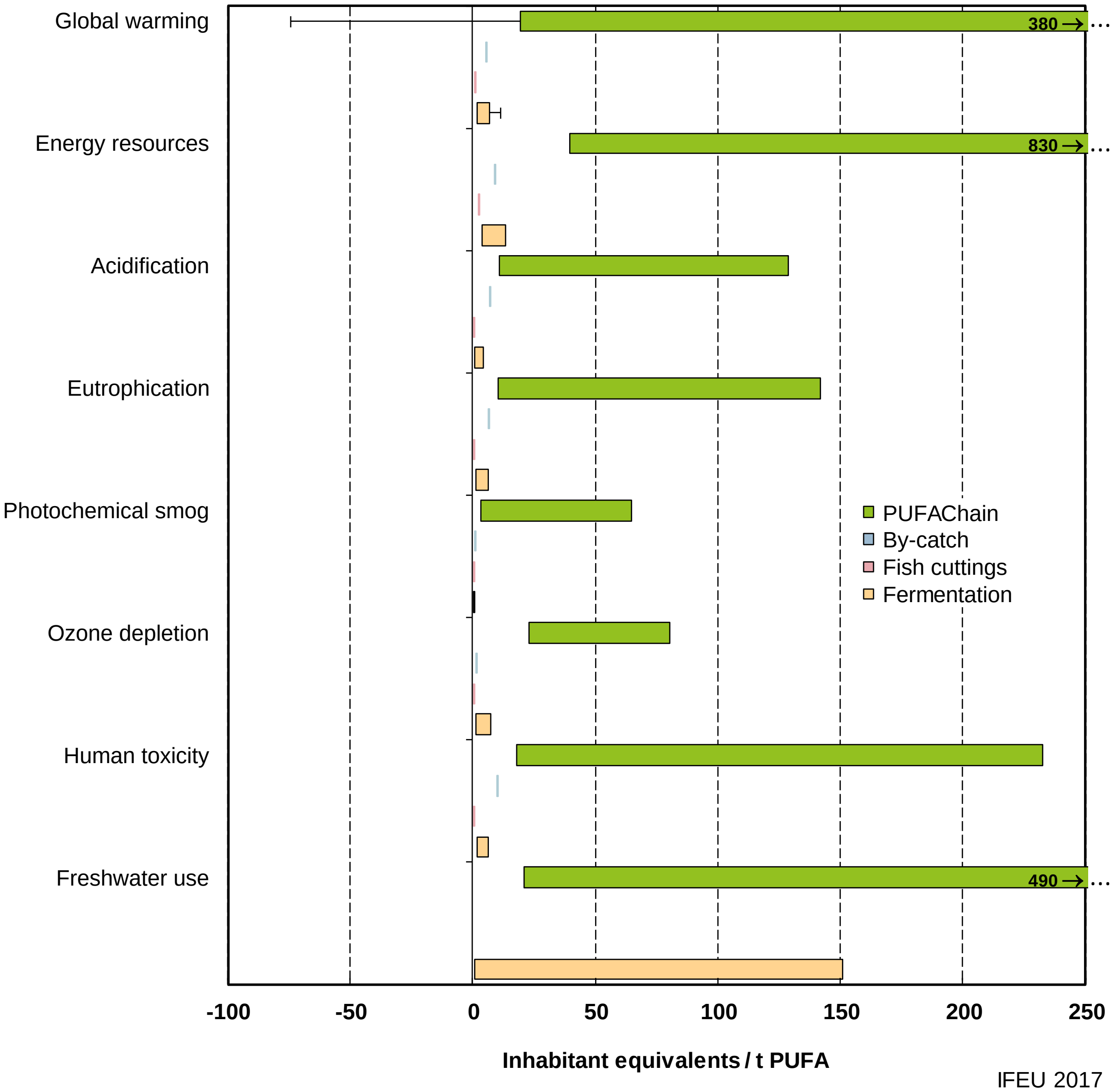

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Fig. 4-4 Ranges of results for all analysed PUFAChain scenarios and all reference systems. For the reference systems fish cuttings and by-catch, ranges only consist of single values. The maximal effect of potential land use changes on global warming are depicted as thin bar. Results are expressed in inhabitant equivalents (IE)[9].

Highly productive, genetically modified organisms used in fermentation have advantages and disadvantages compared to algae cultivation in photobioreactors.

One main reason for the better performance of fermentation processes e.g. regarding their carbon footprints is that the genetically modified heterotrophic microorganisms used in fermenters today reaches up to a 25-fold greater biomass density and up to 5-fold greater PUFA content in the biomass. This means that about 125 times less medium needs to be handled per tonne of PUFA. In contrast, algae from photobioreactors deliver more co-products that can be used as feed. This can avoid enormous environmental burdens elsewhere if conventional feed cultivation (e.g. soybean) is replaced. Thus, optimisation of algae strains should aim at increasing PUFA content while maintaining protein content.

If co-products are efficiently utilised, algae biorefineries can indirectly release more land than they occupy and under certain circumstances even compensate for greenhouse gas emissions.

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 arable 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 may substitute for agricultural products. This can lead to arable land savings up to 7 times greater than the land needed for algae cultivation (Fig. 4-5). 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

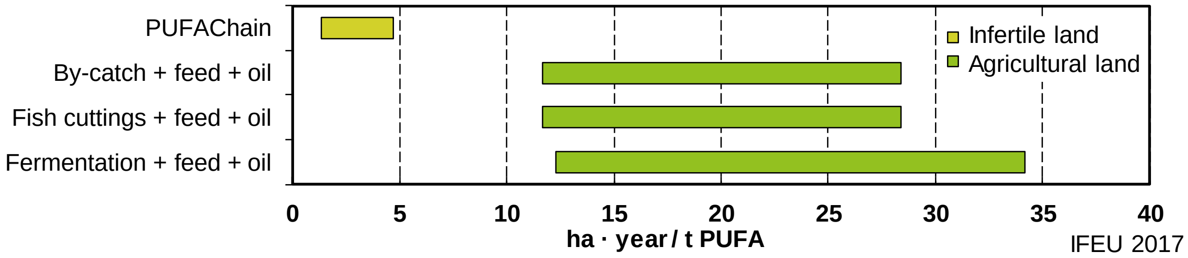

Fig. 4-5 Ranges of direct land use for all analysed PUFAChain scenarios and all reference systems. In contrast to previous figures, PUFAChain scenarios without credits for co-products are compared to a basket of commodities including main and co-products.

4.2.3 Perspectives

Future competition for CO_2 may limit algae cultivation – in particular if mass production is aimed for.

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. 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 instead of mass production.

Whatever the case, it is better to produce PUFAs such as EPA and DHA using algae instead of relying on increased fishing to service the growing demand.

Wild fish catches for the purpose of PUFA extraction cannot be increased much further without risking serious harm or even the total collapse of entire marine populations (chapter 3.3). Cultivated microorganisms such as algae can fill this gap and help save fish populations and thus the marine environment. However, any alternative without strict volume limitations, such as the utilisation of fish residues, requires more effort than established fisheries and fish oil production, regardless of whether algae cultivation of fermentation are used (Fig. 4-4). How far algae cultivation can compete with fermentation processes using decades-old proven technology should be evaluated again once the first industrial scale photobioreactor facilities are operating.

Algae in general harbour great potential as a healthy and environmentally-friendly alternative to food animals.

High-value food constituents, which otherwise are primarily available in foods of animal origin, can be produced using algae. This project has demonstrated that fish-based PUFAs can be substituted. Another example for substitution of food components could be algae-based essential amino acids with application in food and feed supplementation. For the environment, this means that overfishing and its possible catastrophic environmental consequences, or resource-intensive and partially environmentally polluting fish aquaculture[10], can be reduced. In addition, algae contain other healthy bioactive compounds and molecules (carotenoids, phycobilins, other fatty acids, polysaccharides, vitamins, and sterols). To date, only the first steps have been taken to investigate this potential for healthy and environmentally-friendly future nutrition. This study shows that great advances have nevertheless been achieved in only a few years and also demonstrates future approaches for optimising the environmental impacts of algae production.

Moreover, natural algae cultivated under light contain valuable secondary plant substances[11]. A future strategy may therefore be to use natural algae as a whole, without isolating individual components, instead of fish as an ingredient for healthy meals. This is already a common aspect of traditional Asian cuisine using macroalgae (seaweed). This could represent a possible alternative compensating for a less well-balanced and fish-reduced diet caused by overfishing, rather than using capsules and isolated dietary supplements.

Intensified research with regard to utilisation options, production technology and environmental compatibility of algae-based foodstuffs as one component of sustainability is therefore a useful focus of future research, considering the rising global population and declining fish stocks.

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[10] Not an alternative in the case of PUFAs, because fish do not produce PUFAs, but only accumulate them (also see chapter 3.3).

[11] Mostly not present in microorganisms produced in fermenters.

4.3 Summary: socio-economic assessment

A socio-economic assessment was performed for the PUFAChain by the project partner Wageningen University and Research. The result is an international working paper that documents the approach, method and results of this socio-economic assessment [van der Voort et al. 2017]. This includes a macro-economic assessment, a LCC (Life Cycle Costing, micro-economic) analysis, followed by an overall SWOT (strengths, weaknesses, opportunities, and threats) analysis taking into account the different parts with emphasis on the socio-economic aspects.

The **macro-economic assessment** focuses on market analysis and competiveness and provides information about market and price developments. Both peer-reviewed and generic data sources were used. The **LCC (micro-economic) analysis** uses both existing information and tools in development from the Interreg project EnAlgae, combined with data from the project partners. UNEP/SETAC guidelines for LCC were taken into account. The macro- and micro-economic analyses both identify profitability and market competiveness of the systems. The **socio-economic analysis** includes all major social aspects, such as impacts on employment and public acceptance of new technologies. Institutional, legislative and political aspects are included if applicable. UNEP/SETAC guidelines for sLCA (social life cycle assessment) and recent methodological literature are taken into account. The **SWOT analysis** has been updated during the project and takes into account the results of the other three analyses. When useful, reference systems/products were assessed as well.

4.3.1 Macro-economic assessment

The PUFAChain process will produce algae in industrial-scale photobioreactors (PBRs). After oil and PUFA extraction from the algae the extraction cake from these algae can be sold on various markets. The main focus of the PUFAChain is on purified EPA or DHA or EPA/DHA mixtures containing high EPA/DHA levels.

EPA/DHA consumer market- The global EPA/DHA consumer market has been growing fast and is expected to keep on growing in the future.

Driving factors are positive clinical research outcomes, regulatory recognition, increasing consumer health awareness and improved living standards on several continents. The largest EPA/DHA market segments by application are respectively dietary supplements, pharmaceuticals, infant formulas and functional foods. In terms of market value, the largest market segment is concentrates because of their higher prices, particularly for pharmaceuticals. Key suppliers have developed ultra-high concentrates, which have EPA and DHA concentrations of up to 90% for both the pharmaceutical and the nutraceutical market. At the moment the largest share of the EPA/DHA oil market volume and value originates from wild fish and only a minority share from algae, but algae oils have a larger share in market value than in volume. De EPA/DHA consumer market leader sells algae based DHA (mainly for infant formulas) and EPA/DHA products. They are produced by heterotrophic microorganisms that are grown on sugar in closed fermentation vessels. The need to find new sources of EPA and DHA because of depleting wild fish stocks and concerns about contaminations is an opportunity for algae based PUFAs. The absence of fishy taste/smell and appealing labels like “vegetarian/vegan”, “kosher” or “organic” distinguish algal oil from fish oil. For the time being algae EPA/DHA producers have to deal with higher production costs than their fish oil based EPA/DHA competitors, highly competitive pricing and a high price sensitivity among food industries and final consumers. In addition PUFAs from algae have to compete with PUFAs from fermentation that are in the same or lower price range and contain higher lipid/PUFA levels. In addition, new market players have to deal with powerful food and pharmaceutical multinationals. Only five companies have about 75% of the EPA/DHA market share.

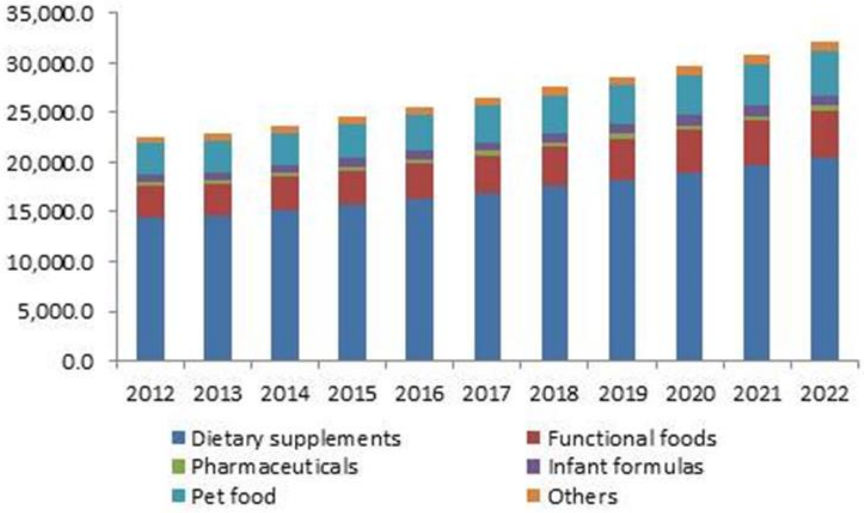

Fig. 4-6 European EPA/DHA ingredients market size by application, 2012-2022 (tonnes) (From: [Packaged Facts 2012])

Aquaculture feed market- At the moment already more than half of the fish we consume is farmed rather than wild caught. This leads to an equally increasing aquaculture feed market. The main ingredient in global aquafeed is soybean meal followed by fish meal. Leading companies in the aquafeed sector are increasingly looking at ways in which algae and other ‘alternative’ ingredients can reduce the sector’s dependence on fish meal (FM) and fish oil (FO). One of the market key players is now able to provide (approved) feed formulations with different EPA/DHA ratios from fermentation.

Livestock feed market- To feed the future world population we will have to produce much more food and the demand for meat and dairy is expected to increase even stronger relative to population growth. In the Netherlands, where several global feed market leaders are located, there is a search for feed alternatives as substitution for imported soya, and algae production is possible alternative for regionally produced protein. To be able to compete with soybean as protein source, with fish oil as PUFA source and with other livestock feed additives, the production price of algae must be decreased.

4.3.2 LCC (micro-economic) analysis

The LCA and LCC focused on a potential PUFA supply chain for 2025. Two main regions were assessed in six scenarios (see also Table 3-1): Southern Europe (Lisbon) and Central Europe (Munich). In addition, one scenario for Northern Europe (Oslo) was added. Either a 10 hectare (net) area or a 100 hectare (net) area was taken into account per scenario, respectively representing conservative and optimistic scenarios for 2025. The following strains of algae were used for the calculations: *Prorocentrum cassubicum*, *Thalassiosira weissflogii* and a combination of *Chloridella simplex* and *Raphidonema nivale* Lagerheim. The potential algae strains were screened during the course of the project.

The LCC is therefore mainly assessing the influence of geography/climate, scale and algae strain on the costs of a potential mature production plant for 2025. This analysis leads to more insight whether a potential PUFA supply chain based on algae can compete with other sources of EPA / DHA. The capital and operational costs of all separate supply chain steps (algae production and processing, algae harvesting, cell disruption and drying and algae biomass processing by supercritical CO_2-extraction and oil processing) for producing PUFAs from different algae strains are taken into account. This results in a cost price per kg PUFA (functional unit). The LCC and this cost price highlight the most significant cost items in relation to the overall production yield per strain. The LCC offers insights and options for improvements in the PUFAChain to achieve a mature supply chain for 2025.

Table 4-2 and Table 4-3 show LCC outcomes for PUFA production from *Prorocentrum* and *Thalassiosira* in Southern and Central Europe for conservative conditions (including a scale of 10 ha) and optimistic conditions (including a scale of 100 ha) .

Table 4-2 LCC outcome for combined PUFA production (Prorocentrum cassubicum) in Southern and Central Europe under conservative and optimistic conditions (on 10 and 100 ha scale, respectively)

	Values for combined PUFA production	
Scenario/cost price PUFA (€/kg)	**Conservative (10 ha)**	**Optimistic (100 ha)**
Southern Europe	848	704
Central Europe	1,196	997

Table 4-3 LCC outcome for initial combined PUFA production (Thalassiosira weissflogii) in Southern and Central Europe under conservative and optimistic conditions (on 10 and 100 ha scale, respectively)

	Values for initial combined PUFA production	
Scenario/cost price PUFA (€/kg)	**Conservative (10 ha)**	**Optimistic (100 ha)**
Southern Europe	1,359	468
Central Europe	2,058	753

Fig. 4-7 and Fig. 4-8 show the share of each per process/supply chain step in the total costs for PUFA production from combined PUFA production in Southern and Central Europe for conservative conditions (including a scale of 10 ha) and optimistic conditions (including a scale of 100 ha).

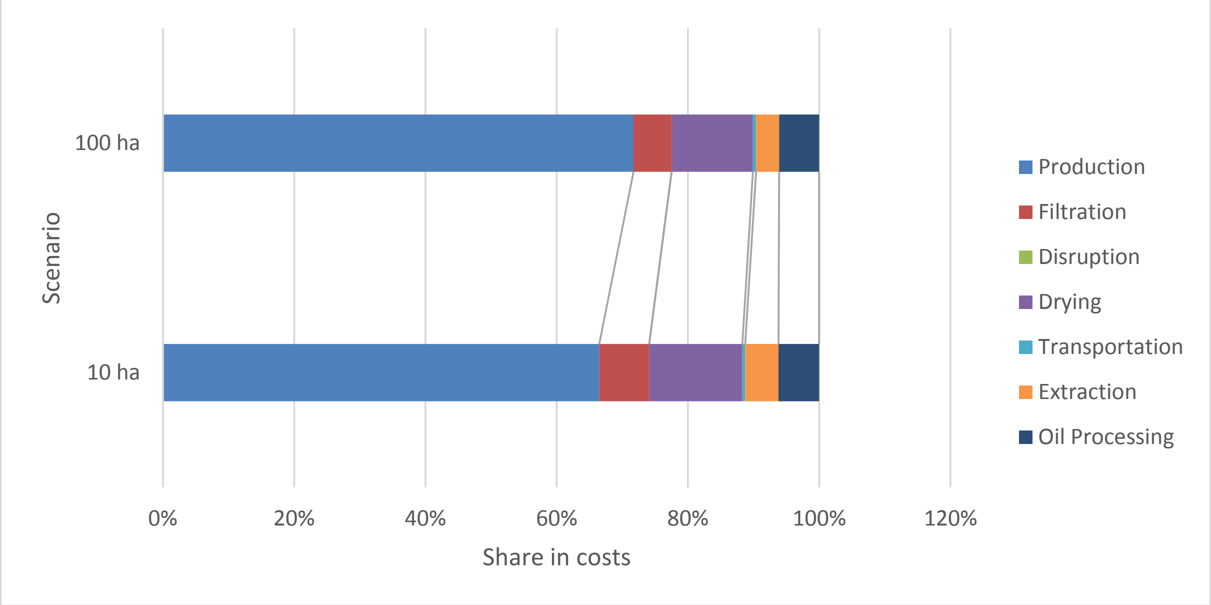

Fig. 4-7 LCC outcome for combined PUFA production in Southern Europe under conservative or optimistic conditions (on 10 and 100 ha scale, respectively)

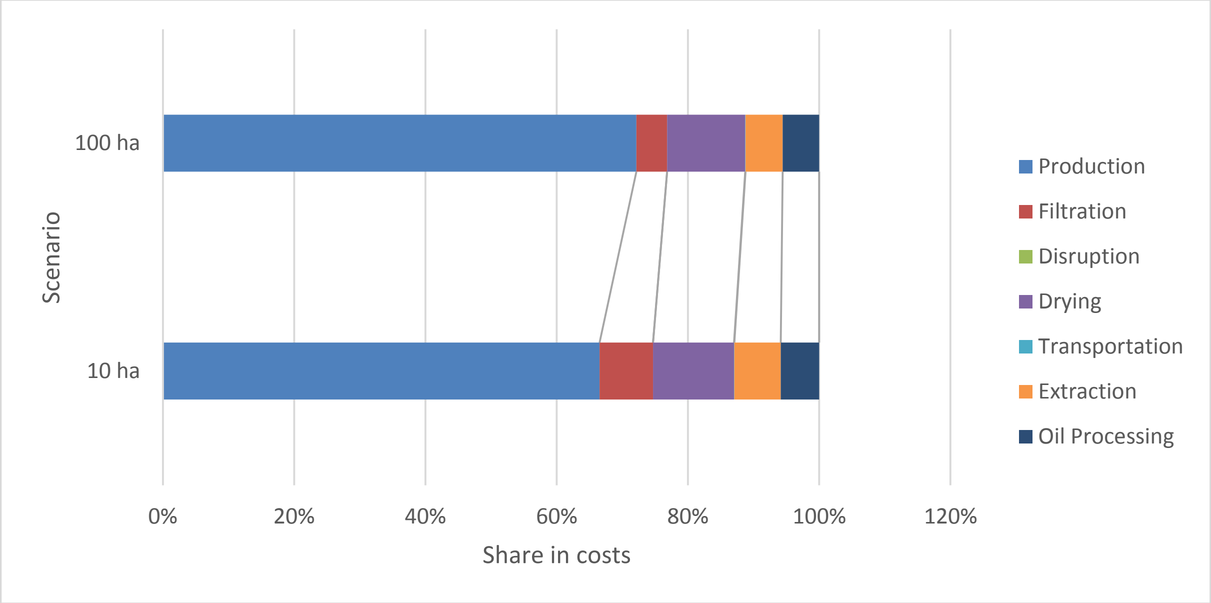

Fig. 4-8 LCC outcome for combined PUFA production in Central Europe under conservative or optimistic conditions (on 10 and 100 ha scale, respectively)

In Table 4-4 LCC outcomes for PUFA production from Algal Crop Rotation (ACR) scenarios for Southern and Central Europe under conservative conditions (including a scale of 10 ha) and under optimistic conditions (including a scale of 100 ha) as well as Northern Europe (optimistic conditions, 100 ha) are shown.

Table 4-4 LCC outcome for dedicated EPA production in Southern and Central Europe

	Values for dedicated EPA production	
Scenario/cost price PUFA (€/kg)	**Conservative (10 ha)**	**Optimistic (100 ha)**
Southern Europe	1,156	932
Central Europe	2,344	1,915
Northern Europe	-	3,909

Based on the macro-economic information the price ranges for algae or fish oil are around €400 – €1,500 per kg EPA/DHA. This price range is certainly achievable for EPA/DHA from algae under most of the current expected mature production scenarios. The first conclusion is that economically viable production of PUFAs from algae is feasible.

To determine the most viable option for improvement of the PUFA value chain, production costs were considered the most logical first assessment parameter. Depending on the scenario, production costs varied between 62% and 80% of the total costs. Therefore the effects of three different options were analysed: increase of biomass production, decrease in production CAPEX and decrease in production OPEX. In the sensitivity analysis the biggest production costs were selected to determine the focus for further improvements. The following results were found.

- Yield; a yield increase translates almost directly into a similar decrease in costs, thus a lower cost price. This effect is similar for all scenarios.
- CAPEX; a reduction of the CAPEX for the production costs of algae of 5% translates into around 2% reduction in cost prices. This effect is slightly stronger for Central Europe due to the higher CAPEX for production of algae in Central Europe.
- OPEX; a reduction of the OPEX for the production costs of algae of 5% translates into around 2% reduction in cost prices. This effect is slightly stronger for Southern Europe compared to Central Europe.

Additionally, two alternative options were investigated. First, a cheaper location was considered. All scenarios turned out to be the most expensive areas/regions for each country. A change to a more rural community would significantly impact the cost of land per scenario. The second option was related to the LCA assessment. Renewable energy, in this case solar power plants, is competitive in price with fossil energy. Based on research on price developments of solar parks in Europe a lower price of electricity was considered. Based on the research, the effect of these options on the reduction of cost prices is as follows:

- The effect of a change in location is almost 20% for Southern Europe and almost 30% for Central Europe.
- The effect of cheaper electricity is around 8% for Southern Europe and around 7% for Central Europe.

Both land and electricity prices constituted a major part of production costs. The current production scenarios are all in the vicinity of big cities/capitals of each country. A shift toward a more rural community for production would have a significant effect on cost prices. Electricity costs were based on a market report for solar power plant installations. Local renewable energy power plants, especially solar based, could provide cheaper electricity.

The LCC analysis outcome shows that production in Southern Europe (Lisbon) seems a more viable option compared to production in Central Europe (Munich). The scenario Initial combined PUFA production (*Thalassiosira*) under optimistic conditions (including a scale of 100 ha) in Southern Europe has the best expected performance, followed by three other scenarios; Combined PUFA production (*Prorocentrum*) under optimistic conditions (including a scale of 100 ha) in Southern Europe, Initial combined PUFA production (*Thalassiosira*) under optimistic conditions (including a scale of 100 ha) in Central Europe and Combined PUFA production (*Prorocentrum*) under conservative conditions (including a scale of 10 ha) in Southern Europe.

4.3.3 Socio-economic analysis

A socio-economic evaluation was performed for aspects of (an assumed mature) PUFAChain concerning communities on a local level (Labour conditions (health and safety), employment opportunity, access to material resources and living conditions) and society in general (Consumers' health and safety, public commitment to sustainability issues, legal regulatory barriers and public perception). For labour conditions (both health and safety) no differences are expected for the different production scenarios in PUFAChain. Employment opportunities are expected to be more important in Lisbon as opposed to Munich and Oslo. No differences are expected between the three regions in how algae production affects access to material resources by local populations. Living conditions, similar to employment opportunities are expected to improve most for Lisbon, compared to the other regions. This is because production in Portugal will take place in more remote areas where the contribution to living conditions and employment opportunities is relatively more substantial. Consumers' health and safety, public commitment to sustainability issues and public perception are not expected to be different among the scenarios. For all scenarios in the PUFAChain however, legal regulatory barriers are to be expected, i.e. have to be resolved. Expectations for the different PUFAChain scenarios were compared to three alternative scenarios: PUFAs produced by fermentation, from fish cuttings or from by-catch. Safety conditions for PUFAs from fish cuttings and by-catch are expected to be more hazardous and in these sectors less employment opportunities are expected since they are part of a well-developed supply chain. PUFA production by fermentation is expected to be less advantageous concerning access to material resources as there is a large demand for sugar production for this process which requires arable land. PUFAs from fish cuttings and by-catch are expected to be less advantageous to health, regarding the risk for contaminants and impurities in natural food chains. In addition, both processes are linked to unsustainable fisheries and therefore will trigger less public commitment. Regarding legislation, PUFAs from fermentation are already authorised for feed/food/nutraceuticals, while PUFAs from fish oil are questioned regarding their application in infant formula. Finally, PUFAs from fish oil are linked to unsustainable fisheries, those from fermentation to land use for sugar (food) production, while the PUFAChain process mainly requires light and CO_2.

4.3.4 SWOT analysis

Fig. 4-9 shows a SWOT analysis for the (assumed mature) PUFAChain. It is based on several micro- and macroeconomic factors as well as socio-economic and general sustainability issues. Environmental issues are left out of this SWOT analysis since they are addressed in more detail in the LCA by IFEU - Institute for Energy and Environmental Research Heidelberg.

Strengths

The production of omega 3 from algae has several strong advantages compared to other sources of omega 3.

- Production of pure EPA/DHA enabling tailor-made dosing
- Production process does not contribute to pressure on wild fish stocks, is environmentally friendly, does not need arable land and can be labelled as vegan/vegetarian, bio-based, halal, kosher and non-GM
- Production can be (presumably) located in colder climates and combined with fermentation processes.
- EPA/DHA from PUFAChain are pure and high value products and by-products can be used for feed applications

Weaknesses

Weaknesses of PUFAChain consist of risks on one hand and insecurities in the development of the PUFAChain on the other.

- Energy consumption for mixing may be equal to or higher than for fermentation
- PUFA production from fish oil and fermentation are already mature production chains. This involves selection of suitable algae species, optimum growing conditions for PUFA production, optimum PUFA extraction from algae biomass, optimum PUFA purification technologies and shelf life optimization
- Profitability is still questionable due to productivity, difficulty of patenting, uncertain business plans and extensive authorization procedures

Opportunities

The present situation holds a number of opportunities for the production and marketing of omega3 from algae. These include:

- Search for PUFA alternatives due to declining fish stocks
- Growing market demand
- Positive image

Threats

The present situation holds a number of threats that could have a negative effect on the development of the PUFAChain production process.

- New competitors producing PUFA from algae or yeasts
- More strict regulations for algae products in pharm, food and feed
- Risk of allowance products in EU derived from GMO
- Dropping market prices due to higher PUFA availability, increased production or decreased demand
- New (negative) insights on health effects of DHA/EPA from PUFAChain
- Public questioning of sustainability of algae PUFA

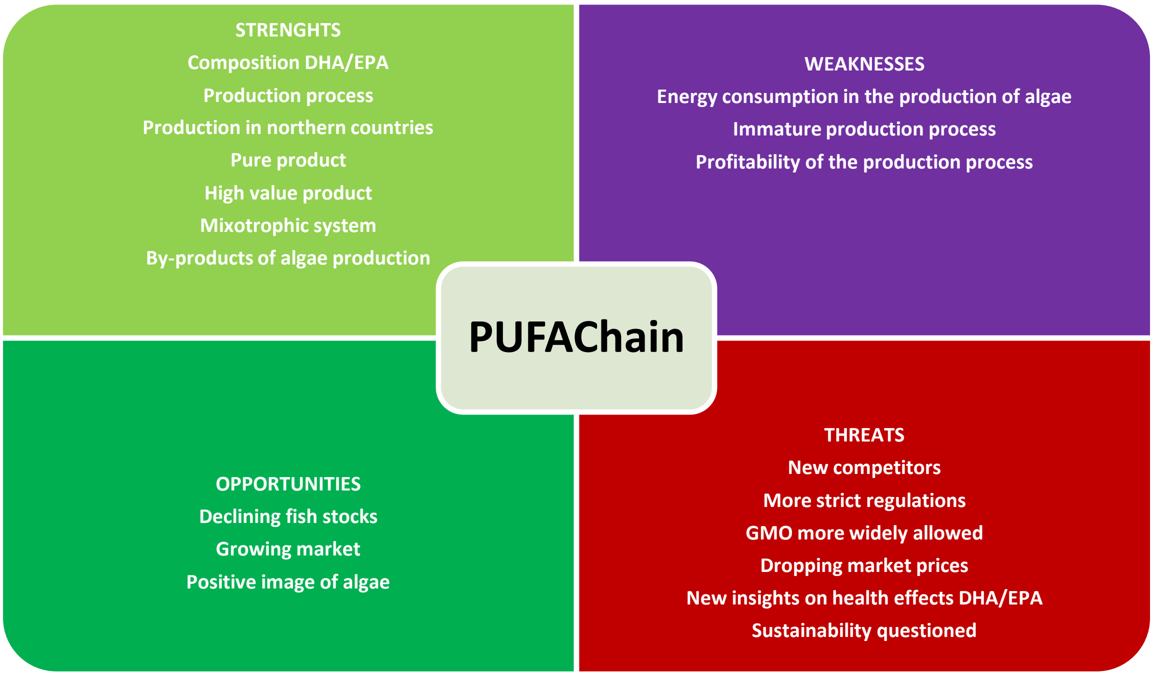

Fig. 4-9 SWOT analysis for the (assumed mature) PUFAChain

4.4 Integrated assessment

The integrated sustainability assessment joins and connects results on individual sustainability aspects to give an integrated view on sustainability of algae-based PUFA production.

In a first step (chapter 4.4.1), indicators and results for relevant scenarios were collected from the assessments of individual sustainability aspects (for summaries see chapters 4.1 – 4.3). These scenarios represent potential algae biorefineries according to the PUFAChain concept and of alternative systems that would be replaced, respectively. This results in an overview of all relevant sustainability impacts.

In a second step (chapter 4.4.2), scenarios are compared to each other to determine, which advantages and disadvantages may result from the realisation of selected front-runner scenarios.

4.4.1 Overview of sustainability impacts

Selection of indicators

Various technological, environmental and socio-economic aspects relevant for sustainability have been studied in individual assessments, which form the basis of this integrated sustainability assessment (for summaries see chapters 4.1 – 4.3). The performance of assessed PUFAChain scenarios and conventional reference systems regarding all these aspects is quantified or qualitatively rated using various indicators.

They include sustainability indicators in the strict sense, which depict impacts on objects of protection such as climate or consumers' health. Further indicators depict barriers that may prevent the realisation of the scenario. Such barriers may lead to substantially worse real sustainability impacts when trying to realise a scenario, for which low potential impacts were anticipated. Another type of indicators reflects risks that may lead to substantially worse sustainability impacts in case of accidents etc. This is needed because scenarios are only assessed under routine operation conditions thus excluding such rare incidents by definition. The suitability and scientific validity of the indicators has been verified in the individual assessments. In the integrated sustainability assessment, those indicators were chosen from the set of available indicators, which give additional information that is relevant for decisions between the assessed options. Indicators on local environmental impacts have been combined into five summarising indicators (see [Keller et al. 2017] for original indicators). For an overview and a short description of the indicators see Table 4-5.

Additional indicators

There are indicators like CO_2 avoidance costs, which connect aspects of more than one pillar of sustainability (here: environment and economy) so that they can only be added in the integrated assessment. They indicate the efficiency of reaching a certain target and can only be interpreted if it is sufficiently certain that the target (in this example avoidance of greenhouse gas emissions compared to a certain reference) is reached. Since this is not the case in any assessed scenario taking the bandwidths from conservative to optimistic into account, such indicators were not added.

Table 4-5: Overview of sustainability indicators selected for the integrated assessment

Impact category	Short description
Technology	
Maturity	Technical maturity of involved processes (potential barrier).
Availability of infrastructure	This indicator refers to the availability of required plants, installations and facilities (potential barrier).
Use of limited feedstock	Dependence on e. g. by-products of other processes as main feedstock or arable land for its production (potential barrier).
Use of GMOs	Use of genetically modified organisms (here: microorganisms) in closed fermentation facilities (risk).
Toxicity risks	Risk of toxic effects e. g. by contaminants in products (risk). This is not connected to toxic effects of emissions in routine operations (see indicator human toxicity).
Risk of explosions and fires	Risk of explosions and fires within industrial facilities like biorefineries (risk).
Environment	
Global warming	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide (CO_2), a number of other gases like methane (CH_4) and nitrous oxide (N_2O) are included.
Energy resources	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Acidification	Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword ‘acid rain’).
Eutrophication	Input of excess nutrients into sensitive ecosystems. E.g. nitrogen and phosphorous species contribute to this.
Photochemical smog	Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword ‘ozone alert’ or ‘summer smog’).
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as chlorofluorocarbons (CFCs) or nitrous oxide (keyword ‘ozone hole’).
Human toxicity (respiratory inorganics)	Damage to human health due to air pollutants from routine operation such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword ‘winter smog’ or ‘London smog’). This is not connected to toxicity risks from exceptional product contaminations (see indicator toxicity risks).
Freshwater use	Use of fresh surface and groundwater resources (‘blue’ water)
Water	Local water availability for ecosystems and its quality.
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Fauna	Local biodiversity among animals is affected e.g. by the presence of diverse habitats.
Flora	Biodiversity among plants on and around cultivated areas is affected e.g. by weed control measures.
Landscape	Characteristics and diversity of the landscape.

Table 4-5 (continued)

Impact category	Short description
Economy	
Fixed capital investment	Sum of invested capital for the biorefinery facility.
Production costs	Costs of producing a certain amount of product.
Society	
Labour conditions (safety)	Workplace safety: Protection against accidents, toxic effects etc.
Employment opportunity	Job generation in a local community
Living conditions	Effects on living conditions such as landscape changes, economic development etc.
Consumers' health and safety	Protection against toxic effects by product contaminations etc.
Public commitment to sustainability issues	Support of the facility and its products by the public because of (perceived) sustainability advantages.
Legal regulatory barriers	Existing regulation that are hard to fulfil in particular for SMEs developing new processes and products.
Public perception	Image of the production facility and its products.

Categorisation

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly. Results are categorised on a five-part scale like the qualitative indicators. Each bin represents 20 % of the range from worst to best result for each indicator.

Identification of front-runner scenarios

Results for indicators and assessed standard scenarios are shown in Table 4-6**.** None of the scenarios scores best in all indicators. Therefore, no best solution can be identified on an entirely scientific basis without value-based choices. This is an almost unavoidable result if the sustainability assessment of a system with a certain degree of complex is truly comprehensive. Valuable decision support can still be provided to involved stakeholders such as businesses, policymakers or consumers if advantages and disadvantages of selected decision options are made transparent. The following front-runner scenarios, which perform best regarding certain indicators, are selected for a detailed discussion in chapter 4.4.2:

- PUFAs from fish cuttings: This scenario shows lowest potential global / regional environmental impacts.
- PUFAs from fermentation: This option performs in several aspects similar to PUFAs from fish cuttings but does is not as strictly limited by feedstock availability.
- Initial combined PUFA production, Southern Europe under optimistic conditions: This scenario potentially performs best in costs and is among the best in many other categories such as toxicity risks, local environmental impacts or employment opportunities.

Table 4-6: Overview of results for PUFAChain scenarios and its alternatives. GMO: genetically modified organism, N/D: no data.

			Conservative						
			PUFAChain scenarios						
	Indicator	Unit	Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North
Technology	Maturity	-	-	0	-	- -	0	- -	- -
	Availability of infrastructure	-	-	-	- -	-	-	- -	- -
	Use of limited feedstock	-	0	0	0	0	0	0	0
	Use of GMOs	-	+	+	+	+	+	+	+
	Toxicity risks	-	+	+	+	+	+	+	+
	Risk of explosions and fires	-	0	0	0	0	0	0	0
Environment	Global warming	t CO_2 eq. / kg PUFAs	1.0	1.7	1.0	2.3	4.0	1.7	2.1
	Energy resources	GJ / kg PUFAs	17.9	30.4	17.5	40.1	68.4	30.2	36.9
	Acidification	kg SO_2 eq. / kg PUFAs	3.4	5.7	3.3	5.4	9.0	5.6	6.9
	Eutrophication	kg PO_4 eq. / kg PUFAs	0.2	0.4	0.2	0.5	0.8	0.4	0.5
	Photochemical smog	kg ethene eq. / kg PUFAs	0.2	0.4	0.2	0.8	1.3	0.4	0.5
	Ozone depletion	g CFC-11 eq. / kg PUFAs	2.9	4.7	2.5	3.4	5.6	4.1	5.1
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg PUFAs	3.4	5.7	3.3	5.5	9.3	5.7	7.0
	Freshwater use	m³ / kg PUFAs	26.1	46.7	29.6	5.4	10.2	4.0	5.0
	Water	-	- -	- -	- -	-	-	-	0
	Soil	-	-	-	-	-	-	-	-
	Fauna	-	-	-	-	-	-	-	-
	Flora	-	-	-	-	-	-	-	-
	Landscape	-	0	0	0	0	0	0	0
Economy	Production costs	€ / kg PUFAs	848	1359	1156	1196	2058	2344	N/D
	Fixed capital investment	Million €	59	59	61	68	68	70	N/D
Society	Local community								
	Labour conditions safety	-	+	+	+	+	+	+	+
	Employment opportunity	-	++	++	++	+	+	+	+
	Living conditions	-	+	+	+	0	0	0	0
	General society								
	Consumers' health and safety	-	++	++	++	++	++	++	++
	Public commitment to sustainability issues	-	+	+	+	+	+	+	+
	Legal regulatory barriers	-	- -	- -	- -	- -	- -	- -	- -
	Public perception	-	++	++	++	++	++	++	++

Legend:	worst 20% of range	20%-40% of range	average +/- 10%	60%-80% of range	best 20% of range

Table 4-6 (continued)

Optimistic										
PUFAChain scenarios							Alternatives to PUFAChain			
Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North	PUFAs from fermentation (high)	PUFAs from fermentation (low)	PUFAs from fish cuttings	PUFAs from by-catch
- -	-	- -	- -	-	- -	- -	0	0	0	0
-	-	- -	-	-	- -	- -	0	0	0	0
0	0	0	0	0	0	0	0	0	- -	-
+	+	+	+	+	+	+	-	-	+	+
+	+	+	+	+	+	+	+	+	0	0
0	0	0	0	0	0	0	-	-	0	0
0.3	0.2	0.2	0.4	1.0	0.3	0.4	0.07	0.02	0.01	0.06
4.1	3.2	3.9	6.2	16.6	4.9	6.0	1.1	0.3	0.2	0.7
0.8	0.8	0.9	1.4	2.0	1.2	1.5	0.29	0.07	0.01	0.47
0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.04	0.01	0.00	0.04
0.1	0.1	0.1	0.1	0.4	0.1	0.2	0.02	0.00	0.00	0.02
2.2	1.6	1.7	2.2	1.9	1.8	1.8	0.51	0.08	0.00	0.08
0.7	0.7	0.9	1.4	2.0	1.2	1.6	0.25	0.07	0.02	0.40
3.6	17.1	22.1	4.8	4.0	2.0	2.0	14.4	0.05	0.00	0.00
-	-	-	0	0	0	0	- -	- -	-	-
+	+	+	+	+	+	+	- -	- -	0	0
+	+	+	+	+	+	+	- -	- -	-	-
+	+	+	+	+	+	+	- -	- -	-	-
0	0	0	0	0	0	0	-	-	+	+
704	468	932	997	753	1915	3903	900	900	900	850
545	545	569	628	628	645	867	N/D	N/D	N/D	N/D
+	+	+	+	+	+	+	+	+	-	-
++	++	++	+	+	+	+	+	+	0	0
+	+	+	0	0	0	0	0	0	0	0
++	++	++	++	++	++	++	++	++	+	+
+	+	+	+	+	+	+	+	+	- -	- -
- -	- -	- -	- -	- -	- -	- -	++	++	+	+
++	++	++	++	++	++	++	+	+	-	-

4.4.2 Comparison of options for PUFA production

This chapter discusses advantages and disadvantages that are expected to arise from the realisation of selected front-runner scenarios (see chapter 4.4.1 for selection criteria). To this end, all scenarios are compared to one front-runner scenario at a time, which serves as a benchmark. Alternatives are considered advantageous (+) and disadvantageous (-) regarding a certain aspect if they have qualitative rating differing by one grade or if quantitative values are below 75% (3/4) and above 133% (4/3) of the benchmark value, respectively. The rating very advantageous (++) and very disadvantageous (- -) are given if a qualitative rating are at least two grades different or if the ratio of quantitative ratings is below 33% or above 3.

PUFAs from fish cuttings

This scenario is an alternative to PUFA provision from algae. If this would be realised, the following advantages are to be expected and the following disadvantages have to be accepted (Table 4-7):

- No other assessed option for PUFA provisions performs substantially better regarding the following indicators: Maturity, Availability of infrastructure, Use of GMOs, Toxicity
- risks, Risk of explosions and fires, Climate change, Energy resources, Acidification, Eutrophication, Photochemical smog, Ozone depletion, Human toxicity, Freshwater use and Landscape
- Severe drawbacks are:
  - All other scenarios are less dependent on limited resources. Fish cuttings are by-products of fish processing, which are available in limited amounts. Hence it is to be expected that PUFAs from fish cuttings can only satisfy parts of a rising PUFA demand. A further increase of fish residue extraction capacity may lead to unsustainable effects by market pull. For example, fish processing facilities may sell less valuable but still edible parts of fish for PUFA extraction rather than to consumers. This way, the amount of consumed PUFAs stays about constant but extraction causes e.g. unnecessary costs and environmental impacts.
  - Under optimistic conditions, PUFA provision from algae can cause much lower local environmental impacts on fauna and flora and lower impacts on soil and partially on water. If co-products of algae-based PUFA production are converted into valuable products such as feed, they can replace substantial amounts of conventional feed. This potential is expected to be lower for fish cuttings. This way, algae-based PUFA production can indirectly set much more arable land free than the land it uses. If algae cultivation additionally uses sites such as disused industrial areas and takes ecological optimisation measures such as establishing meadows underneath photobioreactors, its local environmental performance can be positive. These potential advantages cannot be achieved by PUFA production from fish cuttings.
  - Workplace safety and employment opportunity are expected to be much better for many other scenarios.

  - PUFA extraction from fish residues is linked to unsustainable fisheries in public perception and is therefore expected trigger less public commitment. Lack of support may hinder the realisation of such fish residue extraction facilities.
- Further smaller drawbacks exists where smaller advantages of individual other scenarios are not realised (see (+) ratings in Table 4-7).

Similar advantages and disadvantages would result from PUFA extraction from by-catch.

Main conclusions on PUFAs from fish cuttings and by-catch:

These options can be used immediately for additional PUFA provision because technology and big parts of the required infrastructure are in place. If issues regarding safety and public perception are solved, there is no major concern about sustainability issues. Therefore, these options should be implemented first. However, their potential contribution to a sustainable PUFA provision is limited because feedstocks are available only in certain amounts. Furthermore, it is not expected that these options can additionally provide as much sustainable feed products as algae-based PUFA production. The problem of feed production thus has to be solved by other means.

PUFAs from fermentation

This scenario is a further alternative to PUFA provision from algae. It has several similar advantages and disadvantages as PUFA provision from fish cuttings with the following important differences (Table 4-8). Since the range of impacts (scenarios low / high) is determined by uncertainty, advantages and disadvantages are discussed in the following for the case with higher impacts:

- It is not strictly limited by availability of by-products to be used as feedstock. Instead, less strict limitations exist because of the need for limited arable land. This is needed to produce the main feedstock sugar.
- It causes mostly higher environmental burdens than PUFAs from fish residues but compares qualitatively similarly to algae-based PUFAs from environmental and economic angles with smaller advantages and bigger disadvantages.
- Algae-based PUFAs have smaller advantages over fermentation-based PUFAs regarding social issues and toxicity risks.
- However, fermentation uses GMOs and may come along with higher hazard risks in production facilities.

Table 4-7: Comparison of all other scenarios to the benchmark scenario “PUFA from fish cuttings”. GMO: genetically modified organism, N/D: no data.

			Conservative						
			PUFAChain scenarios						
	Indicator	Unit	Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North
Technology									
	Maturity	-	-	0	-	- -	0	- -	- -
	Availability of infrastructure	-	-	-	- -	-	-	- -	- -
	Use of limited feedstock	-	++	++	++	++	++	++	++
	Use of GMOs	-	0	0	0	0	0	0	0
	Toxicity risks	-	+	+	+	+	+	+	+
	Risk of explosions and fires	-	0	0	0	0	0	0	0
Environment									
	Global warming	t CO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Energy resources	GJ / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Acidification	kg SO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Eutrophication	kg PO_4 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Photochemical smog	kg ethene eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Ozone depletion	g CFC-11 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Freshwater use	m^3 / kg PUFAs	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	Water	-	-	-	-	0	0	0	+
	Soil	-	-	-	-	-	-	-	-
	Fauna	-	0	0	0	0	0	0	0
	Flora	-	0	0	0	0	0	0	0
	Landscape	-	-	-	-	-	-	-	-
Economy									
	Production costs	€ / kg PUFAs	0	-	0	0	-	-	N/D
	Fixed capital investment	Million €	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Society	Local community								
	Labour conditions safety	-	++	++	++	++	++	++	++
	Employment opportunity	-	++	++	++	+	+	+	+
	Living conditions	-	+	+	+	0	0	0	0
	General society								
	Consumers' health and safety	-	+	+	+	+	+	+	+
	Public commitment to sustainability issues	-	++	++	++	++	++	++	++
	Legal regulatory barriers	-	- -	- -	- -	- -	- -	- -	- -
	Public perception	-	++	++	++	++	++	++	++

Legend:	🟥 very dis-advantageous	🟧 dis-advantageous	🟨 neutral	🟩 advantageous	🟩 very advantageous

Table 4-7 (continued)

Optimistic										
PUFAChain scenarios							**Alternatives to PUFAChain**			
Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North	PUFAs from fermentation (high)	PUFAs from fermentation (low)	PUFAs from fish cuttings	PUFAs from by-catch
- -	-	- -	- -	-	- -	- -	0	0		0
-	-	- -	-	-	- -	- -	0	0		0
++	++	++	++	++	++	++	++	++		+
0	0	0	0	0	0	0	- -	- -		0
+	+	+	+	+	+	+	+	+		0
0	0	0	0	0	0	0	-	-		0
- -	- -	- -	- -	- -	- -	- -	- -	-		- -
- -	- -	- -	- -	- -	- -	- -	- -	-		- -
- -	- -	- -	- -	- -	- -	- -	- -	- -	**BENCHMARK**	- -
- -	- -	- -	- -	- -	- -	- -	- -	- -		- -
- -	- -	- -	- -	- -	- -	- -	- -	0		- -
- -	- -	- -	- -	- -	- -	- -	- -	- -		- -
- -	- -	- -	- -	- -	- -	- -	- -	- -		- -
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
0	0	0	+	+	+	+	-	-		0
+	+	+	+	+	+	+	- -	- -		0
++	++	++	++	++	++	++	-	-		0
++	++	++	++	++	++	++	-	-		0
-	-	-	-	-	-	-	- -	- -		0
0	+	0	0	0	-	- -	0	0		0
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
++	++	++	++	++	++	++	++	++		0
++	++	++	+	+	+	+	+	+		0
+	+	+	0	0	0	0	0	0		0
+	+	+	+	+	+	+	+	+		0
++	++	++	++	++	++	++	++	++		0
- -	- -	- -	- -	- -	- -	- -	+	+		0
++	++	++	++	++	++	++	++	++		0

Table 4-8: Comparison of all other scenarios to the benchmark scenario “PUFA from fermentation” with high impacts. GMO: genetically modified organism, N/D: no data.

			Conservative						
			PUFAChain scenarios						
	Indicator	Unit	Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North
Technology	Maturity	-	-	0	-	- -	0	- -	- -
	Availability of infrastructure	-	-	-	- -	-	-	- -	- -
	Use of limited feedstock	-	0	0	0	0	0	0	0
	Use of GMOs	-	++	++	++	++	++	++	++
	Toxicity risks	-	0	0	0	0	0	0	0
	Risk of explosions and fires	-	+	+	+	+	+	+	+
Environment	Global warming	t CO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Energy resources	GJ / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Acidification	kg SO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Eutrophication	kg PO_4 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Photochemical smog	kg ethene eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Ozone depletion	g CFC-11 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Freshwater use	m³ / kg PUFAs	-	- -	-	+	+	++	+
	Water	-	0	0	0	+	+	+	++
	Soil	-	+	+	+	+	+	+	+
	Fauna	-	+	+	+	+	+	+	+
	Flora	-	+	+	+	+	+	+	+
	Landscape	-	+	+	+	+	+	+	+
Economy	Production costs	€ / kg PUFAs	0	-	0	0	-	-	N/D
	Fixed capital investment	Million €	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Society	Local community								
	Labour conditions safety	-	0	0	0	0	0	0	0
	Employment opportunity	-	+	+	+	0	0	0	0
	Living conditions	-	+	+	+	0	0	0	0
	General society								
	Consumers' health and safety	-	0	0	0	0	0	0	0
	Public commitment to sustainability issues	-	0	0	0	0	0	0	0
	Legal regulatory barriers	-	- -	- -	- -	- -	- -	- -	- -
	Public perception	-	+	+	+	+	+	+	+

Legend:	very dis-advantageous	dis-advantageous	neutral	advantageous	very advantageous

Table 4-8 (continued)

Optimistic										
PUFAChain scenarios							Alternatives to PUFAChain			
Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North	PUFAs from fermentation (high)	PUFAs from fermentation (low)	PUFAs from fish cuttings	PUFAs from by-catch
- -	-	- -	- -	-	- -	- -		0	0	0
-	-	- -	-	-	- -	- -		0	0	0
0	0	0	0	0	0	0		0	- -	-
++	++	++	++	++	++	++		0	++	++
0	0	0	0	0	0	0		0	-	-
+	+	+	+	+	+	+		0	+	+
- -	-	- -	- -	- -	- -	- -		++	++	0
- -	-	- -	- -	- -	- -	- -		++	++	+
-	-	- -	- -	- -	- -	- -	BENCHMARK	++	++	-
-	-	-	- -	- -	-	- -		++	++	0
- -	- -	- -	- -	- -	- -	- -		++	++	0
- -	- -	- -	- -	- -	- -	- -		++	++	++
-	-	- -	- -	- -	- -	- -		++	++	-
++	0	-	++	++	++	++		++	N/D	N/D
+	+	+	++	++	++	++		0	+	+
++	++	++	++	++	++	++		0	++	++
++	++	++	++	++	++	++		0	+	+
++	++	++	++	++	++	++		0	+	+
+	+	+	+	+	+	+		0	++	++
0	+	0	0	0	-	- -		0	0	0
N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D	N/D	N/D
0	0	0	0	0	0	0		0	- -	- -
+	+	+	0	0	0	0		0	-	-
+	+	+	0	0	0	0		0	0	0
0	0	0	0	0	0	0		0	-	-
0	0	0	0	0	0	0		0	- -	- -
- -	- -	- -	- -	- -	- -	- -		0	-	-
+	+	+	+	+	+	+		0	- -	- -

Initial combined PUFA production in Southern Europe

Algae-based combined production of DHA and EPA in Southern Europe using the initially selected algae strain Thalassiosira has the potential to overcome many of the drawbacks of PUFAs from fish cuttings. Prerequisite is that the performance depicted in the scenario under optimistic conditions can be reached in practise. One key technological issue is to succeed in a largely complete extraction of PUFAs from the biomass, which is still a challenge. If this would be realised, the following advantages are to be expected and the following disadvantages have to be accepted (Table 4-9):

- No other assessed option for PUFA provisions performs substantially better regarding the following indicators: Use of limited feedstock, Use of GMOs, Toxicity risks, Risk of explosions and fires, Soil, Fauna, Flora, Production costs, Labour conditions Safety, Employment opportunity, Living conditions, Consumers' health and safety, Public commitment to sustainability issues and Public perception.
- Severe drawbacks are:
  - PUFAs from alternative sources (fermentation, fish cuttings and by-catch) have significantly or much lower global / regional environmental impacts except for freshwater use. Disadvantages regarding climate change could only be compensated under certain conditions: If co-products of algae-based PUFA production replace agricultural products like feed and if natural vegetation such as rainforests would otherwise be cleared for that feed production, this would prevent massive greenhouse gas emissions. These potentially indirectly prevented emissions could be greater than emissions directly caused by algae cultivation. However, such indirect benefits are very uncertain.
  - Several algae cultivation scenarios can be realised with much less freshwater use – in particular in Central or Northern Europe – and / or with much less capital investment – in particular on a 10 times smaller scale as set for conservative conditions.
  - PUFA production from alternative sources (fermentation, fish cuttings and by-catch) is more mature. Infrastructure required for those technologies is already in place and compliance to legal regulations is already documented. This makes an immediate realisation of alternatives possible despite higher expected production costs.

Further algae-based PUFA production scenarios

- **Algae-based combined production of DHA, EPA and stearidonic acid (SDA) in Southern Europe using the newly selected algae strain Prorocentrum** is an option with different technological challenges than Thalassiosira. Prorocentrum was selected as most promising strain because technological challenges in particular in downstream processing seem easier to overcome although maturity in general is lower. It has very similar advantages and disadvantages as the scenario “Initial combined PUFA production in Southern Europe” (see ratings of this scenario in Table 4-9). Therefore, it is a further promising option for algae-based PUFAs if challenges in Thalassiosira processing are not overcome.

- **Algae-based dedicated production of EPA in Southern Europe** also performs similarly and can be a further option depending on market demand for the individual PUFAs EPA and/or DHA and the further maturation of the involved processes.
- **PUFA production in Central or Northern Europe** is possible but requires generally more resources per amount of product. Hence, most environmental impacts and costs are higher. Differences can however be reduced if efficient concepts for heating are in place. Advantageous for sites further north is that water-related impacts are lower.

Main conclusions on algae-based PUFAs and PUFAs from fermentation:

These options are expected to be the main competitor because they can both provide more PUFAs once potentials from residue use are exploited. Fermentation is not as innovative and therefore already available. It depends on boundary conditions if it is more or less costly than algae-based PUFAs. If enough arable land would be available in the future, fermentation would be a preferred choice from an environmental angle because it requires rather low energy and material inputs. If not, fermentation will most likely lead to higher local environmental impacts due to intensified land use and/or clearing of natural ecosystems for crop cultivation. Under some conditions, this can even indirectly lead to higher climate impacts for fermentation than for algae cultivation. Therefore, it depends on boundary conditions and value-based choices which system to prefer. If algae-based PUFA production is developed and optimised further, it thus has the potential to get established as option for PUFA provision besides fermentation in the future.

Table 4-9: Comparison of all other scenarios to the benchmark scenario "Initial combined PUFA production in Southern Europe" under optimistic conditions. GMO: genetically modified organism, N/D: no data.

			Conservative						
			PUFAChain scenarios						
	Indicator	Unit	Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North
Technology									
	Maturity	-	0	+	0	-	+	-	-
	Availability of infrastructure	-	0	0	-	0	0	-	-
	Use of limited feedstock	-	0	0	0	0	0	0	0
	Use of GMOs	-	0	0	0	0	0	0	0
	Toxicity risks	-	0	0	0	0	0	0	0
	Risk of explosions and fires	-	0	0	0	0	0	0	0
Environment									
	Global warming	t CO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Energy resources	GJ / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Acidification	kg SO_2 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Eutrophication	kg PO_4 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Photochemical smog	kg ethene eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Ozone depletion	g CFC-11 eq. / kg PUFAs	-	-	-	-	- -	-	- -
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg PUFAs	- -	- -	- -	- -	- -	- -	- -
	Freshwater use	m³ / kg PUFAs	-	-	-	++	+	++	++
	Water	-	-	-	-	0	0	0	+
	Soil	-	- -	- -	- -	- -	- -	- -	- -
	Fauna	-	- -	- -	- -	- -	- -	- -	- -
	Flora	-	- -	- -	- -	- -	- -	- -	- -
	Landscape	-	0	0	0	0	0	0	0
Economy									
	Production costs	€ / kg PUFAs	-	-	-	-	- -	- -	N/D
	Fixed capital investment	Million €	++	++	++	++	++	++	N/D
Society	Local community								
	Labour conditions safety	-	0	0	0	0	0	0	0
	Employment opportunity	-	0	0	0	-	-	-	-
	Living conditions	-	0	0	0	-	-	-	-
	General society								
	Consumers' health and safety	-	0	0	0	0	0	0	0
	Public commitment to sustainability issues	-	0	0	0	0	0	0	0
	Legal regulatory barriers	-	0	0	0	0	0	0	0
	Public perception	-	0	0	0	0	0	0	0

Legend:	very dis-advantageous	dis-advantageous	neutral	advantageous	very advantageous

Table 4-9 (continued)

Optimistic										
PUFAChain scenarios							Alternatives to PUFAChain			
Combined PUFA production, South	Initial combined PUFA production, South	Dedicated EPA production, South	Combined PUFA production, Central	Initial combined PUFA production, Central	Dedicated EPA production, Central	Dedicated EPA production, North	PUFAs from fermenta-tion (high)	PUFAs from fermenta-tion (low)	PUFAs from fish cuttings	PUFAs from by-catch
-		-	-	0	-	-	+	+	+	+
0		-	0	0	-	-	+	+	+	+
0		0	0	0	0	0	0	0	- -	-
0		0	0	0	0	0	- -	- -	0	0
0		0	0	0	0	0	0	0	-	-
0		0	0	0	0	0	-	-	0	0
0		0	-	- -	-	-	+	++	++	++
0		0	-	- -	-	-	+	++	++	++
0		0	-	-	-	-	+	++	++	+
0	**BENCHMARK**	0	-	- -	-	-	+	++	++	+
-		0	-	- -	-	-	++	++	++	++
-		0	-	0	0	0	++	++	++	++
0		0	-	-	-	-	+	++	++	+
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5 Recommendations

Based on the results and conclusions presented in chapter 4 and detailed background information available in the reports on technological, environmental and socio-economic assessment [Keller et al. 2017; Reyer et al. 2017; van der Voort et al. 2017], the following recommendations can be made to policymakers, to the algae community in business and science and to consumers from an environmental perspective:

5.1 To the algae community in business and science

Continue the successful optimisation of algae cultivation and utilisation in order to be prepared for implementation at a large, industrial-scale. Exploit the insights of this, and other, environmental analyses in order to also improve economically less relevant, but environmentally important, aspects. We specifically recommend:

- **Choose the site of a facility carefully because it can crucially influence profitability, environmental and social impacts.**
  The following aspects should be taken into account:
  - Only plan new algae cultivation facilities on land that cannot be used as arable land, has no great ecological value and with sufficient local freshwater availability. This could for example be former industrial sites or restored opencast mining sites. The advantage of PBRs is that they do not require fertile land. In view of the growing global population in decades to come, this advantage ideally should be exploited. The conversion of existing arable land to PBR land could lead to the creation of arable land in other parts of the world as a result of indirect effects. This could lead to the deforestation of virgin forest or other land, with partially very serious consequences for biodiversity, as well as numerous other ecological aspects. However, because infertile land or land formerly used for military purposes, for example, can also be highly biodiverse, a project-specific environmental impact assessment is necessary.

    
  - If the land is in rural communities and infrastructure and qualified personnel are also available there, the costs may be considerably lower. It can be expected that the standard of living and employment will improve most in rural communities, since the relative contributions of a new algae cultivation facility are highest there.
  - Because closed algae cultivation systems in PBRs may still require substantial amounts of water, sufficient availability of fresh water[12] must be ensured, in particular in semi-arid and arid regions, but also in the Mediterranean region.

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[12] More precisely: blue water

Image: © Thomas Leya for Fraunhofer IZI-BB, Potsdam, Germany

Existing water use in a catchment area[13] must be taken into consideration. The use of fossil groundwater is not sustainable.

- **Use as much of your own renewable energy, in particular photovoltaics, as possible to run algae cultivation.**

  

  A reduction in the environmental burdens, in particular of the required electricity, and independence of energy market prices does not depend on a general energy revolution. Both the timing and the location of electricity demand for algae cultivation are ideally suited to the installation of a photovoltaic system for internal consumption. Only in this way can low environmental burdens be achieved in algae facilities such as those analysed here. Analyse, optimise and flexibilise the daily and seasonal load profiles in order to service as much of the electricity demand as possible using a photovoltaic system. Depending on site and concept, solar power can be cheaper than power from the grid. To reduce the effective land requirement, solar modules should be installed in locations such as roofs and slopes that cannot be utilised for algae cultivation.

- **Reduce the energy and water demand for cooling, heating and drying as part of an optimised and integrated concept.**

  

  From the portfolio of available technologies and concepts, use those that most effectively reduce environmental burdens and costs across the entire product life cycle at the site in question. Here, it may make sense to produce less than the maximum possible product volume. This project has addressed among others the following options[14]: water sprinkler cooling (given high water availability in summer), heat exchanger cooling using a suitable heat sink, integration of cooling and biomass drying, belt drying using solar heat, a variety of spray dryers, avoiding drying by the use of alternative extraction/processing methods, reducing heating by the use of greenhouses, winter breaks, cold-tolerant algae strains as part of an algae crop rotation, integration of heating and cooling using seasonal heat stores.

- **Clarify regulatory questions early.**

  Because algae-based products and processes are largely relatively new, the effort needed for approval compliant with the various regulations is also relatively high. Because, the risks for algae-based PUFAs are generally no greater than for competing products and processes, this should not, in principle, be a hindrance. However, this must be demonstrated on a case-by-case basis, which can involve considerable time and money.

- **Convert all algae constituents to products.**

  

  From an economic perspective, this can bring about additional revenues, even if they are not especially high, depending on the concept. If the production of agricultural raw materials, e.g. for feedstuff, and the associated occupation of arable land can be avoided, this results in a clear advantage for algae from an environmental perspective.

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[13] In technical jargon: environmental flow requirements

[14] Details can e.g. be found in the environmental assessment report [Keller et al. 2017].

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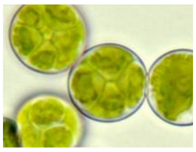
- **Optimise algae strain productivity.**
  
  Algae for use in photobioreactors (PBRs) are substantially less productive in comparison to the heterotrophic microorganisms used in fermenters. Intensified research into the development of newly cultivated, wild algae strains to form efficient production strains therefore appears worthwhile. Substantial environmental benefits are to be expected if, on one side, PUFA content can be increased markedly and on the other side protein content can be at least maintained. This would, on one side, reduce energy consumption of algae cultivation and processing and on the other side still achieve high environmental benefits due to avoided conventional feedstuff production. When considering whether to optimise algae by classic breeding, classic genetic modification or new techniques such as genome editing (e.g. CRISPR/Cas) the following points should be taken into account:
  - Feasibility
  - Biological safety, in particular safe containment of genetically modified organisms in photobioreactor tubes
  - Legal aspects: Currently it is e.g. still unclear if organisms created by genome editing necessarily count as GMOs according to European law and if co-products from such organisms qualify as feed.
  - Public acceptance: Currently, PUFAs from genetically modified heterotrophic microorganisms are largely accepted. However, it is to be assumed that one reason for it is that only few consumers are aware of GMOs being used here.
- **Ensure ecological design of the facility.**
  
  When an algae cultivation facility is built, unused areas, in particular, should be used for nature conservation. This allows nature conservation, improvement of landscape and thus local quality of life and algae production to be achieved simultaneously. In addition, this can increase local and general acceptance. Possible measures include:
  - creation of meadow instead of gravel fill or concrete beneath PBRs and planting hedges, e.g. around the site boundary. Both create and enhance habitats for flora and fauna and thus promote biodiversity.
  - Fencing beneficial to small animals, beginning at a height of 20 cm, which allows small animals that do not impair the facility to enter.
- **New options for utilising algae as a food instead of fish should be investigated.**
  
  A future strategy may therefore be to use natural (micro) algae as a whole, without isolating individual components, instead of fish as an ingredient for healthy meals. For example, this is already a common aspect of traditional Asian cuisine using macroalgae (seaweed). In view of the rising global population and declining fish stocks, it appears plausible that a market niche may develop that can be filled by algae.

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5.2 To policymakers

- **Do not expect completely mature algae cultivation technology and utilisation within only a few years.**

  

  As this report demonstrates, enormous improvements of environmental compatibility and costs have been achieved in only a few years. In addition, new optimisation measures and objectives have been identified, which would not even have been addressable without the previous improvements. It is anticipated that some of these new optimisation approaches will require longer term testing and development in pilot facilities, because various boundary conditions, such as seasonality, must be taken into consideration.

- **If the aim is to establish algae cultivation as a long-term technology, its optimisation must also be correspondingly funded in the long-term.**

  

  Whether a facility could be built in 2025 that would subsequently be regarded as generally technically mature, or currently observed developments continue to advance dynamically, cannot be foreseen at this time. Research and funding concepts should therefore be regularly adapted to reflect the state of the art every few years.

- **Supplying the population with PUFAs such as EPA and DHA can initially be improved by promoting the use of fish residues and by-catch, before an assessment is possible of whether algae production for PUFAs is mature enough for start-up funding of industrial facilities.**

  

  Given the capital costs, financial start-up support may prove useful if algae cultivation for PUFAs is to be established in the public interest. As long as no experience is available from several years of operating a demonstration facility covering a few hectares, it is however difficult to foresee when and whether the environmental burdens caused by algae-based PUFAs cultivated in PBRs can be reduced enough that they achieve similar magnitudes to the alternative PUFA production methods. Moreover, it is not clear whether the costs determined under optimistic boundary condition can actually be achieved. This is required, however, for such a facility to be profitable in the long term. Therefore, the use of fish cuttings available from fish processing and unused by-catch for PUFA extraction should initially be promoted. A public funding decision with regard to algae-based PUFA production facilities should be made following appropriate technology development.

- **Examine which regulatory requirements can be softened without sacrificing safety or support approvals financially.**

  Regulatory hurdles can mean disproportionate costs and delays for a new technology such as algae cultivation. If there is a societal interest in its introduction, these hurdles should be lowered or be made easier to overcome.

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- **Alternatives to established fish oil applications should be introduced as quickly as possible in order to reduce overfishing incentives.**

  

  In addition to using fish residues and by-catch, further options for the provision of PUFAs such as EPA and DHA should be identified and investigated. Which groups of people are able to eat healthily with plant-based PUFAs such as α-linolenic acid (ALA) should also be further investigated.

- **Maintain the focus of algae cultivation and use funding programmes on high-value products instead of mass products.**

  

  At least within the EU, the long-term development potentials of algae facilities appear limited as a result of land competition (e.g. with photovoltaic systems) and, in a few decades, the remaining point sources of CO_2 (e.g. with synthetic 'power-to-X' fuels). High-value specialty algae products should therefore be primarily aimed for instead of mass production.

- **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 shifting of CO_2 emissions does not help the environment. If any kind of bonus or incentive would be available for such shifting, it may 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.

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- **New options for utilising algae as a food instead of fish may be a useful subject for research funding.**
  A future strategy may therefore be to utilise natural (micro) algae as a whole, without isolating individual components, instead of fish as an ingredient for healthy meals. This is a common aspect of traditional Asian cuisine using macroalgae (seaweed). This could represent a possible alternative compensating for a less well-balanced and fish-reduced diet caused by overfishing, rather than using capsules and isolated dietary supplements. Here, intensified research with regard to utilisation options, production technology and environmental compatibility of algae-based foodstuffs as one component of sustainability can therefore make a contribution to saving fish stocks, considering the rising global population.

5.3 To consumers

- **Only take PUFAs as dietary supplements if this is beneficial for your personal health.**
  
  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. Currently, the production of fish oil capsules using PUFAs exploits strictly limited fish stocks. Any production from fish residues, which may be intensified in the future, also builds on limited resources. Other methods of producing PUFA capsules are not currently feasible without substantially greater environmental burdens. PUFAs should therefore only be consumed as dietary supplements by people who need them for health reasons.

- **Be open for new vegetable foodstuffs, e.g. from algae.**
  
  The 'western' diet is characterised by the consumption of animal-based foods. An increasing proportion of the constantly growing global population live by this standard. However, the world's resources are not sufficient to provide a large proportion of the global population with this type of nutrition. A healthy diet is nevertheless to a large extent possible on a vegetarian basis. Both microalgae and macroalgae (seaweed) can play an important role here, as is already partially common in Asian cuisine, for example.

- **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 most foodstuffs, including algae-based products, in particular.

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6 Glossary and abbreviations

ACR	Algae crop rotation
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.
ALA	α-linolenic acid (ALA) is a certain omega-3 PUFA also found in plants such as flax. The human body can only convert it inefficiently into EPA and DHA
Algae cultivation	In this report used for the cultivation of (photoautotrophic) microalgae, which use sunlight and CO_2 as resources. (see also “fermentation” and “photoautotrophic”). Competing fermentation processes use various protists fed with agriculturally produced sugar ('heterotrophic microorganisms'), which are often also termed ‘heterotrophic algae’. According to the current scientific consensus, these microorganisms are however not classified as algae. To differentiate both processes in this report, 'fermentation' refers to processes using heterotrophic microorganisms.
Blue water	Fresh surface and groundwater, in other words, the water in freshwater lakes, rivers and aquifers.
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.
CAPEX	Capital expenditures are funds used by a company to acquire physical assets such as property, industrial buildings or equipment.
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 “power-to-X”).
CFC	Chlorofluorocarbon, substance contributing to ozone depletion.
DHA	Docosahexaenoic acid, a certain omega-3 PUFA only produced by algae

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(e)LCA	(environmental) life cycle assessment
EPA	Eicosapentaenoic acid
Fatty acid	Carboxylic acid including but not limited to EPA and DHA, which can be part of e.g. triglycerides, phospholipids or can be present as free fatty acid.
Fermentation	In this report used for processes, in which heterotrophic microorganisms such as fungi or other protists are used to convert agriculturally produced sugar into products. At least some of these heterotrophic microorganisms are often also termed 'heterotrophic algae'. According to the current scientific consensus, these microorganisms are however not classified as algae. (see also "algae cultivation" and "heterotrophic").
Free fatty acid	Fatty acid, which is not part of molecules such as triglycerides, phospholipids or others.
Freshwater	Freshwater refers to so called "blue water", which includes tap water, water from wells, rivers or lakes for irrigation but not rainwater.
FM	Fish meal
FO	Fish oil
GMO	Genetically modified organism
Greenfield site	Land currently used for agriculture or (semi)natural ecosystems left to evolve naturally
Heterotrophic	Microorganisms that use organic material such as agriculturally produced sugar as energy source. At least some of heterotrophic microorganisms used to produce PUFAs are often also termed 'heterotrophic algae'. According to the current scientific consensus, these microorganisms are however not classified as algae. (see also "photoautotrophic" and "fermentation")
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
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
LCC	Life cycle costing
NOx	Nitrogen oxides

Omega-3 PUFA	A subgroup of PUFAs that is characterised by the position of the last double bond three carbon atoms before the end of the aliphatic chain. PUFAs of this subgroup cannot be synthesised by the human body but only converted into each other with some restrictions and thus have to be consumed with the diet. Certain omega-3 PUFAs provide cardiovascular health benefits. These are EPA and DHA as well as with some restrictions ALA.
OPEX	Operational expenditure is an ongoing cost for running a product, business, or system.
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 (see also “heterotrophic” and “algae cultivation”).
Power-to-X	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.
PUFA	Polyunsaturated fatty acids. In general, any fatty acid with multiple double bonds in the aliphatic chain. The particular PUFAs concerned in this project are omega-3 PUFAs.
PUFAChain	Project acronym, “*The Value Chain from Microalgae to PUFA”*
PV	Photovoltaic
$scCO_2$	Supercritical Carbon Dioxide can be used as solvent for extraction processes.
SDA	Stearidonic acid, a certain omega-3 PUFA, which is a metabolic precursor of EPA and DHA
sLCA	Social life cycle assessment
SO_2	Sulphur dioxide
SWOT	Acronym for strengths, weaknesses, opportunities, and threats
UHT-PBR	Unilayer horizontal tubular photobioreactor, a certain kind of PBRs used in this project.

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