Deliverable 9.3

Final report: Environmental assessment of algae-based PUFA production

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PUFAChain:

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Deliverable 9.3:
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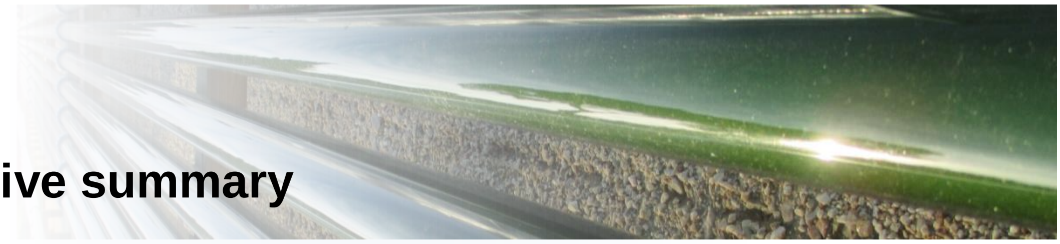

Executive summary

Polyunsaturated fatty acids (PUFAs), especially omega-3 fatty acids such as eicosa-pentaenoic acid (EPA) or docosahexaenoic acid (DHA) are very important constituents of a healthy human diet. 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. The EU funded project "*The Value Chain from Microalgae to polyunsaturated fatty acids"* investigates new processes with photoautotrophic algae to produce PUFAs using sunlight as energy source and CO_2 as carbon source.

Within the sustainability assessment of the project, IFEU – Institute for Energy and Environmental Research Heidelberg, Germany, assessed the environmental impacts of the newly devised processes. It consists of an assessment of global and regional impacts in a screening life cycle assessment (LCA see chapter 2.3 for methodology) and an analysis of local environmental impacts by life cycle environmental impact assessment (LC-EIA, see chapter 2.4 for methodology).

The most important insights are summarised below as key statements with references to background information. Concrete recommendations to the algae community in business and science, to policy makers and to consumers deduced from these insights can be found in chapter 5.

1. **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 (chapter 4.1.3). Algae-based products are therefore not intrinsically environmentally friendly, nor do they necessarily contribute to mitigating climate change just because algae consume CO_2.

2. **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. 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 (chapter 4.1.2). 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.

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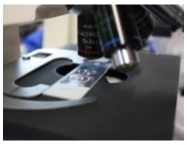
3. **The greatest environmental improvements can be achieved by using improved algae strains, renewable energy sources such as an on-site solar power supply and optimised algae biomass drying strategies.**

In addition, strategies for reducing heating energy requirements in regions with cold winters are needed (chapter 4.1.2). 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 cryophilic algal strains newly identified in this project still need optimisation and the whole cultivation concept would need further adaptations to Northern European conditions to achieve environmental benefits.
These, and other, optimisation strategies were investigated in the project and adopted for planning optimised facilities. 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.

4. **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 freshwater use, land use, soil and biodiversity (chapter 4.2.4). However, algae cultivation does not require fertile land. If brownfield sites[1] are used instead of greenfield sites[2], it may even be possible to enhance areas if their design is ecologically optimised. 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.

5. **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 (chapter 4.1.3). 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.

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

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

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6. **Based on currently foreseeable technological developments, algae[3]-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 (chapter 4.1.4):

- 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.
  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. 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 agricultural 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 (chapter 4.2.4).

- **PUFAs from fish cuttings and by-catch** generally cause considerably lower global and regional environmental burdens, because here a previously underused but available resource can be utilised with relatively little effort. 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 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.

7. **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

3 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.

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 (chapter 4.1.4). 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.

8. **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 agricultural land and exacerbate related problems such as the consequences of indirect land use change. In the worst case, this can lead to deforestation in other parts of the world. A similar effect is known from ground-mounted photovoltaic systems, the land use of which is limited by funding regulations in some EU member states. They additionally compete with algae for the same infertile land with high solar irradiation.

However, in contrast to photovoltaics, co-products from algae cultivation may substitute for agricultural products. This can lead to agricultural land savings up to 7 times greater than the land needed for algae cultivation (chapter 4.1.4). If this was to help avoid the conversion of rainforest into new agricultural land, the greenhouse gas emissions saved in this way may, under some circumstances, even exceed the emissions from algae production. It is therefore vital that all algae biomass fractions are utilised. In this case, sealing of a small area for algae cultivation, with the associated local environmental disadvantages, could be justified if much more land becomes available and if part of that is used as an ecological compensation site. Despite potential restrictions to large scale algae cultivation in Europe, we urgently recommend the strict use of only infertile land for such cultivation facilities.

9. **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 (chapter 8.3.3). 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.

10. **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

Images from top to bottom: © Peter Smola/pixelio.de; Frank-Andreas Jütte/pixelio.de; Rike/pixelio.de 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 (chapter 4.1.4). 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.

11. **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[4], 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[5]. 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.

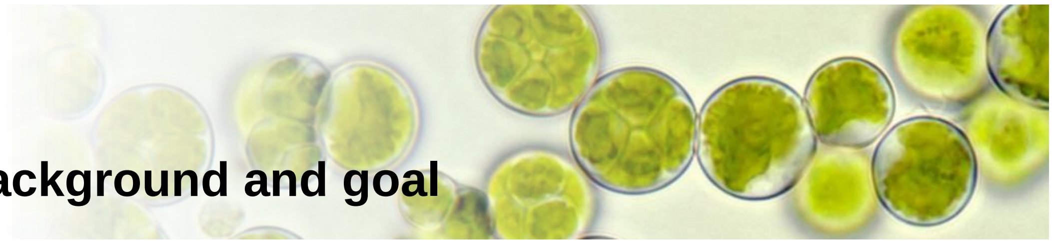
Intensified research with regard to utilisation options, production technology and environmental compatibility of algae-based foodstuffs as one component of sustainability is therefore a useful focus of future research, considering the rising global population and declining fish stocks.

12. **Environmental analyses investigating algae must, in principle, be viewed in the context of a comprehensive sustainability assessment.**

The insights and recommendations derived here are based solely on environmental impacts. Additional aspects – in particular economic, social, technical and regulatory – need to be addressed with regard to sustainable algae utilisation.

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

5 Mostly not present in microorganisms produced in fermenters.



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 environmental 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). This report covers the analysis of environmental impacts along this life cycle. Its results are integrated with the results of the parallel technological and socio-economic assessment [Reyer et al. 2017; van der Voort et al. 2017] into an overall picture in the integrated sustainability assessment [Keller et al. 2017].

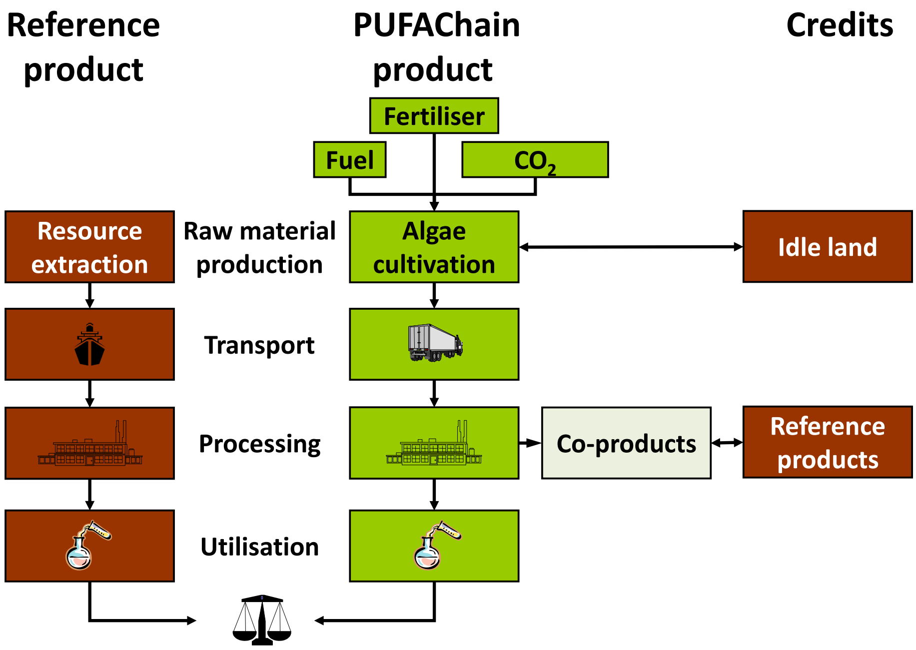


Fig. 1-1 Sustainability assessment in PUFAChain: The concept of life cycle sustainability assessment, which compares the whole life cycles of two products

2 Definitions, settings and methodology

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 2.2. Specific definitions and settings that are only relevant for the environmental assessment are described in chapter 2.3.

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 relevant for this environmental assessment:

- 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?
  - 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?
- How does the PUFAChain concept perform compared to alternative options of meeting the increasing demand of PUFAs?

2.2 Common definitions and settings

The analysis of the life cycles within PUFAChain follows the integrated life cycle sustainability assessment (ILCSA)methodology [Keller et al. 2015]. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing

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[Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009].

2.2.1 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.

2.2.2 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 "n^{th} 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.

2.2.3 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.

2.2.4 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.

2.2.5 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.

2.2.6 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.

2.3 Specific definitions, settings and methodology for LCA

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

2.3.1 Settings for Life Cycle Inventory (LCI)

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. 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. A summary of this data can be found in the annex (chapter 8.2).

Secondary data:

Data on background processes (e.g. provision of non-biomass material inputs and conventional reference products of the PUFAChain products) are based on the IFEU internal database [IFEU 2017] and the ecoinvent database [Ecoinvent 2017]. Life cycles of reference products were modelled by the project partners Wageningen University and Research (WUR) and IFEU - Institute for Energy and Environmental Research Heidelberg based on several publicly available sources and expertise by the project partner IOI Oleo GmbH (experts in the field who did not have access to confidential data of competitors).

A summary of the most important input data can be found in chapter 8.2 in the annex.

Attributional vs. consequential modelling

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

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

Co-products handling

The main focus of this project is on the provision of DHA and EPA. As the product portfolio is dominated by DHA and EPA, co-products are assessed by so-called system expansion (substitution approach) that should preferentially be applied in consequential modelling according to ILCD Handbook: the impacts of a multi-output system are balanced with the avoided impacts of the reference products that are replaced by the products of the multi-output system. For example, if residues from biomass processing are used for bioenergy generation in a biogas plant, the avoided burdens of the fossil energy, which is replaced by this bioenergy, are deduced from or credited to the environmental burdens of the main products.

Indirect effects such as indirect land use change

New systems using biomass can indirectly affect the environment by withdrawing resources from other (former) uses. This can result in appropriation of biomass or land formerly not extracted or used by man, respectively. This can lead to indirect land use changes (iLUC): Biomass formerly used for other purposes (e.g. as food or feed) has to be produced elsewhere (e.g. outside of Europe) if it is now used for new products. This can indirectly cause a clearing of (semi-)natural ecosystems and hence changes in organic carbon stocks, damages to biodiversity etc. There is an ongoing international debate about these effects, mainly focussing on organic carbon stocks. Since the estimates on so called iLUC factors regarding carbon stocks are less certain and less is known about the influence of iLUC on other environmental impact categories, quantitative iLUC effects are only reported separately and only for the impact category global warming. Additionally, they are discussed qualitatively in the LC-EIA part. For other potentially limited resources, please refer to chapter 8.3.3 in the annex.

Biogenic carbon

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

2.3.2 Settings for Life Cycle Impact Assessment (LCIA)

Impact categories: Midpoint vs. endpoint level

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

Selection of relevant midpoint-level impact categories

The LCA assesses the midpoint indicators tick-marked in Table 2-1. The selected impact categories are well-established categories in life cycle assessments [JRC-IES 2010b].

Regarding the LCIA methods, the CML methods were selected as preferred choice because they cover all impact categories in a consistent way [CML 2016].

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

Table 2-1 Environmental impact categories covered in PUFAChain

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

Some impact categories, which are not tick-marked in Table 2-1, are excluded because they are i) irrelevant for the PUFAChain biorefinery concept (e.g. ionising radiation) or ii) still under methodological development (e.g. human toxicity and ecotoxicity, resource depletion: water and land use; classified as level II/III or III in the ILCD Handbook). Please note that in this environmental assessment „Land use“ and „Resource depletion: water“ are analysed on the level of the life cycle inventory within the LCA with a separate discussion of qualitative impacts within the LC-EIA. The LC-EIA is meant to supplement the LCA which is known to be less suitable for addressing local environmental impacts, especially in areas where methodological development of LCA is still ongoing. Moreover, LCI data quality for 2025 is limiting particularly for human toxicity and ecotoxicity, which cover an extensive list of substances. The data available today is not suitable to derive results, which are balanced enough for decision support. Therefore, these categories are excluded from the LCA. Instead important ecotoxicity impacts on biodiversity, land use and “resource depletion: water” are covered within the LC-EIA part.

Normalisation

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

In the PUFAChain LCA study, the environmental advantages and disadvantages are related to the environmental situation in the EU25+3. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called inhabitant equivalent (IE). The reference values are presented in Table 8-1 in the annex for all environmental impact categories.

Weighting

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

2.4 Specific definitions, settings and methodology for LC-EIA

There are a number of environmental management tools which differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (LCA), for example, addresses potential environmental impacts of a product system (see chapter 2.3). However, for a comprehensive picture of environmental impacts, also local/site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these local/site-specific impacts are not yet covered in standard LCA studies. Thus, for the time being, LCA has to be supplemented by elements borrowed from other tools.

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

2.4.1 Introduction to EIA methodology

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

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

Regulatory frameworks related to EIA

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

EIA methodology

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

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

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

An EIA generally includes the following steps:

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

Screening

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

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

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

Scoping

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

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

EIA report

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

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

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

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

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

Monitoring and auditing measures

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

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

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

2.4.2 The LC-EIA approach in PUFAChain

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

Environmental impact assessment (EIA), however, is usually conducted specifically for a planned (actual) project (see previous chapter 2.4.1). For the purpose of the PUFAChain project, which neither encompasses the construction of an actual algae cultivation facility nor the construction of a PUFA provision plant (only existing demo facilities are used), it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures are omitted within PUFAChain. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the PUFAChain systems at a generic level.

The elements of EIA used in this project are shown in Fig. 2-1.

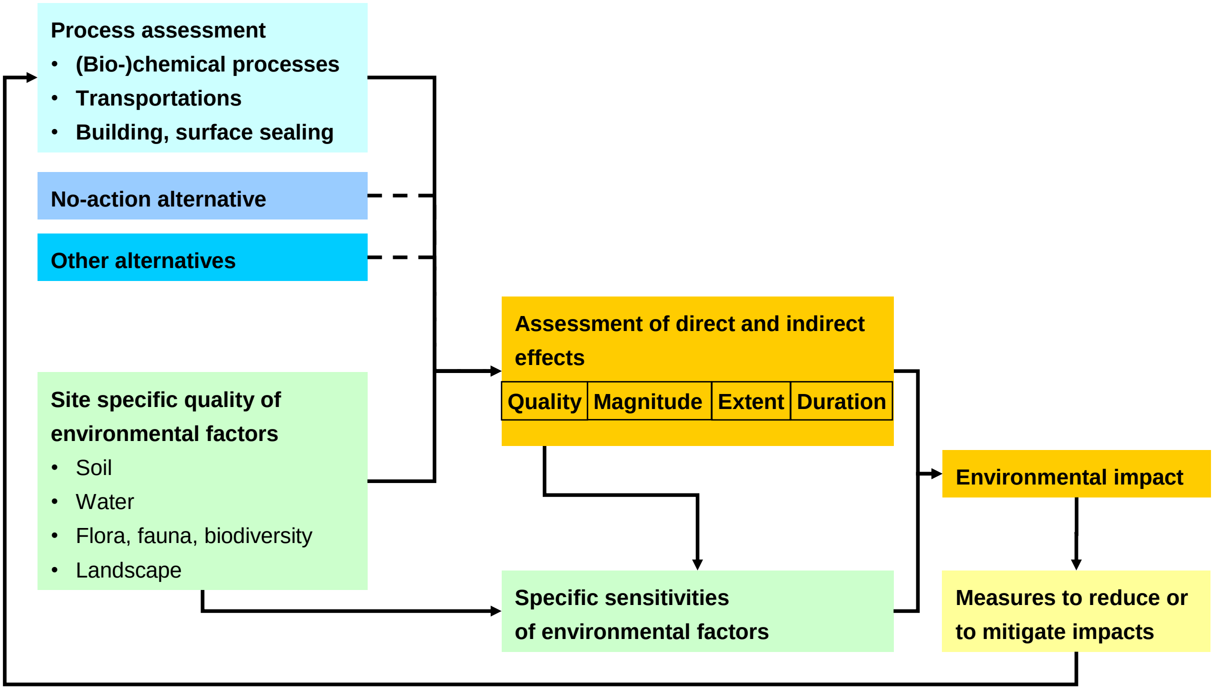

Fig. 2-1 Structure of an LC-EIA in the PUFAChain project.

Reference systems

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

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

Impact assessment

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

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

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

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

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

For dedicated crops, which occur both in the PUFAChain system (avoided cultivation of soybeans and rapeseed) and in case PUFA provision from fermentation processes (cultivation of sugar/starch crops), crop-specific conflict matrices were used (see chapters 8.4.1 and 8.4.2 in the annex). An example is provided in the following Table 2-3.

Table 2-3 Risks associated with the cultivation a specific annual/perennial crop

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

Categories: positive - neutral – negative

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

- “positive”: compared to the reference system, biomass cultivation is more favourable

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

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

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, 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].

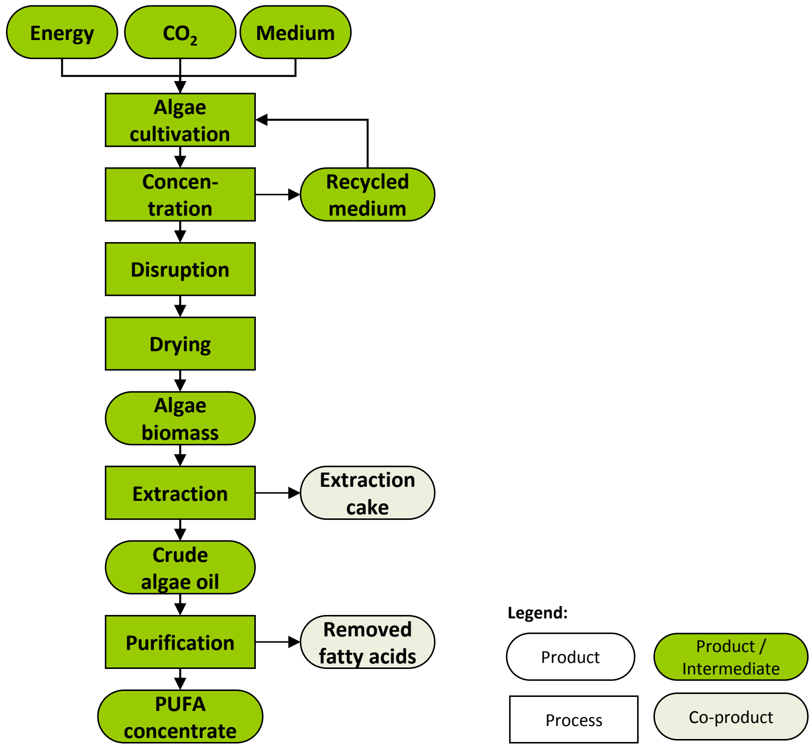

Fig. 3-1 Overview of life cycle stages depicted in the assessed scenarios for the PUFAChain system.

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 range 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.

3.2 Detailed process descriptions for the PUFAChain system

3.2.1 Algae cultivation, harvesting and biomass processing

This section is subdivided into the following topics:

- Algae strains and crop rotation
- Algae cultivation process
- Algae harvesting process and medium recycling
- Utility provision and wastewater treatment
- Disruption
- Drying
- Transportation

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 2.2.4, 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.

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.

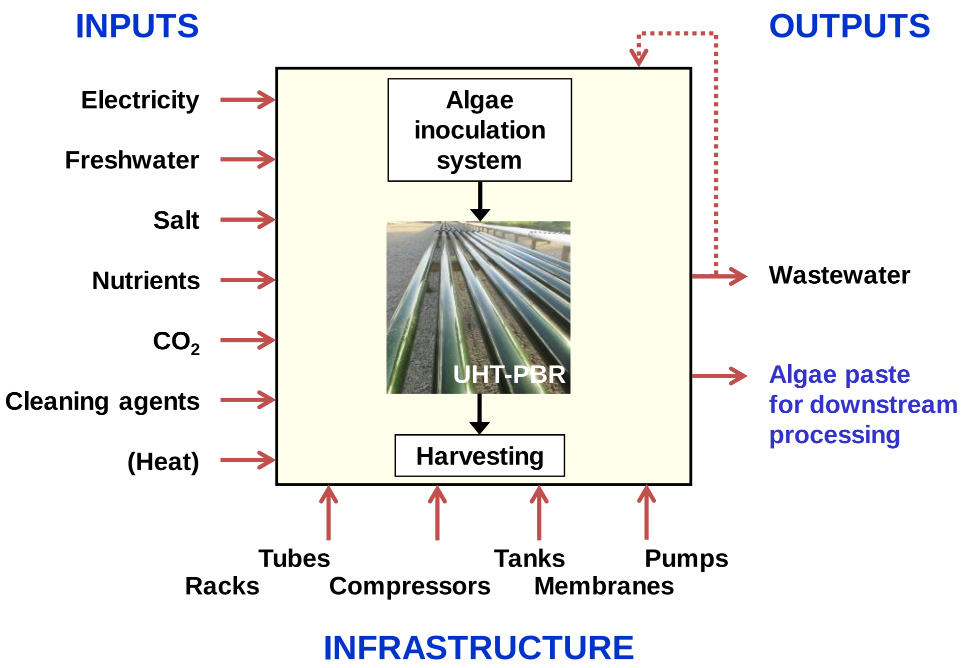

Fig. 3-2 Schematic input/output diagram for algae cultivation in photobioreactors (UHT-PBRs).

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:

<u>Prorocentrum:</u>

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.

<u>All other algae (Chloridella, Raphidonema, Thalassiosira):</u>

For these algae, a more standard approach is followed. Free 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[6].

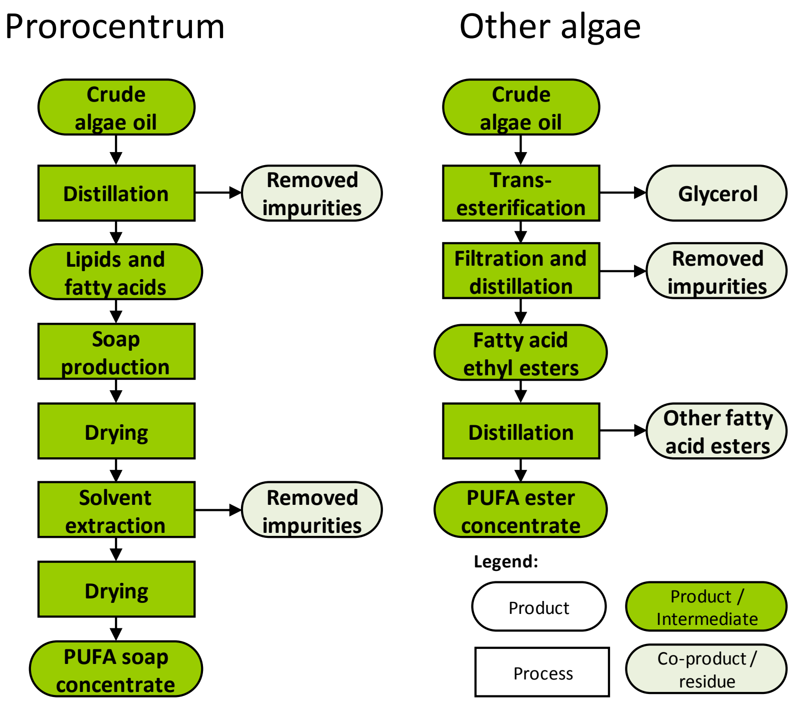

Fig. 3-3 Schematic diagram for algae oil purification.

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 require certain EPA + DHA (+ SDA)

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6 In other than the analysed scenarios, hydrolysis of lipids may also occur at an earlier stage and hence glycerol would not be obtained as separate co-product but as part of the extraction cake.

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.[7] or tuna etc.[8] 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.

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

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

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 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.

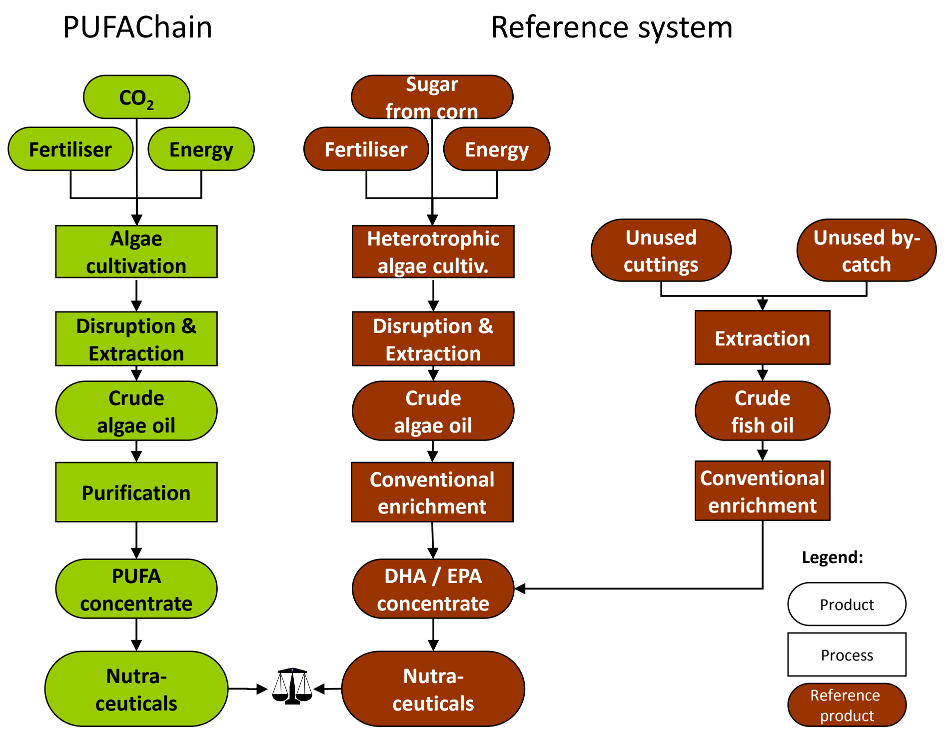


Fig. 3-4 Life cycle comparison scheme for PUFAChain products.

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.
- α-linolenic acid from plants such as flax. α-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.

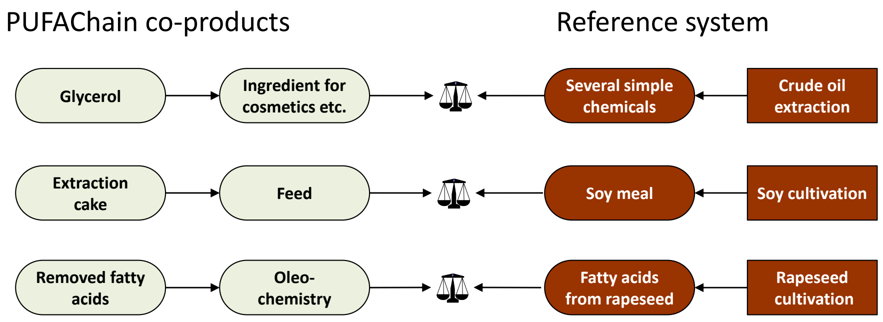


Fig. 3-5 Life cycle comparison scheme for PUFAChain co-products.

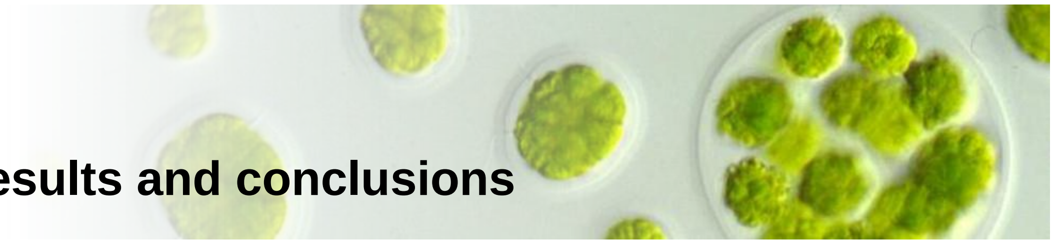
Land use reference system

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[9] 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

9 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.

value, which is lost if algae farms are built. Additionally to direct land use change effects, 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

4.1 Global/regional environmental impacts

Global and regional environmental impacts of the PUFAChain systems and competing reference systems were studied in a screening life cycle assessment (LCA). Chapter 4.1.1 exemplarily details the contributions to the results. Chapter 4.1.2 focusses on the reductions of environmental impacts during the PUFAChain project. The studied PUFAChain locations are compared in chapter 4.1.3 and comparisons to reference systems are shown in chapter 4.1.4.

4.1.1 Contribution of life cycle stages

The overall screening LCA results for each scenario and each environmental impact category consist of contributions by many individual processes, inputs and life cycle stages. These are detailed exemplarily for one scenario and impact category in Fig. 4-1. The selected scenario is the combined PUFA production using Thalassiosira as a production strain in Southern Europe. It is a conservative scenario depicting the performance in 2025 (the reference year of this study), which only includes gradual improvements during the transition from current performance mainly in pilot scale to industrial scale. This is the starting point to which all combined PUFA production scenarios are compared in chapter 4.1.2.

The most important contributions to the carbon footprint (global warming potential) are energy for drying of the biomass after membrane concentration, the energy for cultivation (mainly mixing of the culture) and nutrients like nitrogen. The latter contributes about as much to the results as the whole downstream processing of the dried algae powder (“extraction & purification”).

Besides these emissions caused by PUFA production and use, emissions are avoided because co-products replace other conventional products. Thus, those conventional reference products do not need to be produced any more and the emissions associated with that production are avoided. In this scenario, the algae extraction cake from supercritical CO_2 extraction of the algae powder is used as feed replacing conventional feed (see also Fig. 3-4). In this case, only small credits arise from this substitution (negative values in Fig. 4-1).

4.1.2 Reductions in environmental impacts

A main goal of the PUFAChain project was to optimise the production of PUFAs by photoautotrophic algae cultivation and conversion. Two major concepts were studied in detail: The combined PUFA production (simultaneously yielding the PUFAs DHA, EPA and partially SDA) and the dedicated EPA production. Both systems were optimised individually.

Many aspects of the PUFA production were studied and improved. In the following, the reductions in environmental impacts by the most important achievements are highlighted.

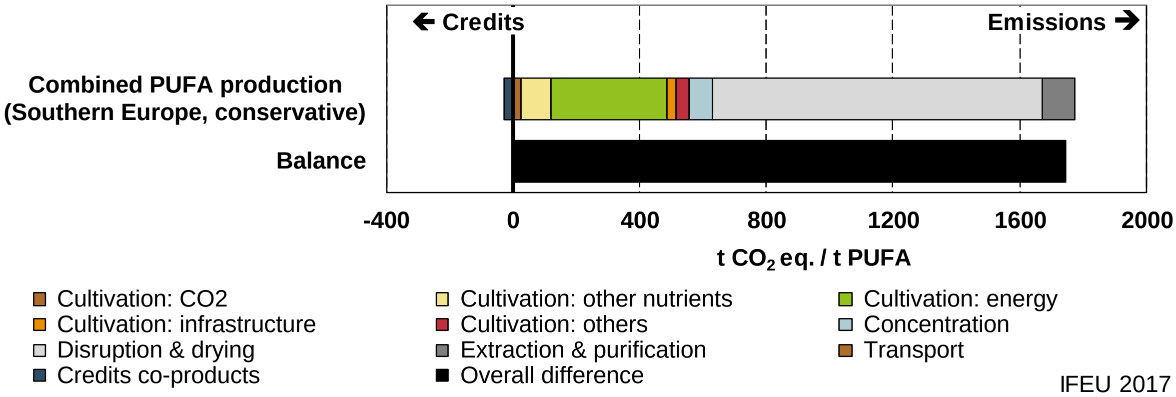


Fig. 4-1 Contribution of life cycle stages to the environmental impact category global warming potential for one exemplary scenario.

How to read Fig. 4-1:

Under conservative conditions, combined PUFA production in Southern Europe causes about 1800 t of greenhouse gas emissions per tonne of PUFA (expressed in CO_2 equivalents, right part of first bar). The biggest contribution is caused by disruption & drying (about 1.000 t CO_2 eq., light grey bar) followed by energy requirements for cultivation (about 350 t CO_2 eq., green bar). On the other hand, about 30 t of greenhouse gas emissions are avoided by co-products (credits, see left part of first bar). This results in additional net greenhouse gas emissions of about 1.750 t CO_2 eq. per tonne of PUFA (see second bar).

Process optimisation

Process optimisation is analysed in detail for the combined production of PUFAs. In a first step, many strains were screened for optimal properties. This led to the selection of *Prorocentrum* for combined PUFA production instead of the already established strain *Thalassiosira*.

The resulting reductions in environmental impacts to be expected in an industrial scale plant in 2025 are shown in Fig. 4-2. The savings in all environmental impact categories are in the range of 40%. However, the contributions causing main part of the reductions are very different in each impact category. Reductions in energy demands in cultivation and drying are important for most environmental impacts whereas reduction in nitrogen fertiliser inputs dominate the reduction of the ozone depletion potential.

A main part of work within the PUFAChain project consisted in the optimisation of many small details along the value chain. In particular algae cultivation and conversion was studied in detail. The optimised combined PUFA production by Prorocentrum can save up to 60% of environmental burdens compared to the starting point of combined PUFA production using Thalassiosira (Fig. 4-3). These shown improvements are gradual improvements of many different aspects. The pattern of improvements in the respective environmental impact categories differs slightly from the pattern seen in Fig. 4-2 but the qualitative impacts are the same in all categories: These improvements lead to reductions in all impact categories. Trade-offs do not occur.

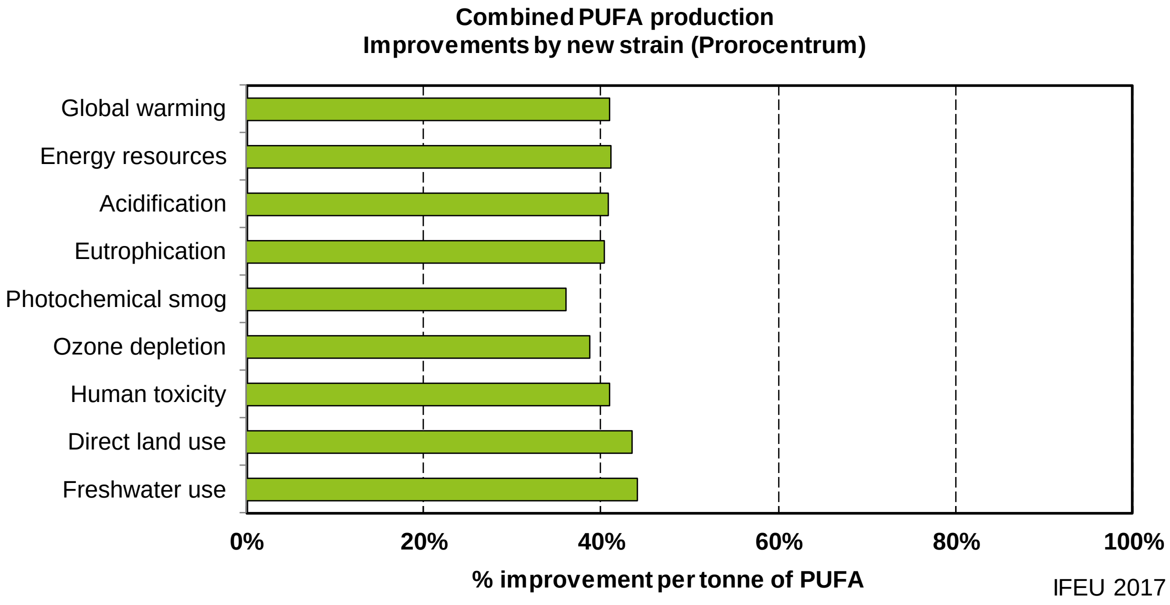


Fig. 4-2 Reduction of environmental impacts by selection of Prorocentrum as new production strain instead of Thalassiosira (Combined PUFA production with Prorocentrum under conservative conditions in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

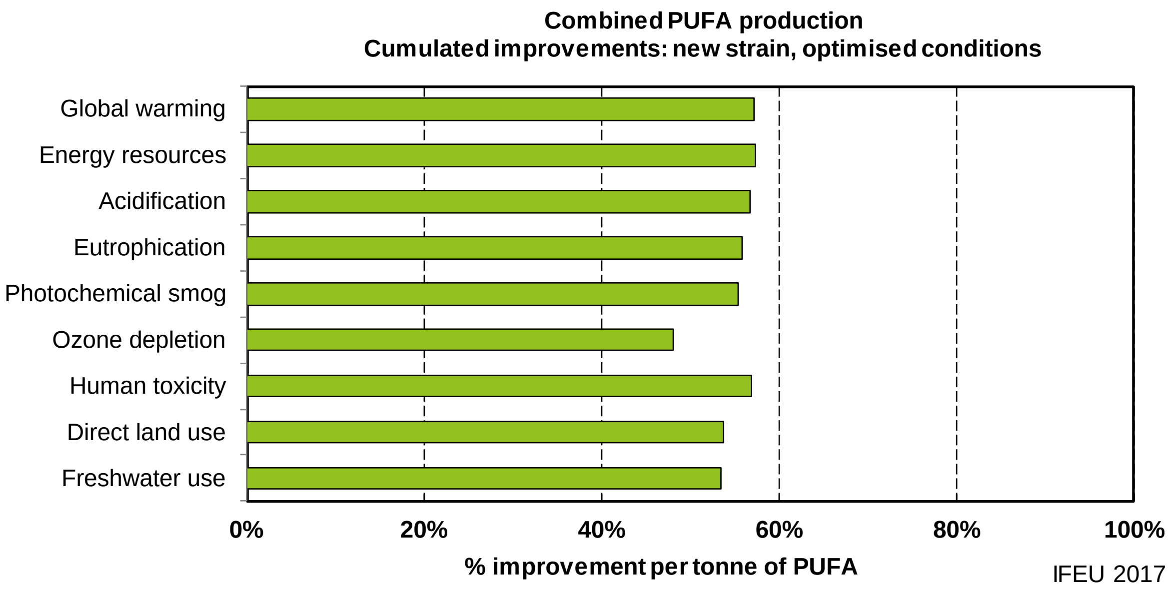


Fig. 4-3 Cumulated reduction of environmental impacts by additional various gradual improvements in algae cultivation and conversion processes (Combined PUFA production with Prorocentrum under optimistic conditions in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

Further substantial improvements can be reached by using on-site solar power (photovoltaics) instead of power from the electricity grid (Fig. 4-4). Supply and demand of solar power should be matching very well because most electricity demand that cannot be shifted in time stems from the mixing of algae cultures. Its demand is highest when the sun is shining. Therefore, the scenario is based on the supply of 80% of the electricity demand at the cultivation site (i.e. up to the transport of dried algae biomass, see also Fig. 3-1).

However, the installation of an on-site solar power system requires additional land. This compensates most of the savings thorough efficiency gains compared to the initial scenario. If this additionally used land is unused infertile land, then this does not lead to further environmental impacts on a global/regional scale. However, local impacts may occur (see chapter 4.2 for details). This additional land use should be reduced by placing part of the modules on buildings or installations other than photobioreactors (PBRs). Furthermore, space available for PBRs would not be reduced if area unsuitable for PBRs such as sloped land or too small pieces of land would be used for solar power instead. Thus, solar power causes trade-offs between direct land use[10] and other environmental impacts that can and should be minimised by a careful use of space on each individual site.

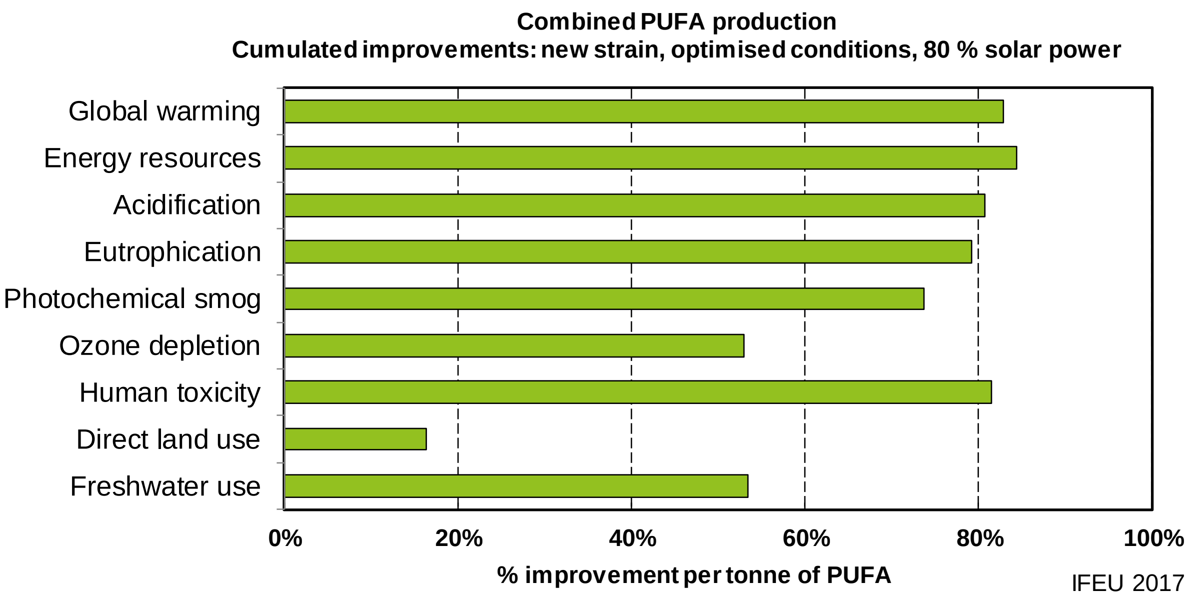


Fig. 4-4 Cumulated reduction of environmental impacts by additionally powering algae cultivation to 80% with solar power (Combined PUFA production with Prorocentrum under optimistic conditions with 80% PV in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

The reduction of freshwater consumption is a major concern in many regions suitable for algae production. The scenarios shown above are optimised for energy used and utilise evaporative spray cooling of PBR tubes. This causes a major part of the water consumption remaining after general optimisation measures including efficient cultivation medium recycling. The replacement of water sprinklers by electric cooling systems based on heat

[10] 'Direct land use' only depicts the land used by the algae production facility including on-site photovoltaics to support the discussion relevant here. For overall land use including credits for co-products please refer to Fig. 4-15.

exchangers reduces water consumption significantly, as seen in a sensitivity analysis (Fig. 4-5). As a downside, electric cooling needs more elaborate installations, which are however not relevant in terms of environmental impacts. Additionally, it needs more electricity, which can be powered to a large extent by solar power because cooling is only needed at peak solar irradiation. This requires land for additional photovoltaics installations, which is however expected to be rather small. Thus, unless regional availability of freshwater in summer months is high or water can be collected from rainwater runoff and stored, sprinkler cooling should be replaced by heat exchanger cooling from an environmental perspective. A detailed construction plan should furthermore be analysed for options to integrate heat exchanger cooling with algae biomass drying.

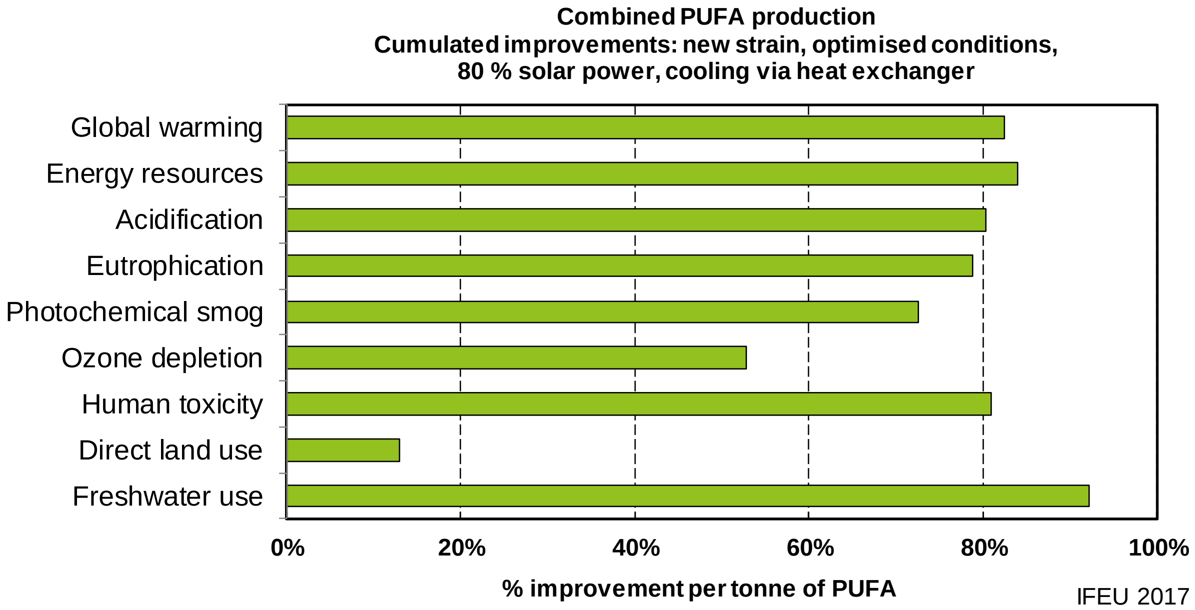


Fig. 4-5 Sensitivity analysis: Cumulated reduction of environmental impacts by replacing spray cooling with heat exchanger cooling (Combined PUFA production with Prorocentrum under optimistic conditions with 80% PV and heat exchanger cooling in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

Another process that consumes a lot of resources is the drying of algae biomass before supercritical CO_2 extraction. As sensitivity analysis was performed on the option of spray drying with natural gas instead of electricity (Fig. 4-6). When compared to Fig. 4-4, a significant further reduction of land use for solar power can be seen. If other environmental impacts and the use of non-renewable energy resources increase or decrease depends on the efficiencies of both drying systems at conditions optimised for the respective algae biomass and the residual share of power from the grid that is needed to dry algae biomass before it spoils also at times of low solar irradiation. This question cannot be answered without demo scale testing for extended periods of time. Another option that could not be investigated in this report is the use of belt dryers using solar heat possibly combined with heat recovered from cooling of PBRs and peak load natural gas boilers. These systems exist [Emminger 2016] but need to be optimised for the algae biomass and subsequent extraction process in question. Optimally, drying could be avoided completely by using an extraction technology that works with wet algae biomass. For this purpose, propane extraction was developed within the PUFAChain project. Unfortunately, not enough experience was available with this technology to quantitatively model it in the context of an industrial scale plant. Thus, it could not be assessed in this screening LCA. If extraction efficiencies similar to supercritical CO_2 extraction can be reached, the potentials for environmental advantages are big. From this we conclude that drying should be optimised further although this may require extended periods of testing such as one or few complete seasons under conditions already optimised for other parameters.

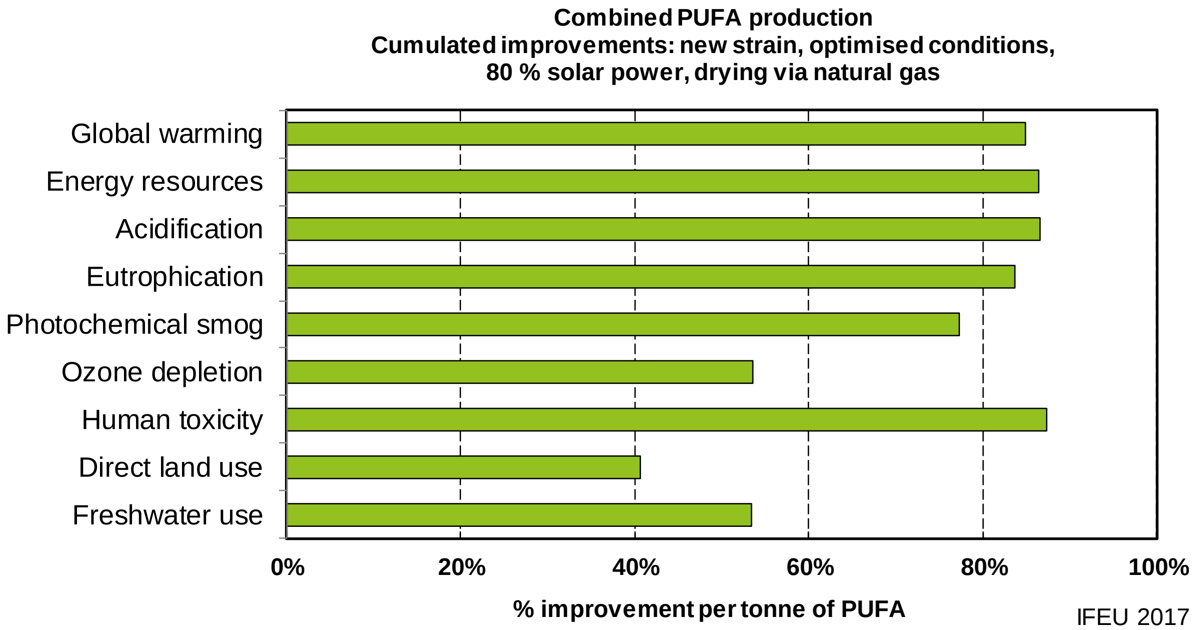


Fig. 4-6 Sensitivity analysis: Cumulated reduction of environmental impacts by replacing electric drying with optimised natural gas drying (Combined PUFA production with Prorocentrum under optimistic conditions with 80% PV and optimised drying by natural gas in Southern Europe vs. Combined PUFA production with Thalassiosira under conservative conditions in Southern Europe).

The overall optimisation process from the initial scenario to the optimised scenario reached reductions of environmental impacts of 80-90% in many impact categories (Fig. 4-4, Fig. 4-5 and Fig. 4-6). This shifted the relative contributions of individual processes or inputs (Fig. 4-7). In the exemplary category global warming, the initially biggest contributions, energy for biomass drying and cultivation, could be massively reduced with further optimisation potentials for drying described above (see also Fig. 4-6). This makes initially minor contributions to life cycle greenhouse gas emissions substantial contributors in the optimised scenario. This applies to the provision of nutrients such as nitrogen ("Cultivation: other nutrients") or downstream processing ("Extraction and purification"). Environmental burdens of nutrient inputs could for example be reduced by using certain kinds of wastewater containing such nutrients for medium preparation. All optimisations such as wastewater use that tend to destabilise the production as a downside should only be addressed once enough experience in simpler current conditions is gathered. Extraction and purification strategies could not be compared in this study unlike proposed in the goal & scope questions (chapter 2.1) because efforts in the project were focussed on one alternative each. Besides these, many other initially negligible and now still small but in total relevant contributions need to be and can be optimised for a further reduction of environmental impacts. For example, by-products such as feed avoid emissions elsewhere in the feed industry, which generates a minor emission credit now which could possibly be increased in the future (chapter 8.3.1 in the annex. This demonstrates on the one hand the enormous achievements within this project and on the other hand the optimisation potentials that can be addressed now or in the near future based on the knowledge gained.

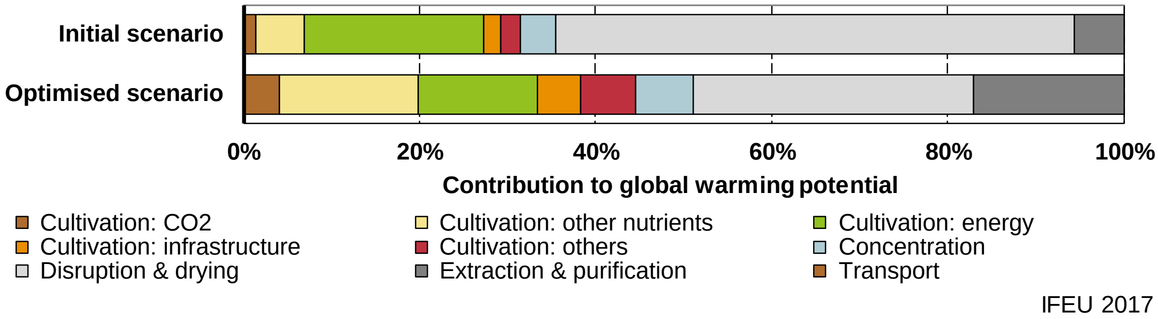


Fig. 4-7 Contributions of processes or inputs to greenhouse gas emissions before and after optimisation (Initial: combined PUFA production with Thalassiosira under conservative conditions in Southern Europe, optimised: combined PUFA production with Prorocentrum under optimistic conditions with 80% PV in Southern Europe).

Main conclusions on process optimisation:

- The gain of knowledge during the PUFAChain project makes the reduction of many environmental impacts by 80-90% possible. This means, if the value chain of PUFA production and used would be realised according to optimised scenarios instead of according to scenarios based on initial knowledge at the beginning of the project, such savings would arise. The main contributions to most environmental impacts such as global warming have been successfully addressed.
- The current state of knowledge allows for further optimisations – some of which are foreseeable but cannot be quantified in terms of their impacts yet. Furthermore, after the original optimisation goals had been achieved, new optimisation goals were determined albeit without concretely identified measures for the time being.
- 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.

Optimisation of seasonality

The PUFAChain project aimed at low impact algae cultivation by using algae at optimal temperature and light conditions instead of heating, cooling or artificially irradiating the cultures. This can be achieved either by finding algae species dedicated to certain seasons and/or locations or by the interruption of cultivation in certain seasons – very much like it is done in traditional agriculture.

This analysis concentrates on algae cultivation in Central Europe during winter months as one example. Comparing the contributions to global warming for optimised combined PUFA production in Southern and Central Europe (Fig. 4-8), on can immediately see the dramatically increase energy consumption mainly due to heating PBRs in winter. Thus, a simple transfer of the all-year cultivation concept from Southern Europe to Central Europe seems unfeasible.

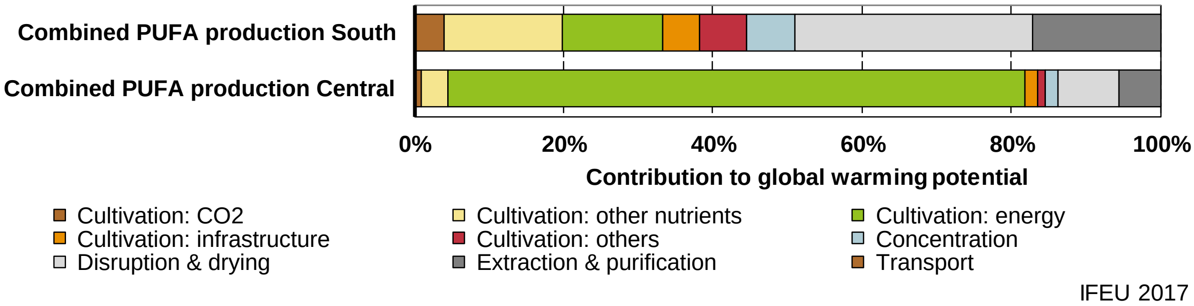


Fig. 4-8 Contributions of processes or inputs to greenhouse gas emissions in Southern and Central Europe (Both scenarios: combined PUFA production with Prorocentrum under optimistic conditions with 80% PV).

During the PUFAChain project, only little experience could be gathered on adaptation to Centrals or Northern European climate because large scale experiments were done in Portugal. The following sensitivity analyses examine proposed optimisation measures for both combined PUFA production and dedicated EPA production.

For combined PUFA production with Prorocentrum, a big part of the heating could be avoided if the cultivation plant made a winter break. This results in significantly reduced environmental impacts per tonne of PUFA product in most impact categories (Fig. 4-9). Generally, the reduced overall yield leads to a higher share of burdens caused by infrastructure construction for each t of produced product. This can be seen in particular in the land use impact (overall disadvantage). For all energy-related impacts such as global warming, the saved heating is however much more important than the lower rate of capacity utilisation (overall improvement by winter break). Freshwater use is not affected.

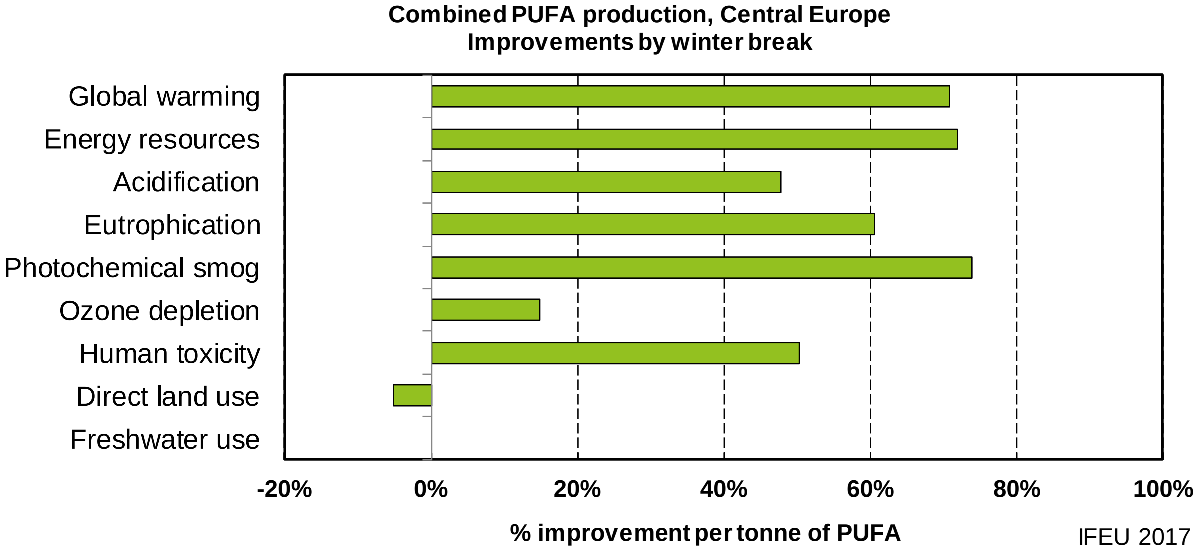


Fig. 4-9 Sensitivity analysis: Reduction/increase of environmental impacts by introducing a three months winter break (Both scenarios: combined PUFA production with Prorocentrum under optimistic conditions with 80% PV in Central Europe).

Another strategy is to cultivate a cold-adapted algae strain during winter months. This was studied for dedicated EPA production. The strain Chloridella is suitable for warm conditions. The strain Raphidonema was selected from a culture collection for its unusual abilities to grow very well in cold conditions. Both are grown alternatingly in the same installation – Chloridella in summer and Raphidonema in winter. This was termed algae crop rotation principle. Shares of cultivation time differ depending on the location. If the cultivation unit is instead left empty in the colder season (seven month in Central Europe), this however mostly leads to environmental improvements (Fig. 4-10). The reason can be seen in Fig. 4-11: While a winter break increases the burdens for infrastructure construction per tonne of product, energy consumption and other utilities decrease mainly due to lower EPA yields by Raphidonema. In total this leads to a reduction in impacts similar to what can be seen in Fig. 4-9 for the combined PUFA production. The disadvantageous performance of Raphidonema in this project at least partially also results from great reductions in the burdens of PBR construction during the project so that a lower degree of utilisation has less of an impacts.

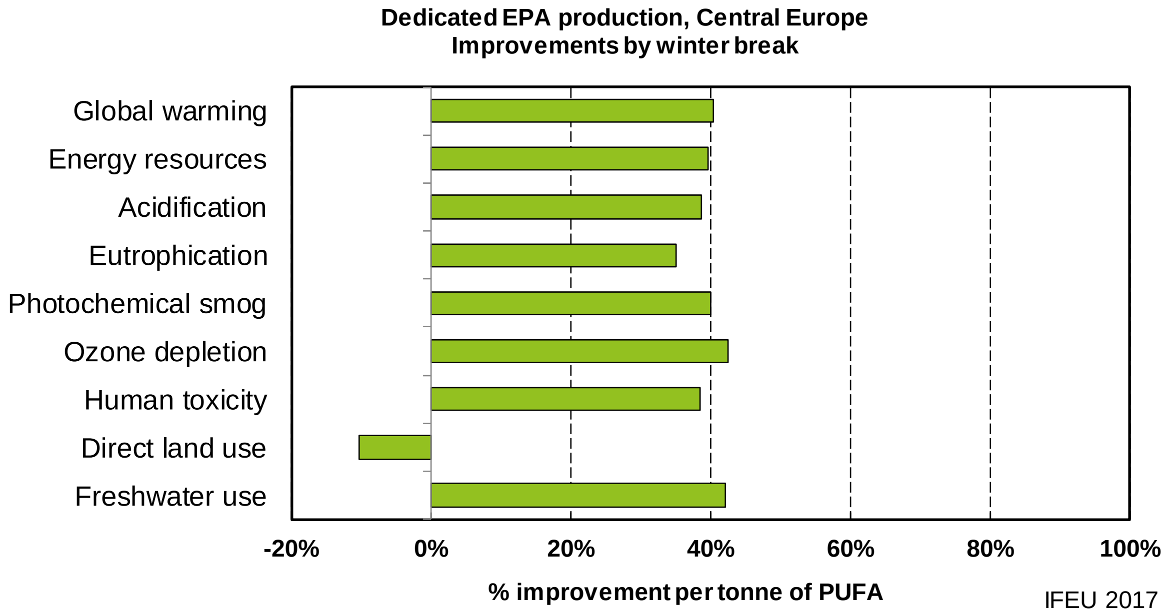


Fig. 4-10 Sensitivity analysis: Reduction/increase of environmental impacts by introducing a seven months winter break instead of Raphidonema cultivation (Both scenarios: dedicated EPA production under optimistic conditions with 80% PV in Central Europe).

Overall, an adaptation of the cultivation concept to climatic conditions can reduce environmental burdens. However, this is for now only successful by introducing winter breaks and not by algae crop rotation. In traditional agriculture, hundreds of varieties of crops are available for many environmental conditions – some more and others less studied. The selection of algae strains started from largely uncharacterised samples of wild species that were mostly, ab initio, not adapted to cultivation. It cannot be expected that fully domesticated production strains can be developed within two years in part of the project time [Benemann & John 2013]. It is anticipated to take decades for robust production microalgae strains to be available, such as those utilized in commercial production in open cultivation systems in Japan, Hawaii or Israel. Therefore, there are good chances that the principle of seasonal crop rotation can be successfully applied also to algae but this still requires further breeding and maybe also selection of further wild algae strains to get better production strains. Until such winter-adapted productive strains are available, algae cultivation in Central and Northern Europe should be optimised otherwise. This can include winter breaks as studies here, greenhouses around the PBRs or seasonal heat storage like aquifer stores and bore hole heat exchanger stores. All of these measures have to be optimised along the whole life cycle to capture trade-offs between infrastructure utilisation, energy and material consumption and product yield. Optimal settings will be different depending on which environmental (or economic) indicator is analysed. These trade-offs between sustainability indicators should be addressed by an overall sustainability assessment.

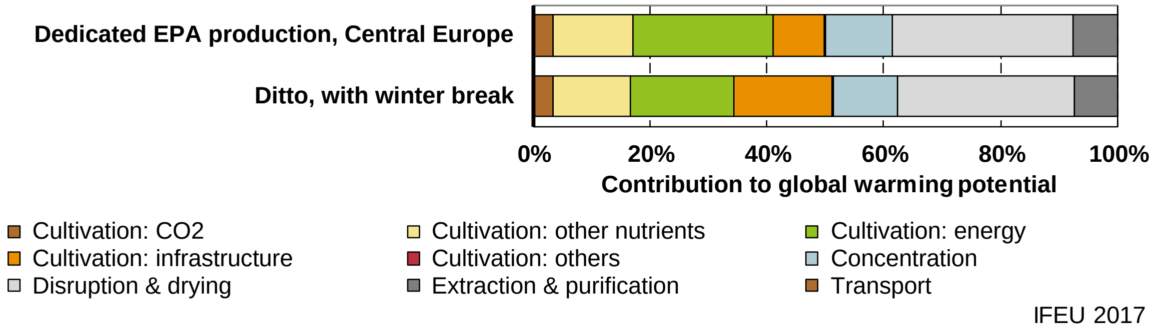


Fig. 4-11 Contributions of processes or inputs to greenhouse gas emissions in Central Europe with seven months winter break or Raphidonema cultivation (Both scenarios: combined PUFA production under optimistic conditions with 80% PV in Central Europe).

Main conclusions on optimisation of seasonality:

- Algae cultivation in regions with cold winters requires not only heating of the facilities but further adaptation towards good production conditions.
- The simplest measure can be winter breaks in order to reduce environmental impacts per tonne of product. This of course leads to a lower product volume per available area.
- Algae crop rotation where cold-tolerant algae strains are used during the winter seasons is another possible measure. At the moment, however, this is largely counterproductive from the environmental point of view because the selected wild algae strains are not (yet) productive enough. These results do not imply that the concept of algae crop rotation is unsuitable. Instead, such strains should be further improved before using them in the production process.
- Further measures for the reduction of heat demand in winter, e.g. the installation of greenhouses or seasonal heat stores should be investigated in follow-up projects.

4.1.3 Comparison of PUFAChain scenarios

In its main scenarios this screening LCA depicts two production strategies (combined PUFA production and dedicated EPA production) and two geographical regions (Southern Europe and Central Europe). Several sub-scenarios/variants are analysed for each main scenario (see also chapter 4.1.2). Additionally, dedicated EPA production in Northern Europe is studied in a sensitivity analysis. The ranges of results are depicted and compared in Fig. 4-12 and Fig. 4-13.

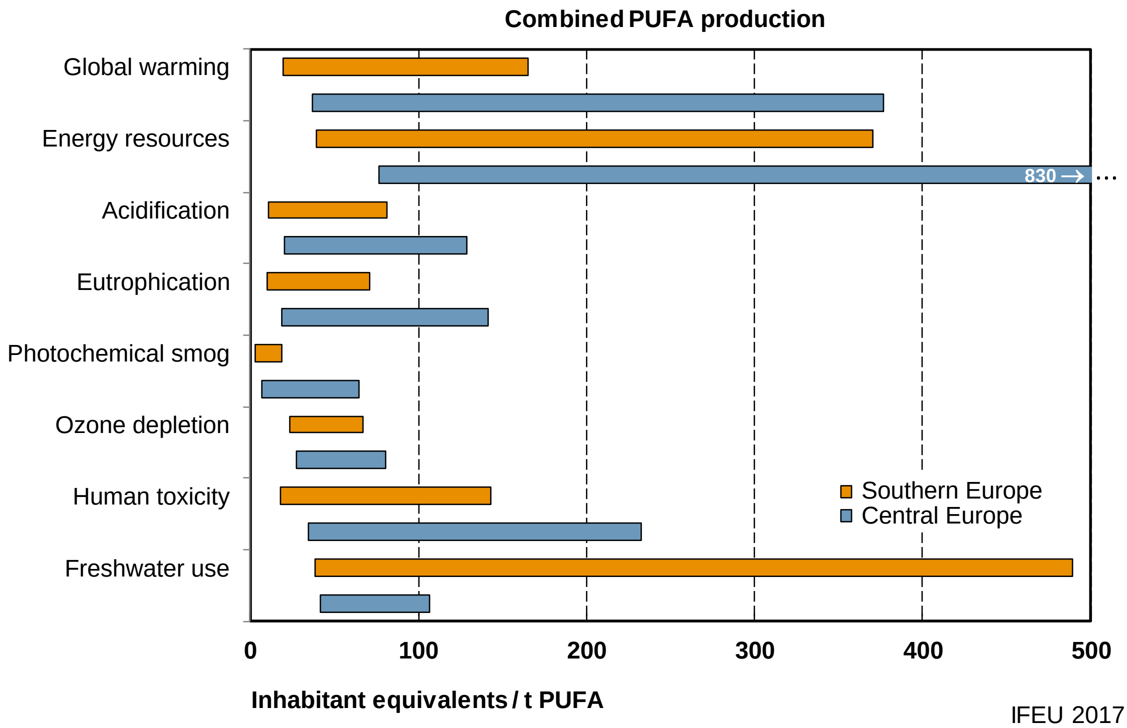


Fig. 4-12 Ranges of results for analysed scenarios of combined PUFA production in Southern and Central Europe. Results are expressed in inhabitant equivalents (IE)[11].

How to read the first bar in Fig 4-12:

The production and use of 1 t of PUFA via combined PUFA production in Southern Europe can cause a wide range of global warming impacts. The amount of greenhouse gas emissions ranges from as much as about 20 inhabitants of Europe are causing on average in one year to emissions of about 170 inhabitants.

The difference in environmental impacts of PUFA products from the various locations is rather small at the lower end of the result range and much bigger at the upper end. Big differences at the upper ends arise to a large degree from heating requirements. If heating can be largely avoided by any kind of measure, which is postulated for the most advantageous scenarios in each region, differences are small. In that case, lower productivities further north are partially compensated by lower cooling demand. It has to be noted that the regional differences in data underlying this screening LCA stem from rather coarse models especially for Northern Europe. Heating and cooling would have to be modelled in greater detail based on more cultivation experience in several locations to derive more precise LCA results in the future. Nevertheless, available results are robust enough to

[11] 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.

conclude that effective algae cultivation is not at all restricted to the Mediterranean region in Europe. If temperature regulation can be managed largely without heating, Western, Central and even Northern Europe can be attractive locations, too. They also in tendency have a higher freshwater availability so that less cultivation medium recycling may be acceptable. That way, energy and material savings in the recycling process could lead to lower overall environmental burdens. As in traditional agriculture, regional differences require regional solutions although closed PBR systems interact much less with the environment than crops on the field.

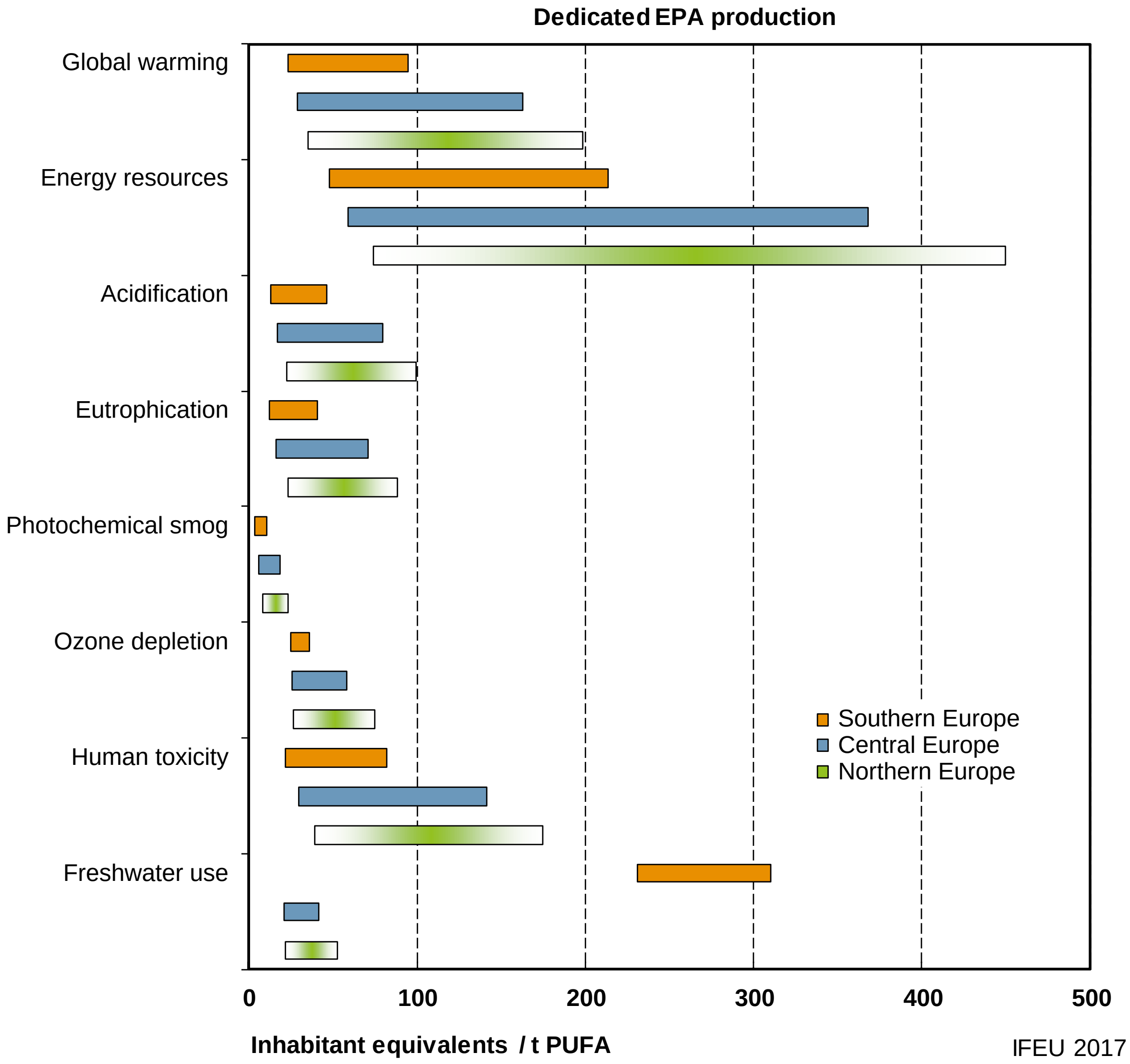


Fig. 4-13 Ranges of results for analysed scenarios of dedicated EPA production in Southern and Central Europe. Results are expressed in inhabitant equivalents (IE)[11].

The environmental impacts of combined PUFA production (yielding DHA, EPA and partially also SDA) and dedicated EPA production are not significantly different[12]. Although especially

[12] The remarkable difference in freshwater use arises from the choice of scenarios but is not significant. If heat exchanger cooling was installed instead of water sprinkler cooling for dedicated EPA production in Southern Europe (not part of selected scenarios), similarly low results could be achieved as for combined PUFA production.

downstream processing differs substantially between scenarios, overall results are similar as long as extraction and purification efficiencies of PUFAs are similar in both systems. The maximally expected potential environmental impacts are lower for combined PUFA production, which may however simply arise from a different status in current development. Furthermore, process development focussed on different aspects in both production systems so that different further success in optimisation is likely. Therefore, preferences for the one or the other production system should be based on how products can be used rather than on the environmental impacts of their production.

Main conclusions on locations and production systems:

- Provided that the heating of PBRs can largely be avoided, algae can be produced in Western, Central and even Northern Europe with only slightly higher environmental impacts than in Southern Europe. However, concepts adapted to the respective regional conditions have to be developed.
- With regard to the environmental impacts of a certain amount of PUFAs, it is irrelevant whether DHA, EPA and possibly SDA are co-produced or whether EPA is produced as a single product. The selection should therefore depend on which product can best be used.

4.1.4 Comparison to reference systems

This chapter compares the PUFAChain concept to alternatives for providing additional PUFAs to the world population in the future. As detailed in chapter 3.3, increased fishery is not an option any more. Relevant alternatives are the use of the so far underutilised residues fish cuttings (from fish processing) and by-catch (from fisheries) as well as fermentation processes. These 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, 'algae cultivation' is for the cultivation of photoautotrophic algae, while 'fermentation' refers to processes using heterotrophic microorganisms. None of these systems so far produces similar amounts of EPA and/or DHA as the established fish oil industry. Furthermore, PUFA production via fermentation processes seems to be a competitive and dynamic market at the moment, for which confidentiality is very important. This makes comparisons difficult because few data sources are available for quantitative modelling of these processes (see chapter 8.2 in the annex for a summary of that data).

Comparing these technologies for deducing conclusions on future potentials of these technologies requires comparing them as (hypothetical future) mature technologies. One main conclusion from the previous chapter is that it is very hard to estimate how mature industrial scale PUFAChain facilities may look like and when such facilities could be built. The reason is that many ground-breaking improvements have been achieved recently and that further break-throughs are likely to happen before maturity of the technology. This makes any comparison to the reference systems on the level of mature technologies very difficult.

All results in this chapter have to be analysed with these caveats in mind.

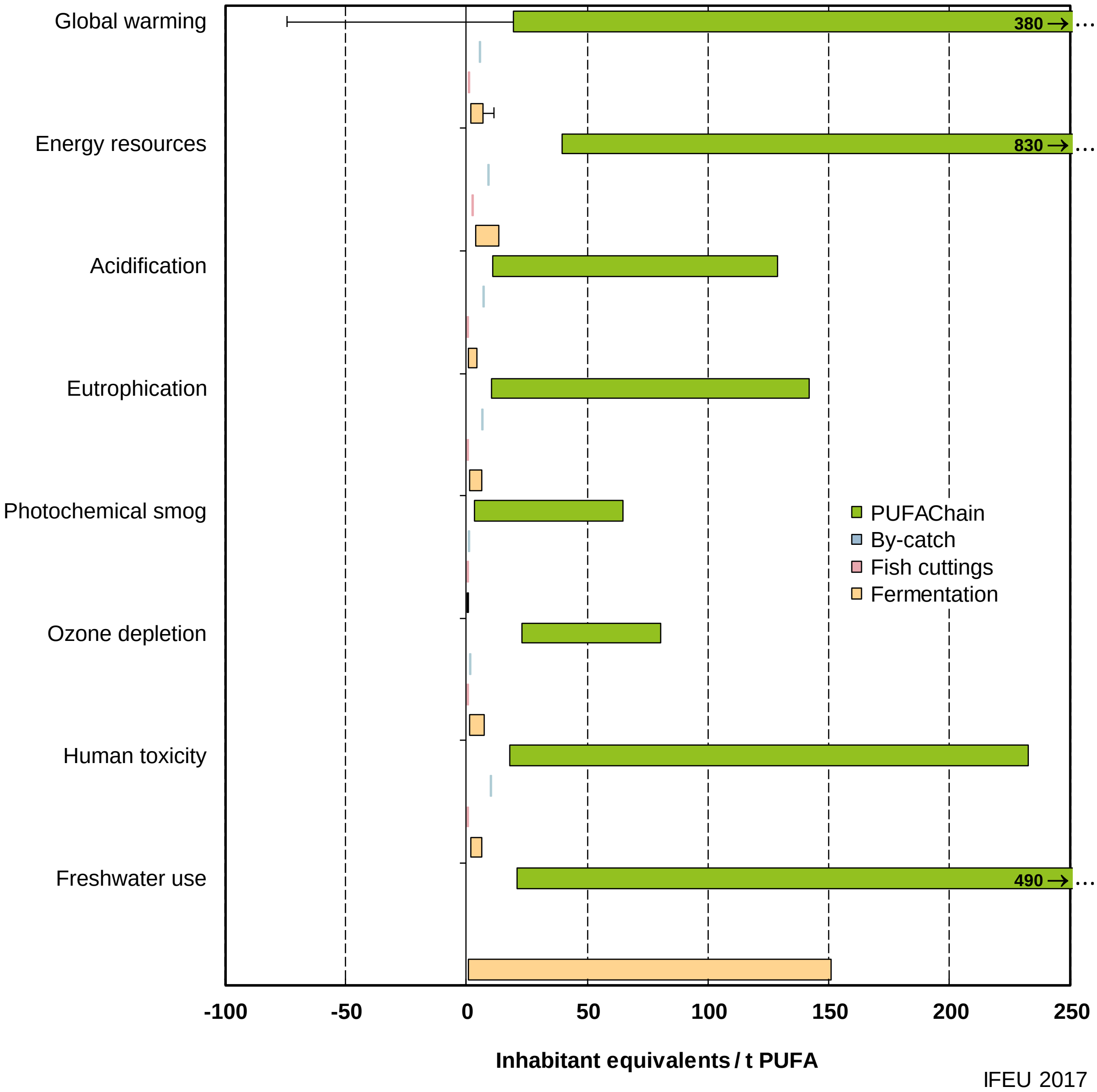


Fig. 4-14 Ranges of results for all analysed PUFAChain scenarios and all reference systems. For the reference systems fish cuttings and by-catch, ranges only consist of single values. The effect of potential land use changes on global warming are depicted as thin bar. Results are expressed in inhabitant equivalents (IE)[11].

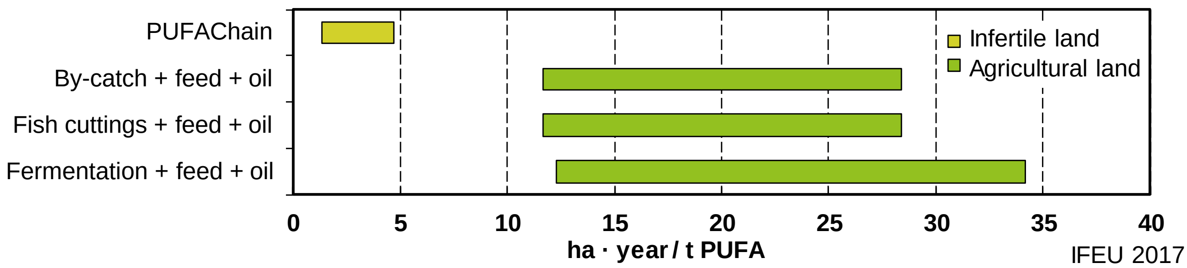


Fig. 4-15 Ranges of land use for all analysed PUFAChain scenarios and all reference systems. Here, PUFAChain scenarios without credits for co-products are compared to a basket of commodities including main and co-products.

Fig. 4-14 and Fig. 4-15 show the ranges of environmental impacts and resource use resulting from the analysis of all PUFAChain scenarios and scenarios on reference systems. In all categories except for freshwater use and land use, all reference systems perform clearly better than all PUFAChain scenarios. This means that a PUFAChain facility planned with current knowledge will very likely cause higher environmental impacts in these categories per tonne of PUFAs than its alternatives. One main reason for better performance of fermentation processes is that heterotrophic microorganisms in fermenters reach a roughly 25-fold biomass density and 5-fold PUFA content in the biomass. This means that about 125 times less medium has to be prepared, handled and removed per tonne of PUFA. Genetically modified organisms (GMOs) are often used for this purpose. The use of GMOs in fermentation is standard and does not pose a substantial risk because the microorganisms are only used in the sealed environment of a fermentation plant. It would also be possible to use genetically modified photoautotrophic algae in PBRs, which are closed systems, too, if adequate safety measures are in place. However, GMOs are mostly not accepted by consumers in Europe if they are aware of their use, which is usually not the case for GMOs used in fermentation processes.

The freshwater use[13] of PUFAs from PBRs can be lower than that of PUFAs from fermentation because its main water use doesn't occur in the fermentations stage itself but can arise from the cultivation of sugar/starch crops. Thus, if sprinkler cooling systems are avoided while fermenters are fed with sugar from irrigated fields, algae cultivation in PBRs consumes less water.

PUFAChain systems can have a clear advantage regarding land use compared to PUFAs from fermenters: Algae PBRs can be constructed on infertile land while agricultural production of sugar for fermentation requires fertile agricultural land. It can be that additional sugar production for fermentation leads to direct or indirect land use changes. This means that (semi-) natural land is converted into agricultural land. In the worst but realistic case, this could lead to logging rain forests. This would have severe consequences for biodiversity and other local environmental aspects and would also promote climate change (see thin line on the fourth bar in Fig. 4-14). Additionally, low value but large volume algae biomass fractions can be converted into products like feed. These can substitute substantial amounts of agricultural products and thus potentially avoid land use change. Under extreme but possible boundary conditions (clearing of rainforests for soy cultivation) the avoided greenhouse gas emissions from land use change can compensate all greenhouse gas emissions from algae cultivation (see thin line on the first bar in Fig. 4-14).

This potential is much lower for extracted biomass from fermentation processes because they contain much less residues per amount of PUFAs and because the used organisms are often genetically modified and may not be permitted as feed at all. If PUFAs are extracted from fish cuttings or by-catch, it is to be expected that no significant amounts of feed are produced additionally. The reason is that parts of the currently unused fish residues may anyway be used as feed in the future. Thus, it is unclear if PUFA extraction leads to more feed production because more fish residues are used or if it leads to less feed production because oil is removed from residues that would otherwise be taken into use for feed production. For these reasons, climate effects of potentially avoided land use change could not be quantified for reference systems.

[13] Freshwater refers to so called „blue water", which includes tap water, water from wells, rivers or lakes for irrigation but not rainwater.

As a consequence, all algae biomass fractions should be used for generating products even if these are economically less relevant. This could avoid enormous environmental damages through deforestation elsewhere. Since this benefit and especially the magnitude of its climate impact are uncertain, this can however not be a reason to accept a less optimised PUFAChain causing higher emissions.

The best overall environmental performance show PUFAs from fish cuttings. If cuttings are really unused otherwise, these PUFAs cause lowest environmental burdens and resource use. However, available amounts are limited. This limitation also applies to PUFAs from by-catch. Its environmental impacts are higher because fishing vessels have to return earlier to the harbour and thus use more fuel if they land the by-catch instead of throwing it over board. If upcoming changes in EU fishery policies should effectively lead to mandatory landing of by-catch then using this anyway available by-catch does not cause any more additional impacts than using available fish cuttings.

Main conclusions on comparisons to reference systems:

The available level of knowledge about future developments in algae cultivation and the available data on reference systems make any comparison very uncertain. Still, the following conclusions can be drawn:

- It is best for the environment to first use available unused resources such as fish cuttings and landed by-catch. However, amounts are limited and may not be sufficient to provide enough PUFAs to a growing world population.
- 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. Thus, at least as far as the production of PUFAs is concerned, no industrial-scale algae cultivation facilities should be funded as long as no experience is available from several years of operating a demonstration facility covering a few hectares.
- One main reason for the better performance of fermentation processes is that 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.
- A clear advantage of PUFAs from PBRs is that no fertile land is required. This is different for PUFAs from fermenters that require carbohydrates such as sugar as inputs, which has to be agriculturally produced e. g. by sugar beet. Thus, future algae cultivation facilities should only be planned on infertile land to save arable land.
- All algae biomass fractions should be used for generating products even if these are economically less relevant. This could avoid enormous environmental damages through deforestation elsewhere.

4.2 Local environmental impacts

Local environmental impacts associated with the PUFAChain systems and competing reference systems were studied following the life cycle environmental impact assessment (LC-EIA) methodology (see chapter 2.4). Chapter 4.2.1 focusses on the local environmental impacts of the PUFAChain systems whereas chapters 4.2.2 and 4.2.3 present the impacts associated with PUFAs from fermentation processes and unused fish cuttings/by-catch, respectively. A comparison of all investigated systems is shown in chapter 4.2.4.

4.2.1 Local environmental impacts of the PUFAChain systems

Following the system description in chapter 3, the PUFAChain systems are divided into several consecutive steps (chapters 3.2.1 to 3.2.3). For the purpose of the LC-EIA, the following steps are evaluated:

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

Dried algal biomass provision takes place in one location and PUFA provision is spatially separated (in two further locations). Thus, intermediate transport and logistics steps are required.

Dried algal biomass provision

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

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

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

Algae cultivation and processing facilities need buildings, infrastructure and installations (UHT-PBRs, photovoltaics system for electricity provision, auxiliary facilities for harvest and algae biomass processing), which usually goes along with sealing of soil. However, mounting systems for both UHT-PBRs and solar panels only require minor soil sealing (~5% of the occupied land) since only poles or small foundations are necessary. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site:

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

Furthermore, the algae cultivation and processing facilities can be designed differently. We distinguish an “eco” variant from a “gravel” variant:

- The “eco” variant is characterised by UHT-PBRs and solar panels on racks,
    - under which a meadow consisting of local, shade-tolerant plant species (sun-tolerant species will be competed out) is growing and which is managed non-intensively either by sheep grazing or mowing. Water infiltration (for groundwater recharge) is not affected
    - which is fenced (to prevent theft and damage), but with a fence that leaves the lowest 20 cm above ground free in order to allow at least smaller animals to enter or cross the area. For larger migratory animals, however, it is a barrier
    - which along the fence also has a hedge made up of local plant species and offers bird species (e.g. birds of prey) raised stands
    - which are constructed in a way that they don’t present a danger to (small) animals, since e.g. birds are known to nest on racks for solar panels.
- The “gravel” variant is characterised by UHT-PBRs and solar panels on racks,
    - under which geo-textile and gravel has been put to prevent plants from growing. Water infiltration (for groundwater recharge) is reduced even if the geo-textile is water-permeable since water can easily evaporate from the large surface of the gravel
    - which is fenced in an animal-unfriendly manner (i.e. without the 20 cm gap for smaller animals)
    - which has no hedge along the fence
    - which are constructed in a way that they present a danger to (small) animals (e.g. due to blinding) or scares them (e.g. due to emission of noise).

Hence, four combinations are possible, whereby the first one can be seen as the best case and the last one as the worst case:

- brownfield (BF) eco: ecological value of previously sealed land increased, e.g. due to de-sealing and planting of a meadow
- brownfield (BF) gravel: ecological value of previously sealed land remains more or less the same; deterioration in case unsealed land is covered
- greenfield (GF) eco: ecological value of previously intensively used arable land could be increased, however, the agricultural production will most likely be displaced to other areas which might indirectly cause either undesired environmental impacts such as indirect land use changes (iLUC) or intensification of existing agricultural land
- greenfield (GF) gravel: involves a substantial decrease in ecological value due to (at least partial) sealing of soil and especially loss of habitats.

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

Impacts from the <u>operation of the facility</u> are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)

- electromagnetic emissions
- risk of accidents, explosions, fires in the facility or storage areas, release of GMO (the latter not applicable in PUFAChain scenarios)

Significance of impacts might vary with the type of technology and the exact location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 2.4.1).

In addition to EPA and DHA, the PUFAChain systems also yield co-products, for which credits (for the avoided manufacture of functionally equivalent products) can be obtained: a protein-rich biomass fraction which could replace soybean meal as an animal feed and an oily residue which could make the cultivation of rapeseed obsolete. The corresponding soybean and rapeseed cultivation areas could be freed up and left to evolve naturally. These areas could be about 5 times larger than the area occupied by the algae cultivation facility.

Transport and logistics

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

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

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

PUFA provision

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

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

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

Algae oil extraction and processing facilities need buildings, infrastructure and installations (processing facilities, energy generation, administration buildings, waste water treatment etc.), which usually goes along with sealing of soil. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site (see chapter 4.2.4).

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

Impacts from the operation of the facility are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- electromagnetic emissions
- risk of accidents, explosions, fires in the facility or storage areas, release of GMO (the latter not applicable in PUFAChain scenarios)

Significance of impacts might vary with the type of technology and the exact location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 2.4.1).

Main conclusions on PUFAChain systems:

- Depending on the site, algae cultivation can have significant impacts on the environmental factors land, soil, biodiversity and landscape. These impacts should be minimised by cultivating algae on (sealed) brownfield sites instead of greenfield sites and by ecologically optimising the algae cultivation facilities (e.g. by means of meadows instead of gravel fill beneath the facilities).
- Co-products such as feed and oily residue are generated in the process of algae cultivation. This might replace conventional soy or rapeseed cultivation. The accompanying negative effects on the environmental factors land, soil, biodiversity and landscape can thus be avoided, indirectly leading to a high credit for the PUFAChain system. Therefore, next to the main product PUFA, all other biomass streams from the PUFA production should be converted into products. This would mean that the above-mentioned direct impacts of algae cultivation could be more than offset – even though this effect develops along complex (agricultural) market mechanisms and can neither be traced back nor assigned to a specific cultivation area. In accordance with the precautionary principle, brownfield sites ought to be preferred anyhow.
- Also depending on the site, significant effects on the environmental factor water can result – both in terms of quantity (especially at sites where water is scarce) and in terms of quality (due to discharge of nutrient-rich waste water). Therefore, it should always be ensured that there is sufficient freshwater supply at planned sites.
- Facility- and production-related impacts are permanent and therefore dominant whereas building-related impacts are temporary and hence less relevant.
- The conversion of dried algae biomass into PUFAs shows typical and partially site-dependent effects of industrial facilities (environmental factors concerned see above). However, since land use is substantially lesser than in algae cultivation, the environmental effects are several times lower. When optimizing local environmental impacts, one should focus on the selection and design of the algae cultivation areas and – where applicable – the photovoltaic system areas.

4.2.2 Local environmental impacts of PUFAs from fermentation processes

Fermentative production of PUFAs is one of the competing reference systems to PUFAChain. It involves the following steps:

- Biomass provision covering the cultivation of sugar/starch crops such as sugar cane, sugar beet or maize
- PUFA provision covering fermentation (using sugar as a carbon source), harvest and biomass processing and oil extraction, processing, use phase and end of life.

It is likely that fermentation and PUFA provision will take place in one single location whereas sugar provision (upstream process) is most likely spatially separated. So, most likely, an intermediate transport and logistics step will be required.

Biomass provision

The main impacts associated with biomass provision via fermentation are expected from the upstream process of sugar provision. Fermentation processes require – among others – a carbon source. In the case of PUFA provision from fermentation, sugar is used, for which sugar/starch crops need to be cultivated on arable land.

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

Table 4-1 compares impacts from the provision of selected sugar/starch crops compared to different land use reference systems. Please note that sugar cane is a perennial crop and is cultivated in a different agro-ecological zone than sugar beet and maize which on top of that are both annual crops. Direct comparisons are therefore not advisable. Detailed conflict matrices for these sugar/starch crops (compared to idle land) can be found in chapter 8.4.1 in the annex.

Table 4-1 Comparison of crop-specific impacts compared to the reference system idle land. Impacts are ranked in five categories; "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor

Feedstock	Sugar cane	Sugar beet	Maize	Avg. of crops
Reference system	Idle land	Idle land	Idle land	Idle land
Soil erosion	C	E	E	D
Soil compaction	D	E	D	D
Loss of soil organic matter	E	E	E	E
Soil chemistry/fertiliser	D	E	E	E
Eutrophication	D	D	D	D
Nutrient leaching	D	D	D	D
Water demand	D	E	D	D
Weed control/pesticides	E	E	E	E
Loss of landscape elements	C	C	C	C
Loss of habitat types	E	D	D	D
Loss of species	E	D	D	D

Impacts depend on whether the increased demand for sugar leads to direct competition for land (for the cultivation of sugar/starch crops) or not. The latter would be the case is if significant amounts of idle land were available (scenario A).

However, the increased demand for sugar could also lead to an expansion of the agricultural frontier at the expense of (semi)natural ecosystems such as grasslands or savannahs (scenario B). The latter probably is more likely. This would for example lead to

- cultivation of sugar cane at the expense of savannah ecosystems (e.g. the Brazilian Cerrado) or rainforest ecosystems (e.g. the Atlantic rainforest in Brazil) or
- cultivation of sugar beet at the expense of grassland (Europe) or
- cultivation of maize at the expense of prairie (USA).

In this case, both the colour coding and ranking in Table 4-1 are shifted towards more unfavourable results.

In addition to the impacts from the cultivation of sugar/starch crops, further impacts are expected from:

- the sugar factory
    - the construction of the facility
    - the facility itself: buildings, infrastructure and installations and
    - operation of the facility
- transport and logistics

Sugar factory

The sugar factory – like any other industrial facility – is expected to have significant impacts on the environmental factors soil, water, fauna, flora, landscape, and biodiversity. Globally seen, there are large differences in the operation of sugar factories, which are partly depending on the type of sugar/starch crop which is being processed. The use of energy carriers covers lignite, hard coal, natural gas or – in the case of sugar cane – bagasse. Other technology-related impacts affect the drain on water resources, waste water production and treatment, and traffic. The latter is especially relevant for sugar cane since the harvested (wet) biomass needs to be processed within a few days after harvest to avoid decay.

However, compared to the local environmental impacts of crop cultivation which affects areas that are multiple times larger than the surface of the sugar factory, the impacts of the sugar factory are not expected to be significant.

Transport and logistics

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

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

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

PUFA provision

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

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

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

Algae oil extraction and processing facilities need buildings, infrastructure and installations (processing facilities, energy generation, administration buildings, waste water treatment etc.), which usually goes along with sealing of soil. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site (see chapter 4.2.4).

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

Impacts from the operation of the facility are expected from:

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

Like many other biotechnological processes, fermentation towards PUFA can involve the use of genetically modified microorganisms, which are ecologically and/or hygienically relevant. Thus, there is a specific risk due to possible releases of GMO, although the “related hazardous potential is classified at the most as ‘low’ and probably as ‘negligible’ [Hoppenheidt et al. 2004]. This risk is absent both in the PUFAChain systems and in case of PUFA provision from unused fish cuttings or by-catch.

Significance of impacts might vary with the type of technology and the exact location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 2.4.1).

Main conclusions on PUFAs from fermentation processes:

- The production of PUFAs by means of fermentation processes can have significant impacts on the environmental factors land, soil, biodiversity and landscape. They are primarily the result of sugar/starch crop cultivation for use as a carbon source. There are differences between the individual crops; for example, the use of corn instead of sugar cane as a carbon source requires approximately 4 times more land. When purchasing goods, care should be taken to buy only certified sugar, meeting the sustainability demands of biofuels, in order to at least exclude goods associated with direct land use changes.
- Fermentation and extraction of PUFAs display the typical, in part site-specific, impacts of an industrial facility (see above for affected environmental factors). However, they are several times smaller than those for algae cultivation, due to the much lower land use. The local environmental impacts should be minimised by building PUFA production facilities on (sealed) brownfield sites and not on greenfield sites.

4.2.3 Local environmental impacts of PUFAs from unused fish cuttings or by-catch

PUFA provision from unused fish cuttings or by-catch, one of the competing reference systems to PUFAChain, involves the following steps:

- Fish biomass provision covering fish biomass collection (collection of unused fish cuttings at the point of fish processing [either directly at or close to the sea] or the landing of by-catch [instead of discarding it directly at sea]) and pre-processing and
- PUFA provision covering oil extraction from fish biomass, processing, use phase and end of life.

It is likely that unused fish biomass provision and PUFA provision will take place in one single location, however, PUFA provision could be spatially separated. If the latter was the case, an intermediate transport and logistics step would be required.

Fish biomass provision

No significant local environmental impacts are expected to be associated with the provision of unused fish cuttings or by-catch since both of them are considered as wastes (or as co-products with – at least today – zero value) which otherwise would have to be disposed of. Collecting and landing by-catch requires extra (fossil) energy consumption, e.g. for fishing boats, fish trawlers or other marine vessels – at least compared to the conventional practice of discarding. In the view of the EU's plan to make landing of by-catch mandatory, the extra (fossil) energy consumption and the related emissions could also be fully attributed to the marketable fish, since it will occur anyway. The corresponding local environmental impacts are not considered to be significant and therefore set zero in the LC-EIA. Please note that due to this system boundary, all impacts on the marine environment are explicitly excluded from this assessment.

Since we expect that this step is combined with the PUFA provision (see below), the associated impacts will be accounted for together with the PUFA provision. If fish biomass provision and PUFA provision took place in separate locations, an intermediate transport and logistics step would be necessary, however, the impacts associated with transportation and logistics are not expected to be significant (see preceding chapters).

PUFA provision

Impacts from implementing a fish oil extraction and processing facility are expected from:

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

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

Fish oil extraction and processing facilities need buildings, infrastructure and installations (processing facilities, energy generation, administration buildings, waste water treatment etc.), which usually goes along with sealing of soil. Differences are expected regarding the location of the facility, depending on whether the project is developed on a greenfield site or on a brownfield site (see chapter 4.2.4).

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

Impacts from the operation of the facility are expected from:

- emissions of gases and fine dust
- drain on water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- electromagnetic emissions
- risk of accidents, explosions, fires in the facility or storage areas, release of GMO (the latter not applicable in this scenario)

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU which would be required before building such a facility (see chapter 2.4.1).

Main conclusions on PUFAs from unused fish cuttings or by-catch:

- The conversion of previously unused fish cuttings and by-catch into PUFAs displays the typical, in part site-specific, impacts of an industrial facility on the environmental factors land, soil, biodiversity and landscape. The local environmental impacts should be minimised by building PUFA production facilities on (sealed) brownfield sites and not on greenfield sites.
- Otherwise, no significant impacts are associated with these scenarios – under the boundary conditions adopted here – with regard to the production of fish biomass, meaning that this type of PUFA production should clearly be given preference. However, the existing potentials are probably insufficient to meet global PUFA demand.

4.2.4 Comparison: PUFAChain systems vs. competing reference systems

Biomass provision

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

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

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

Likely significant impacts, indicated by solid borders in the upper part of Table 4-2, are expected to occur either from the facility itself and/or – in the case of PUFAs from fermentation processes – resulting from the operation of the facility (since the cultivation of sugar/starch crops is required). The following technology-related factor was identified as the main driver for significant impacts (on the environmental factors soil, water, flora, fauna, landscape, and biodiversity):

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

However, facility-related impacts due to soil sealing and compaction are only considered to be significant in case the algae cultivation facility is being built on a greenfield site or if a previously unsealed brownfield site is being (partially) sealed (see chapter 4.2.1 for details).

Since the PUFAChain systems also yield co-products (a protein-rich biomass fraction and an oily residue), for which otherwise soybean and rapeseed would have to be cultivated, **credits for avoided significant impacts** could be obtained. Depending on the exact equivalence factors (today unknown), the corresponding cultivation areas could be freed up and left to evolve naturally. This *indirect* effect could (several times) over-compensate the *direct* impact on land resources related to the PUFAChain facility. An objective weighting of the impacts of one against the other, however, is unfortunately not possible on the generic level, on which the LC-EIA is conducted.

In addition, there are **potentially significant impacts** resulting from the operation of the facility which depend on the exact location and local surrounding of the facility. This site-dependency is indicated by dashed borders in the upper part of Table 4-2. The following technology-related factors:

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

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

Comparison of systems

Comparing only the four investigated PUFAChain systems to each other, no differences are expected in terms of impacts related to the construction of the facility and operation of the

Table 4-2 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								
Algal/fish biomass (1-7) or biomass (8+9) provision	**Brown field eco**	**Brown field gravel**	**Green field eco**	**Green field gravel**	**Fer-men-tation**	**Cut-tings**	**By-catch**	**Soy-bean**	**Rape-seed**
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

facility. Regarding impacts from the facility itself, there are enormous differences between the four investigated PUFAChain systems, depending on where exactly the algae cultivation facility is being built (see chapter 4.2.1 for details).

However, these impacts are absent in the case of PUFA provision from unused fish biomass (fish cuttings and by-catch), respectively, because fish biomass provision does not require cultivation sites. In other words, the PUFAChain systems are at a disadvantage.

When comparing the PUFAChain systems to PUFA provision from fermentation processes, it becomes clear that the impacts of the latter are dominated by the cultivation of sugar/starch crops, i.e. by agricultural operations. Local environmental impacts related to the sugar factory (e.g. soil sealing) as well as impacts related to sugar transport and logistics are not considered to be significant (in relation to the vast area used for sugar/starch crop cultivation) and therefore set zero in the LC-EIA. Looking only at the *direct* impacts of each system, the worst-case implementation of PUFAChain, greenfield (GF) gravel, could be viewed as less favourable than PUFA provision from fermentation processes. One could come to this view if one considers the impacts related to the sealing of former agricultural land to be more severe than the impacts related to the management of agricultural land for sugar/starch crop cultivation. Such judgements, however, involve value choices and are therefore no longer scientifically objective. This is because objective criteria are missing which would allow a quantification and comparison of ecological values across different agro-ecological zones or between different types of land use.

All other implementations of PUFAChain would already perform better. However, if the co-products obtained from the PUFAChain system avoid the heavy-impacting cultivation of soybeans and rapeseed, the avoided environmental impacts thereof would be credited to the PUFAChain system. This would lead to a considerable advantage for the PUFAChain systems.

PUFA provision

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

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

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

Likely significant impacts, indicated by solid borders in the lower part of Table 4-2, are expected to occur from the operation of the facility. The following technology-related factor was identified as the main driver for significant impacts (on the environmental factors soil, water, flora, fauna, landscape, and biodiversity):

- risk of accidents, explosions, fires and GMO release.

In addition, there are **potentially significant impacts** from the facility itself (i.e. buildings, infrastructure and installations) as well as from the operation of the facility which depend on the exact location and local surrounding of the facility. This site-dependency is indicated by dashed borders in the lower part of Table 4-2.

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

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

However, facility-related impacts due to soil sealing and compaction are only considered to be significant in case the facility is being built on a greenfield site or if a previously unsealed brownfield site is being (partially) sealed (see chapter 4.2.1 for details)

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

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

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

Comparison of systems

Differences between the investigated systems mainly occur during the operation of the facility in terms of:

- waste water production and treatment
  The risk for negative impacts (e.g. through eutrophication) on water quality of surface water bodies, fauna and flora is considered to be higher in case unused cuttings and by-catch are processed without appropriate waste water treatment (ranking “E” instead of “D”), e.g. as a consequence of corruption and/or weak law enforcement
- traffic
  Risks for collisions and emissions are considered to be higher in case sugar is imported from other agro-ecological zones (ranking “D” instead of “C”)
- risk of accidents, explosions, fires and GMO release.
  In contrast to the PUFAChain systems and PUFA provision from unused fish biomass (both GMO-free), PUFA provision from fermentation processes entails the risk of GMO release (ranking “D”). This could lead to significantly negative impacts on soil, water, fauna, flora and biodiversity.

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

Main conclusions on comparison of PUFA provision pathways:

- The different PUFA production pathways differ considerably in terms of the local environmental impacts. The smallest impacts are expected from PUFAs from unused fish cuttings and by-catch, because no significant environmental impacts are associated with biomass production. However, the existing potentials are probably insufficient to meet global PUFA demand.
- A comparison of algae-based PUFA production with fermentation processes leads to ambiguous results in terms of the local environmental impacts. If PUFAChain leads to the sealing of arable land (by covering with geotextiles and gravel), the environmental impacts on the environmental factors land, soil, water and biodiversity associated with this could be regarded as more grave than sugar/starch crop cultivation for PUFA production in fermenters. This means that when implementing the PUFAChain system, it is important that, ideally, a (sealed) brownfield site is selected. If arable land has to be used, the design of the facility should be as ecological as possible. This kind of coverage of arable land may be justified, in particular if all land-related, complementary PUFAChain system products are utilised which have the potential to release arable land in other parts of the world to an extent several times larger than the land directly used by the PUFAChain system.
- Irrespective of the problems of land use, sufficient water supply must be guaranteed at the planned site in order to implement the PUFAChain system.

5 Recommendations

Based on the conclusions drawn in chapter 4, the following recommendations can be made to the algae community in business and science, to policymakers and to consumers from an environmental perspective:

To the algae community in business and science

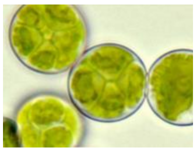
Continue the successful optimisation of algae cultivation and utilisation in order to be prepared for implementation at a large, industrial-scale. Exploit the insights of this, and other, environmental analyses in order to also improve economically less relevant, but environmentally important, aspects.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

- **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, 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. 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 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 report has addressed among others the following options: 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 or cold-tolerant algae strains as part of an algae crop rotation, integration of heating and cooling using seasonal heat stores. Details can be found in the results section.

- **Convert all algae constituents to products, even if they may be economically less relevant.**
  
  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.

Images from top to bottom: © Thomas Leya for Fraunhofer IZI-BB, Potsdam, Germany; Jürgen Frey/pixelio.de; Rainer Sturm/pixelio.de; Peter Smola/pixelio.de

- **Optimise algae strain productivity.**

Algae for use in photobioreactors (PBRs) are substantially less productive in comparison to the 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.
- **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.
Because closed algae cultivation systems in PBRs may still require substantial amounts of water, sufficient availability of freshwater[14] must be ensured, in particular in semi-arid and arid regions, but also in the Mediterranean region. Existing water use in a catchment area[15] must be taken into consideration. The use of fossil groundwater is not sustainable.

[14] More precisely: blue water

[15] In technical jargon: environmental flow requirements

- **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 and algae production synergies to be achieved. 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.

To policymakers

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

As this report demonstrates, enormous environmental compatibility improvements 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.**

As long as no experience is available from several years of operating a demonstration facility covering a few hectares, it is 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. Instead, the use of fish cuttings available from fish processing and unused by-catch for PUFA extraction should initially be promoted.

- **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.

- **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.

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.

6 Glossary and abbreviations

Agricultural land	Agricultural land is defined as land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.
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.
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
Blue water	Fresh surface and groundwater, in other words, the water in freshwater lakes, rivers and aquifers.
BF	Brownfield (see also “brownfield site”)
Brownfield site	Land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.
CCS	Carbon capture and storage is the process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, and depositing it in e. g. underground geological formations.
CCU	Carbon capture and use summarises various process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, to use it for producing products (see also “algae cultivation” and “power-to-X”).
CFC	Chlorofluorocarbon, substance contributing to ozone depletion.
DHA	Docosahexaenoic acid, a certain omega-3 PUFA only produced by algae
DW	Dry weight
EIA	Environmental impact assessment

EPA	Eicosapentaenoic acid, a certain omega-3 PUFA only produced by algae
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.
GF	Greenfield (see also "greenfield site")
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 is a methodology for comprehensive sustainability assessment of products. see also [Keller et al. 2015].
iLUC	Indirect land use change
LC-EIA	Life cycle environmental assessment is a methodology for the assessment of local environmental impacts that cannot (yet) be adequately covered by LCA.
LCA	Life cycle assessment
LCI	Life cycle inventory, its creation is part of an LCA study
LCIA	Life cycle impact assessment, part of an LCA study

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.
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.
SEA	Strategic environmental assessment
SDA	Stearidonic acid, a certain omega-3 PUFA, which is a metabolic precursor of EPA and DHA
UHT-PBR	Unilayer horizontal tubular photobioreactors, a certain kind of PBRs used in this project.

7 References

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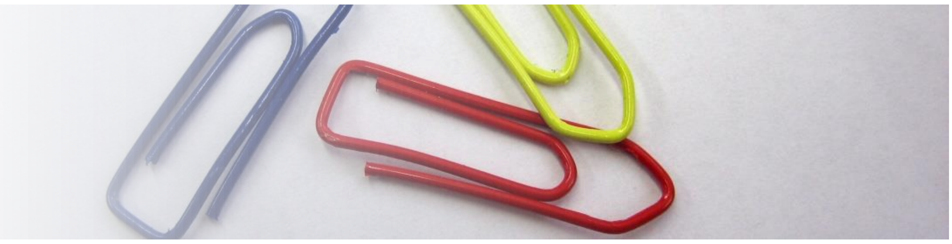

8 Annex

This chapter contains additional information and data supplementing the main part of the report.

8.1 Normalisation factors

The factors used to normalise the environmental impacts are:

Table 8-1 EU 25+3 inhabitant equivalents (IE) for the year 2000 [CML 2016; Eurostat 2007; Ravishankara et al. 2009]

Impact category	**Inhabitant equivalent**	
Global warming	10 581	kg/yr
Ozone depletion *	0.07	kg/yr
Photochemical smog	20	kg/yr
Human toxicity (respiratory inorganics)	40	kg/yr
Acidification	70	kg/yr
Eutrophication	5.8	kg/yr
Resource depletion: Non-renewable energy *	82	GJ/yr

*: As described in chapter 2.3.2, these indicators deviate from the CML methodology and thus adapted normalisation factors were used.

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

8.2 Summary of input data

Most important input data for the LCA calculations are summarised in this chapter.

Table 8-2 Summary of most important input data. DW: dry weight, green: life cycle outputs, *: Raphidonema is produced in the same facility as Chloridella

			Initial combined PUFA production		Combined PUFA production		Dedicated EPA production			
	Strain		**Thalassiosira** weissflogii (all year)		**Prorocentrum** cassubicum (all year)		**Chloridella** simplex (summer)		**Raphidonema** nivale Lagerheim (winter)	
	Scenario		Southern Europe, least expected	Southern Europe, optimistic	Southern Europe, least expected	Southern Europe, optimistic	Southern Europe, least expected	Southern Europe, optimistic	Southern Europe, least expected	Southern Europe, optimistic
Cultivation	**Average photosynthetic productivity**	**gDW/m²(PA)/day**	12.0	13.2	12.0	13.2	10.0	11.0	3.0	3.3
	Water type		Saltwater	Saltwater	Saltwater	Saltwater	Freshwater	Freshwater	Freshwater	Freshwater
	Regular production time	**days/year**	330	330	330	330	240	240	90	90
	PBR area (photosynthetic area)	**ha (PA)**	10	100	10	100	10	100	10	100
	Total area	**ha (total)**	12	120	12	120	12	120	0*	0*
	N demand	**kg N/kg DW biomass**	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	CO_2 demand	**kg CO_2/kg DW biomass**	3	3	3	3	3	3	3	3
	Tap water	**m³/kg DW biomass**	0.58	0.53	0.58	0.53	0.79	0.72	0.79	0.72
	Biomass produced	**t DW/year**	390	4300	390	4300	240	2600	27	300
Concen-tration	**Loss during harvesting**	**%**	5%	3%	5%	3%	5%	3%	5%	3%
	Replacement modules	**Modules per year**	21	121	66	304	19	95	8	47
	Freshwater cold	**m³/year**	29 000	320 000	27 000	290 000	0	0	0	0
	Medium recycling	**%**	90%	90%	90%	90%	90%	90%	90%	90%
Disrup-tion	**Disruption method**		Osmotic shock	Osmotic shock	Osmotic shock	Osmotic shock	Bead milling	Bead milling	Bead milling	Bead milling
	Disruption efficiency	**%**	95%	97%	95%	97%	95%	97%	95%	97%
Drying	**Loss during drying**	**%**	5%	3%	5%	3%	5%	3%	5%	3%
Extrac-tion	**CO_2**	**t/year**	250	610	250	610	140	360	16	41
	Spent biomass	**(t DW/year)**	320	3700	330	3800	180	2200	21	240
Purification	**Loss during purification**	**%**	10%	10%	8%	4%	10%	10%	10%	10%
	Tap water	**m³/year**	0	0	34	390	0	0	0	0
	Hexane	**kg/year**	0	0	300	1 700	0	0	0	0
	NaOH	**kg/year**	0	0	1 900	23 000	0	0	0	0
	$Mg(OH)_2$	**kg/year**	0	0	1 400	17 000	0	0	0	0
	EPA + DHA (+SDA) in product	**t PUFA/year**	5	152	10	119	7	86	0	2
	Oily residue	**t/year**	18	200	8	96	10	120	1	14
	Wastewater	**m³/year**	0	0	36	420	0	0	0	0
Energy	**Steam**	**MJ th/year**	1 065 000	9 285 000	1 145 000	15 070 000	678 900	5 518 000	76 673	623 900
	Power (incl. for cooling)	**kWh/year**	10 671 057	90 521 100	10 981 057	95 921 100	6 727 037	61 491 580	1 156 292	11 037 490

Table 8-2 continued

			Initial combined PUFA production		Combined PUFA production		Dedicated EPA production				Dedicated EPA production	
	Strain		Thalassiosira weissflogii (all year)		Prorocentrum cassubicum (all year)		Chloridella simplex (summer)		Raphidonema nivale Lagerheim (winter)		Chloridella	Raphidonema
	Scenario		Central Europe, least expected	Central Europe, optimistic	Central Europe, least expected	Central Europe, optimistic	Central Europe, least expected	Central Europe, optimistic	Central Europe, least expected	Central Europe, optimistic	Northern Europe, optimistic	Northern Europe, optimistic
Cultivation	Average photosynthetic productivity	gDW/m²(PA)/day	8.0	8.8	8.0	8.8	8.0	8.8	4.6	5.1	5.7	4.7
	Water type		Saltwater	Saltwater	Saltwater	Saltwater	Freshwater	Freshwater	Freshwater	Freshwater	Freshwater	Freshwater
	Regular production time	days/year	330	330	330	330	120	120	210	210	80	250
	PBR area (photosynthetic area)	ha (PA)	10	100	10	100	10	100	10	100	100	100
	Total area	ha (total)	12	120	12	120	12	120	0*	0*	120	0*
	N demand	kg N/kg DW biomass	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	CO_2 demand	kg CO_2/kg DW biomass	3	3	3	3	3	3	3	3	3	3
	Tap water	m³/kg DW biomass	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	Biomass produced	t DW/year	260	2900	260	2900	96	1100	97	1100	460	1200
Concen-tration	Loss during harvesting	%	5%	3%	5%	3%	5%	3%	5%	3%	3%	3%
	Replacement modules	Modules per year	15	85	47	213	13	68	12	66	34	29
	Freshwater cold	m³/year	19 000	210 000	17 000	190 000	0	0	0	0	0	0
	Medium recycling	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Disrup-tion	Disruption method		Osmotic shock	Osmotic shock	Osmotic shock	Osmotic shock	Bead milling	Bead milling	Bead milling	Bead milling	Bead milling	Bead milling
	Disruption efficiency	%	95%	97%	95%	97%	95%	97%	95%	97%	97%	97%
Drying	Loss during drying	%	5%	3%	5%	3%	5%	3%	5%	3%	3%	3%
Extrac-tion	CO_2	t/year	170	410	170	410	57	140	58	150	62	160
	Spent biomass	(t DW/year)	210	2500	220	2500	74	860	75	880	370	970
Purification	Loss during purification	%	10%	10%	8%	4%	10%	10%	10%	10%	10%	10%
	Tap water	m³/year	0	0	22	260	0	0	0	0	0	0
	Hexane	kg/year	0	0	200	1200	0	0	0	0	0	0
	NaOH	kg/year	0	0	1300	15000	0	0	0	0	0	0
	$Mg(OH)_2$	kg/year	0	0	940	11000	0	0	0	0	0	0
	EPA + DHA (+SDA) in product	t PUFA/year	4	102	6	79	3	35	0	6	15	6
	Oily residue	t/year	12	140	10	120	4	48	4	49	21	54
	Wastewater	m³/year	0	0	24	280	0	0	0	0	0	0
Energy	Loss during drying	MJ th/year	94 733 000	946 156 000	95 105 000	954 720 000	282 600	2 229 000	291 060	2 301 200	969 300	2 793 600
	Power (incl. for cooling)	kWh/year	7 618 064	68 553 300	8 198 064	74 153 300	2 842 621	28 184 130	3 473 847	33 544 130	11 020 818	40 289 960

Comment to Table 8-2: Data on downstream processing for *Chloridella*, *Raphidonema* und *Thalassiosira* was limited because experimental work in this project focussed on Prorocentrum. Therefore, the following approach was followed:

- Crude algae oil from *Chloridella*, *Raphidonema* und *Thalassiosira* is treated in similar processes as fish oil to reach either nutraceutical grade or pharma grade PUFA products. The data availability on both processes is limited. Therefore, crude algae oil with a certain amount of PUFAs is directly compared to crude fish oil with the same PUFA amount. The remaining purification process is not modelled explicitly because an imbalance of data quality would lead to distorted results.
- Fish oil and algae oil both contain undesired substances, which need to be removed for product safety and product quality, respectively. Both process lead to negligible environmental impacts.
- For the purpose of comparing nutraceutical grade PUFA preparations to each other, 10% loss and 0.5 MJ steam per kg PUFAs are set for the purification of crude fish oil and crude algae oil from *Chloridella*, *Raphidonema* und *Thalassiosira* to nutraceutical grade. These values represent the upper limits of expected figures.

8.3 Specific methodological aspects

Certain contributions to results of life cycle assessments can be strongly dependent on settings and methodological choices. This is examined in sensitivity analyses in this chapter. The assessment of produced by-products (8.3.1), energy used in central processes (8.3.2) and CO_2 as well as infertile land as potentially limited resources of the future (8.3.3) are discussed in the following chapters.

8.3.1 Sensitivity: by-product assessment methods

The assessed scenarios produce the co-products extraction cake, removed fatty acids and partially also glycerol along with the main product PUFAs. LCA methodology offers several options how to distribute the environmental burdens arising from processes needed for both main and co-product production such as cultivation among all products. As detailed in chapter 2.3.1, the so-called system expansion (substitution approach) was followed in all analyses in chapter 4. Following this approach, all emissions are allocated to the main product and credits for emissions avoided elsewhere through co-product use are subtracted (Fig. 8-1, upper panel). Example: If extraction cake is used as feed and the avoided emissions from soy cultivation are credited. An alternative approach is the allocation of burdens to main and co-products according to certain criteria. Physical parameters are to be preferred if they reflect the function of the products e.g. energy content for several fuels produced in a refinery or mass/dry matter content for several largely equivalent foods from one production process such. If no such parameters can be found as is the case for PUFA production, economic value is used for allocation (Fig. 8-1, lower panel). Product prices used for this allocation stem from [van der Voort et al. 2017]. As the comparison of both panels in Fig. 8-1 shows, the by-product assessment method has no relevant influence on the displayed results. The same applies to all other assessed scenarios and environmental impacts.

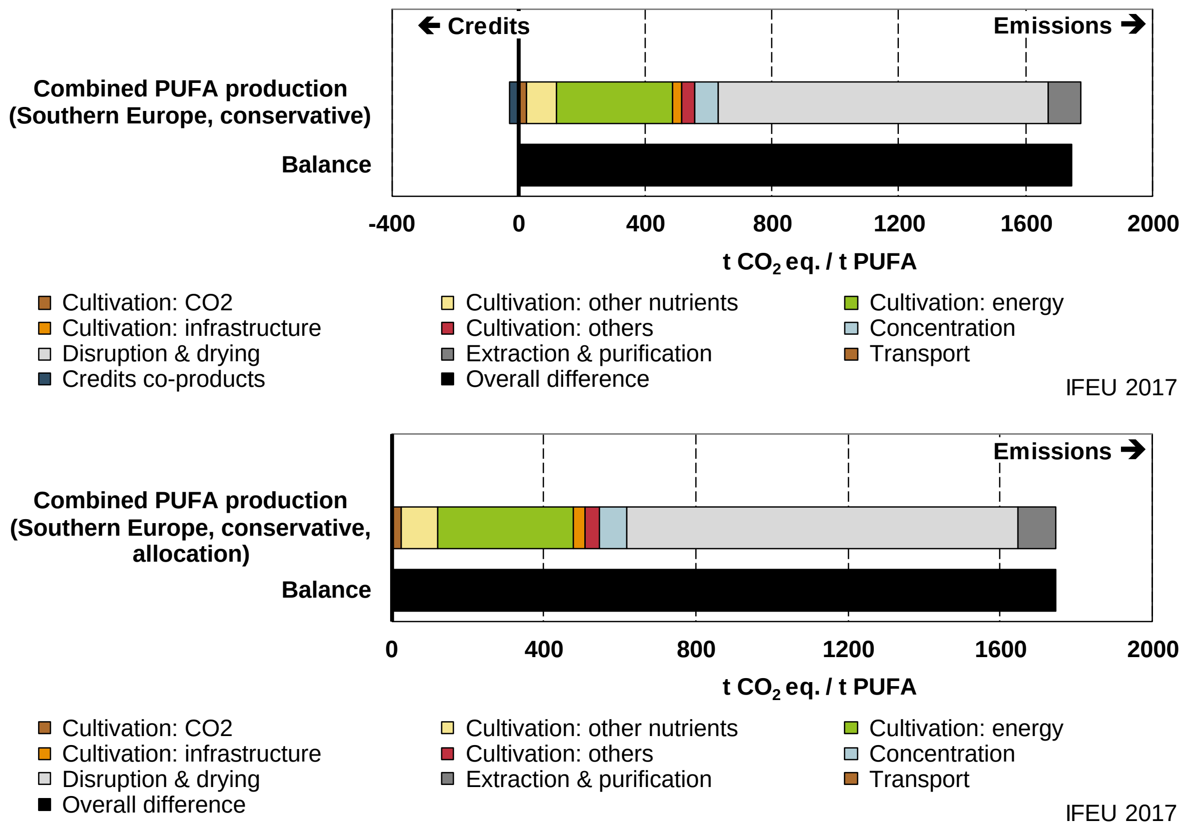

Fig. 8-1 Impact of the method of accounting for co-products on the contribution of life cycle stages to the environmental impact category global warming potential for one exemplary scenario. Upper panel: co-products receive emission credits, lower panel: emissions are allocated to main and co-products by economic value.

8.3.2 Sensitivity: origin of power used for algae cultivation

Depending on the approach used in a LCA study, different data sets have to be chosen including those for power production. As described in chapter 2.3.1, consequential modelling was applied based on the goal and scope of this study. This leads to the use of data sets depicting the so called marginal provision mix of e.g. power. This means that the additional installation of an algae cultivation facility leads to additional (marginal) power production. This does not equal average power production because several types of power production such as renewables and nuclear power are producing at their limits anyway, which are posed by technical and regulatory constraints but (in most European regions and at most times) not by market demand. This means that additionally produced power causes higher environmental burdens because it is dominated by fossil electricity generation.

Additional to this approach, we also calculated sensitivity analyses based on average power provision to the assessed systems (Fig. 8-2). This leads to significantly lower environmental impacts because the influence of the newly installed algae cultivation on power production is not taken into account. Nevertheless, the conclusion in chapter 4.1 was that the environmental impacts of power production are so dominant that on-site solar power should be installed to reduce them. Compared to reductions by on-site solar power as modelled in the main scenarios (Fig. 8-3), the effect of average grid mix is much smaller except for the use of infertile land, which was found to be currently less relevant (see also chapter 8.3.3). Thus, conclusions are not affected by the methodological choice.

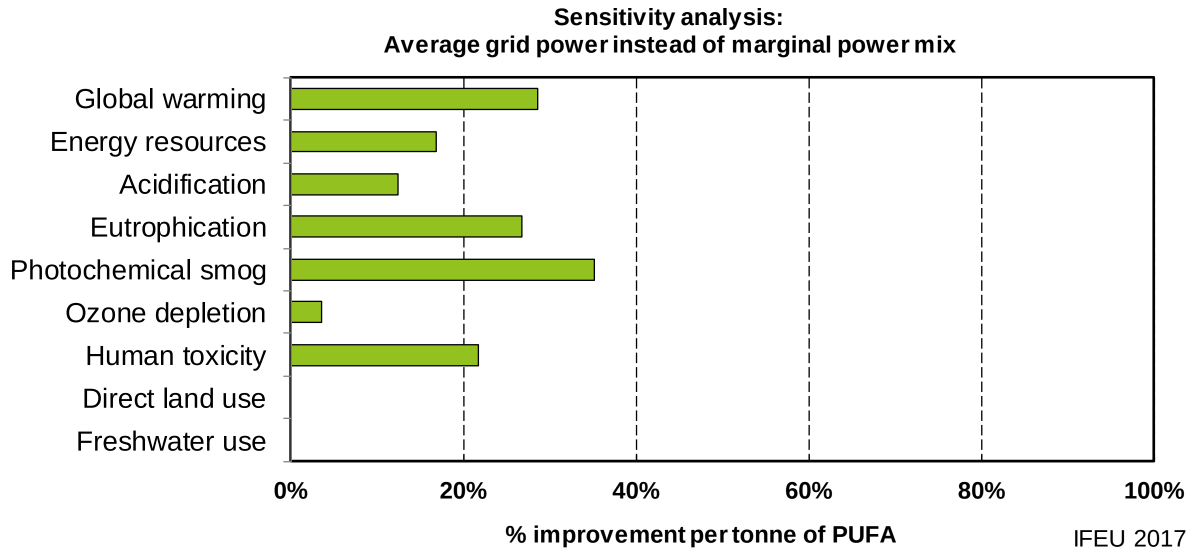

Fig. 8-2 Sensitivity analysis: Reduction of environmental impacts by selection of average power mix instead of marginal power mix in the scenario "Combined PUFA production with Prorocentrum under optimistic conditions in Southern Europe".

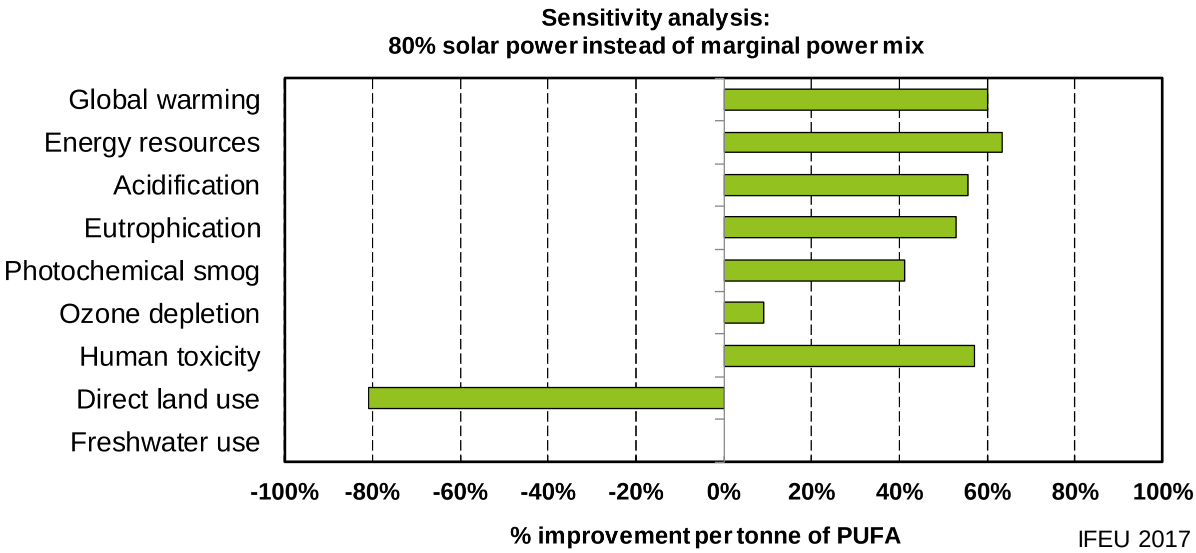

Fig. 8-3 Reduction of environmental impacts by selection of 80% power from on-site photovoltaics instead of marginal power mix in the scenario "Combined PUFA production with Prorocentrum under optimistic conditions in Southern Europe".

The main scenarios are based on the setting chosen for modelling based on expert judgement that only 80% of the power demand can be supplied by on-site solar power as also seen in Fig. 8-3. However, this had to be based on rather weak data. If 100% solar power could be used instead, results would change as depicted in Fig. 8-4. This leads to proportionally higher reductions of most environmental impacts and proportionally higher increase in direct land use. This underlines the conclusion that as much solar power should be used as technically feasible.

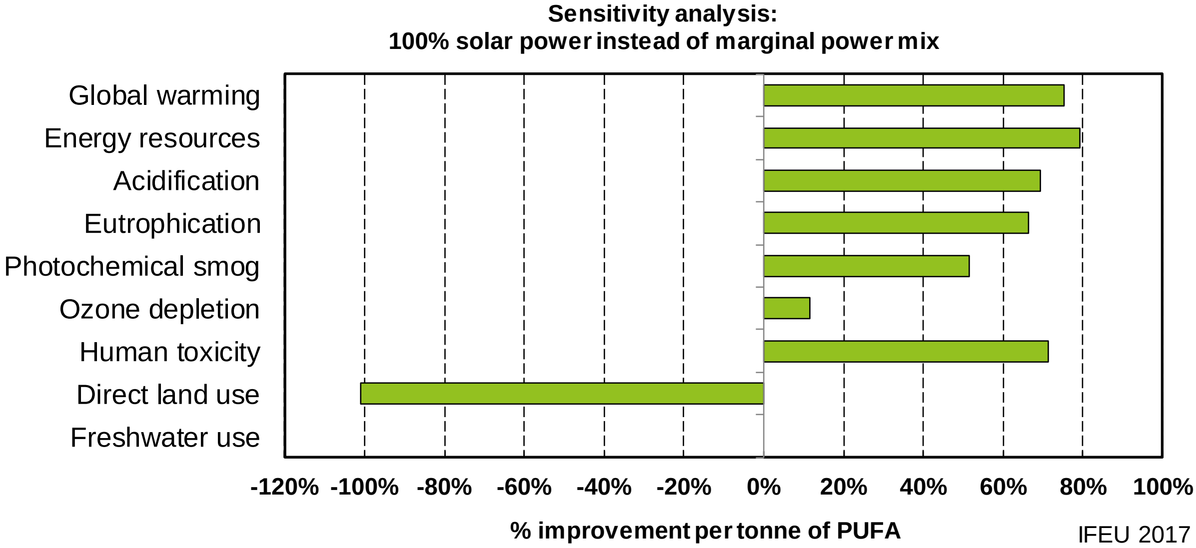

Fig. 8-4 Reduction of environmental impacts by selection of 100% power from on-site photovoltaics instead of marginal power mix in the scenario “Combined PUFA production with Prorocentrum under optimistic conditions in Southern Europe”.

8.3.3 CO_2 and infertile land as potentially limited resources of the future

According to chapter 2.3.1, consequential modelling is applied in this screening LCA. This includes the evaluation of consequences an additional use of limited resources can have. The newly established system can e. g. cause the displacement of another user of this resource. Therefore, it has to be analysed, which resources used by algae production may be limited. This is discussed here for CO_2 and infertile land.

CO_2 as potentially limited resource

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

Infertile land as potentially limited resource

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

8.4 Details regarding local environmental impacts

This chapter contains detailed crop-specific conflict matrices for both sugar/starch crops (chapter 8.4.1) as well as other dedicated crops (chapter 8.4.2) whose cultivation is avoided through the PUFAChain system.

8.4.1 Local environmental impacts of selected sugar/starch crops

In this chapter, detailed information and impact matrices on selected biomass feedstock crops (for fermentative PUFA provision) can be found. Due to limited space, they were not presented in chapter 4.2.2, but only summarised in a table.

Sugar cane

Plantations of sugar cane are restricted to warmer regions (South America, Africa, the Caribbean) as the plants cannot withstand temperatures below zero degrees Celsius. Optimum growth temperature is around 25 °C. The plants prefer heavy soils with high water storage capacity. As sugar cane is highly water consuming the plantations are primarily located in areas with high availability or water (e.g. riparian zones) or in areas, which afford intensive irrigation. Adverse impacts occur in depletion of ground water and often in salinization of soils as a consequence of intensive pumping.

Plantations of sugar cane afford intensive soil management including application of fertiliser and pesticides. The danger of compaction and erosion is very high. Due to monocultures high impacts on plants, animals and biodiversity is expected.

Table 8-3 summarises the risks associated with cultivation of sugar cane on the environmental factors.

Table 8-3 Risks associated with the cultivation of sugar cane compared to the reference system of idle land.

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

1: negative in case of cultivation on the expense of natural habitats (e.g. rain forest, cerrado)

Sugar beet

The cultivation of sugar beet e.g. for bioethanol production requires a high soil quality. Highest yields are achieved on deep soils with homogenous structure. As the young plants are endangered by overgrowth from the surrounding arable flora an intensive weed control is required. Due to a high number maintenance cycles and heavy vehicles (e.g. high applications of fertiliser [120-160 kg N/ha], need of weed and pest controls) there is a high risk of soil compaction. A consequence is an increased risk of nutrient leaching, affecting both groundwater and superficial water, especially by runoff during heavy precipitations. Ploughing of leaves after harvesting in fall will not compensate the loss of nutrients in total (fruit : leave ratio ≈ 1,2 : 0,8 [Schlegel et al. 2005]), so additional supply of organic fertiliser is necessary for soil balance. Intensive processing, use of heavy machines for the application of fertiliser and weed control in combination with the risk of erosion due to late soil coverage can affect plant and animal diversity. Thus succeeding crops (e.g. legumes, winter wheat) are recommended and help to minimise erosion. Potential impacts on landscape are comparable to the reference system of idle land.

Loss of habitat types and species might cause impacts if there is a change in habitat quality e.g. woodland is converted to arable land. The cultivation of sugar beet on arable land is not expected to cause a loss of habitats. Table 8-4 summarises the risks associated with cultivation of sugar beet on the environmental factors.

Table 8-4 Risks associated with the cultivation of sugar beet (ploughing of leaves) compared to the reference system of idle land.

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

1: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;

2: Ploughing of leaves is usually not enough to compensate loss of nutrients)

Maize grain

Techniques and production conditions for maize grains e.g. for production of bioethanol do not differ from maize cultivation for feed or food production. As an essential difference to harvesting the total plant it is assumed, that maize straw is left on the field for green manuring thus reducing the amount of fertiliser (corn : straw ratio ≈ 1 : 1,3 [Kaltschmitt et al. 2009]). Due to high needs of nitrogen especially for the young plants the use of artificial fertiliser is still necessary on most soil types.

The chance of genetic engineering on maize (GMO) to optimise the output of grains might exist. As a market for GMO feedstock in Europe is relatively low it is not expected that GMO maize is grown in a considerable amounts. Nevertheless the risk exists although it is considered relatively low.

Risks of impacts on the environmental factors soil (erosion, compaction due to maintenance cycles), water (nutrient leaching and eutrophication) plants, animals and biodiversity (weed and pest control, monoculture) are effective as well. Table 8-5 summarises the risks associated with cultivation of maize grain on the environmental factors.

Table 8-5 Risks associated with the cultivation of maize (ploughing of straw) compared to the reference system idle land.

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

1: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;
2: Ploughing of straw is usually not enough to compensate loss of nutrients)

8.4.2 Local environmental impacts of crops occurring in reference systems

In this chapter, detailed information and impact matrices for soybean and rapeseed can be found which in chapter 4.2.4 were only presented in an aggregated table.

Soybean

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

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

Especially during the last year genetic modified soy seeds resistant against Glyphosate ("round up") were used allowing airborne application of fertiliser and pesticides on a large scale. As a consequence health problems in the vicinity of treated fields as well as the explosion of Glyphosate-resistant "superweeds" were observed [Antoniou et al. 2010].

Table 8-6 summarises the risks associated with cultivation of soybean on the environmental factors.

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

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

Rapeseed

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

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

Table 8-7 summarises the risks associated with cultivation of rapeseed on the environmental factors.

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

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants/ Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	neutral/ negative[1]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of SOM	neutral/ negative[1,2]			neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1]
Soil chem./ fertiliser	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control/ pesticides		negative	negative	negative	negative				negative
Loss of landsc. el.				neutral	neutral	neutral	neutral	neutral	neutral
Loss of hab. types				neutral/ negative	negative/ positive[2]				negative/ positive[2]
Loss of species				neutral/ negative	negative/ positive[2]				negative/ positive[2]

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

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

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