The value chain from microalgae to PUFA ('PUFAChain')

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Socio-economic assessment of Algae-based PUFA production

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Socio-economic assessment of Algae-based PUFA production

Contents

ABBREVIATIONS

ACR =	algal crop rotation
ALA =	α-linolenic acid, C18:3(n-3)
ARA =	arachidonic acid (also AA) C20:4(n-6)
BRIC =	Brazil, Russia, India and China
CAGR =	Compound Annual Growth Rate
CIP =	cleaning in place, a procedure for cleaning process equipment such as vessels or pipes without disassembling them
DHA =	docosahexaenoic acid, C22:6(n-3)
DM =	dry matter
DPA =	docosahexaenoic acid, C22:5 (n-3)
DSP =	downstream processing
EFSA =	European Food Safety Authority
EPA =	eicosapentaenoic acid, C20:5(n-3)
FA =	fatty acids
FAME =	fatty acid methyl esters
FAO =	Food and Agriculture Organization of the United Nations
FM =	fish meal
FO =	fish oil
FPA =	flat panel airlift
FPB =	flat panel bioreactor
GMO =	genetically modified organism
IFFO =	International Fishmeal and Fish Oil Organisation
MCSGP =	multicolumn counter current solvent gradient purification
PBR =	photobioreactor
PE =	photosynthetic efficiency
PUFA =	polyunsaturated fatty acids
sCO2 =	supercritical CO_2
SCP =	single cell protein
SDA =	stearidonic acid
TAG =	triacylglycerides
UHT-PBR =	unilayer (single layer) horizontal tubular photobioreactor
USP =	upstream processing
WHO =	World Health Organisation

Algae strains used:

Thalassiosira weissflogii	**CCAP 1085/18**
Prorocentrum cassubicum	**SAG 40.80**
Chloridella simplex	**SAG 51.91**
***Raphidonema nivale* Lagerheim**	**CCCryo 381-11**

Summary

In Task 9.4 a socio-economic assessment of the systems defined in Task 9.1 was performed for the PUFAChain process by Wageningen Research (former DLO). The result is an international working paper that documents the approach, method and results of this socio-economic assessment. This includes a macro-economic assessment, a LCC (Life Cycle Costing, micro-economic) analysis, followed by an overall SWOT analysis taking into account the different parts with emphasis on the socio-economic aspects.
The **macro-economic assessment** focuses on market analysis and competiveness and provides information about market and price developments. Both peer-reviewed and generic data sources were used. The **LCC (micro-economic) analysis** uses both existing information and tools in development from the Interreg project EnAlgae, combined with data from Task 9.1 and the project partners. UNEP/SETAC guidelines for LCC were taken into account. The macro- and micro-economic analyses both identify profitability and market competiveness of the systems. The **SWOT analysis** has been updated during the project and takes into account the results of the other three analyses. When useful, reference systems/products were assessed as well. The integrated **socio-economic analysis**, presented in a data table, includes all major social and micro-economic aspects, such as impacts on employment and public acceptance of new technologies. Institutional, legislative and political aspects are included if applicable. UNEP/SETAC guidelines for sLCA (social life cycle assessment) and recent methodological literature are taken into account. The results will be used as input for Task 9.5.

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

EPA/DHA consumer market - The global EPA/DHA consumer market has been growing fast and is expected to keep on growing in the future. Driving factors are positive clinical research outcomes, regulatory recognition, increasing consumer health awareness and improved living standards on several continents. The largest EPA/DHA market segments by application are respectively dietary supplements, pharmaceuticals, infant formulas and functional foods. In terms of market value, the largest market segment is concentrates because of their higher prices, particularly for pharmaceuticals. Key suppliers have developed ultra-high concentrates, which have EPA and DHA concentrations of up to 90 % for both the pharmaceutical and the nutraceutical market. At the moment the largest share of the EPA/DHA oil market volume and value originates from wild fish and only a minority share from algae, but algae oils have a larger share in market value than in volume. The EPA/DHA consumer market leader sells algae based DHA (mainly for infant formulas) and EPA/DHA products. They are produced by protists (also called unicellular marine heterotrophic organisms) that are grown on sugar in closed fermentation vessels (without light contrary to phototrophic algae). The need to find new sources of EPA and DHA because of depleting wild fish stocks and concerns about contaminations is an opportunity for algae based PUFAs. The absence of fishy taste/smell and appealing labels like “vegetarian/vegan”, “kosher” or “organic” distinguish algal oil from fish oil. For the time being algae EPA/DHA producers have to deal with higher production costs than their fish oil based EPA/DHA competitors, highly competitive pricing and a high price sensitivity among food industries and final consumers. In addition, PUFAs from phototrophic algae have to compete with PUFAs from unicellular marine heterotrophic organisms that are in the same or lower price range and contain higher lipid/PUFA levels. In addition, new market players have to deal with powerful food and pharmaceutical multinationals. Only five companies have about 75 % of the EPA/DHA market share.
Aquaculture feed market - At the moment already more than half of the fish we consume is farmed rather than wild caught. This leads to an equally increasing aquaculture feed market. The main ingredient in global aqua feed is soybean meal followed by fish meal. Leading companies in the aqua feed sector are

increasingly looking at ways in which algae and other 'alternative' ingredients can reduce the sector's dependence on fish meal (FM) and fish oil (FO). One of the market key players is now able to provide (approved) feed formulations with different EPA/DHA ratios from unicellular marine heterotrophic organisms.

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

LCC (micro-economic) analysis

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

The LCC is therefore mainly assessing the influence of geography/climate, scale and algae strain on the costs of a potential mature production plant for 2025. This analysis leads to more insight whether a mature future PUFA supply chain based on phototrophic algae can compete with other sources of EPA/DHA. The capital and operational costs of all separate supply chain steps (algae production and processing, algae harvesting, cell disruption and drying and algae biomass processing by supercritical CO_2-extraction and oil processing) for producing EPA/DHA from different algae strains are taken into account. This results in a cost price per kg EPA/DHA (functional unit). The LCC and the cost price per kg highlight the most significant cost items in relation to the overall production yield per strain. The LCC offers insights and options for improvements in the effort of the PUFA Chain to achieve a mature supply chain for 2025.
Based on the macro-economic information the price ranges for algae or fish oil are around €400 – €1,500 per kg EPA/DHA and algae DHA supplements for about € 5,500 per kg DHA (see macro-economic analysis, Chapter 2 of this report). This price range is certainly achievable under most of the current expected mature production scenarios. The first conclusion is that economic viable production of PUFAs from phototrophic algae is feasible.

The production costs represent, in all scenarios, the most important share in total costs (62-80 %). In the sensitivity analysis the highest production costs were taken to determine the focus for further improvements in the PUFAChain process. The following results were found.

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

In addition, two alternative options were investigated: Firstly, locating production in cheaper more rural areas. All scenarios turned out to be the most expensive areas/regions for each country. Choosing a more rural location would significantly impact costs of land for each scenario. The second alternative option was related to the LCA assessment. Renewable energy, in this case solar power plants, is competitive in price with fossil energy. Based on price developments of solar parks in Europe a lower price of electricity was assumed to be realistic. The effect of choosing a more rural location is almost 20 % for Lisbon region and almost 30 % for Munich region. The reduction in cost prices as a result of switching to cheaper electricity sources is around 8 % for Lisbon region and around 7 % for Munich region.

The LCC analysis outcome shows that production in Southern Europe (Lisbon region) seems a more viable option compared to Central Europe (Munich region). The production of *Thalassiosira* at 100 ha optimistic scenario for Southern Europe (Lisbon region) has the best expected performance, followed by three other scenarios; *Prorocentrum* at 100 ha in Southern Europe, Thalassiosira at 100 ha in Central Europe and *Prorocentrum* at 10 ha in Southern Europe.

The Algal Crop Rotation (ACR) option proved an interesting option, but was not researched to its full potential. The ACR scenario for Northern Europe (Oslo region) did not perform well compared to the other ACR options. A significantly lower biomass and EPA/DHA yield is main reason for the lower performance. The LCC offers insights and options for improvements in a mature supply chain for 2025. The most important recommendations are:

- Investigate alternative locations with similar geographical settings, but lower land costs (e.g. brownfield sites or more rural locations)
- Production equipment should be algae strain specific
- Investigate alternative sources of energy
- Increase both biomass production yield and PUFA content of the algae cells

Socio-economic analysis

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

SWOT analysis
The SWOT analysis for the (assumed mature) PUFAChain is based on several micro- and macroeconomic factors as well as socio-economic and general sustainability issues. Environmental issues are left out of this SWOT analysis since they are addressed in more detail in the LCA by IFEU (Keller et al, 2017a).

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

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

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

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

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

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

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

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

Market outlook for algae based PUFAs is positive.
The global EPA/DHA consumer market has been growing recent years and is expected to keep on growing in the future. The need to find new sources of EPA and DHA because of depleting wild fish stocks and concerns about contaminations is an opportunity for algae based PUFAs. The market segment of the aqua

feed is also increasingly looking in too which algae and other ‘alternative’ ingredients which can reduce the sector’s dependence on fish meal (FM) and fish oil (FO).

The production of PUFAs from phototrophic algae is economically viable.
A number of researched scenarios in the micro-economic assessment result in cost prices within the €400 – €1,500 per kg EPA/DHA market price range. The market price range is based on the macro-economic assessment. The PUFAChain scenarios vary between the price ranges of €468 - €3,903 per kg EPA/DHA. The LCC analysis outcome shows that production in Southern Europe (Lisbon) seems a more viable option compared to Central Europe (Munich), but this will not exclude Central Europe as option overall. Within the researched scenarios there is potential to improve the performance even further.

A mature PUFAChain should perform equal or slightly better than competing sources.
Based on the socio-economic evaluation a PUFAChain could potentially score better on employment in Southern Europe scenarios and overall on food safety. PUFAs from fish cuttings and by-catch are expected to be less advantageous to health, regarding the risk for contaminants and impurities in natural food chains. In addition, both processes are linked to unsustainable fisheries and therefore will trigger less public commitment. PUFAs from heterotrophic microorganisms (protists) are already authorised for feed/food/nutraceuticals, while PUFAs from fish oil are questioned regarding their application in infant formula. Heterotrophic PUFA production is expected to be less advantageous concerning access to material resources as there is a large demand for sugar production for this process which requires arable land.

1 Introduction

1.1 Description and goals of the PUFAChain project and work package 9 (Sustainability)

The overall goal of the PUFAChain project is to develop a robust scientific and technological basis for substantiating strategic and technical decisions for the industrial development of high-value products from microalgae[1]. The main targeted application is the use of highly purified omega-3 PUFA (polyunsaturated fatty acids, i.e. DHA (docosahexaenoic acid), EPA (eicosapentaenoic acid) and SDA (stearidonic acid)) from microalgae as building blocks in modern oleo chemistry to gain high value products for nutrition and pharmaceutical applications (Figure 1). The project covers aspects of biology, cultivation technology and downstream technology. The project aims to realize a concrete exemplary supply chain, develop the technical interfaces between the different value adding stages and investigate the still open research aspects on every single stage while addressing the needs of the supply chain as a whole. Finally, an integrated processing, combining all technical steps, will be implemented for demonstration. A comprehensive and holistic sustainability approach will complement the scientific and commercial advances on each value-adding stage. Reference supply chains will be taken into account (Figure 2). A consortium with five companies[2] and four research institutes[3] will integrate state of the art science and technologies in order to assemble a complete process from feedstock production and harvesting to oil extraction and purification. Innovative technologies will be combined taking advantage of a complimentary partnership with the best available expertise in the sector in Europe. These processes will be evaluated for their sustainability and scaled-up from lab to demonstrative prototype level.

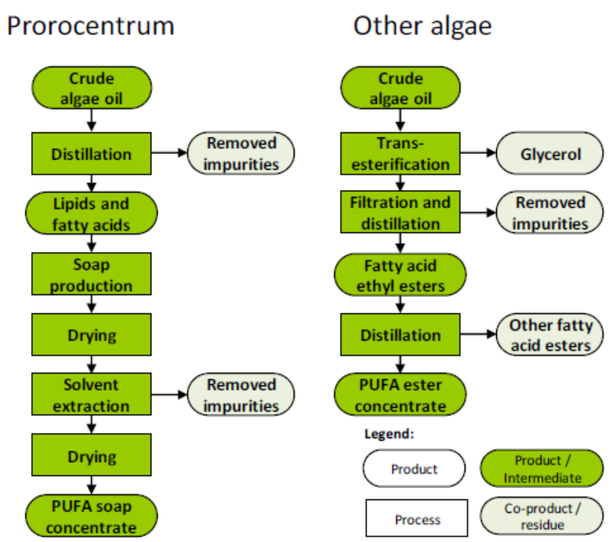

Figure 1 Overview of PUFAChain process (From: Keller et al, 2017b)

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[1] www.pufachain.eu
[2] A4F Algafuel SA, MAHLE InnoWa GmbH, Natex Prozesstechnologie GesmbH, Cremer OLEO GmbH & Co. KG, EurA Consult AG
[3] Georg-August-University Goettingen, Fraunhofer IZI-BB, Wageningen Research (former Stichting Dienst Landbouwkundig Onderzoek (DLO)), IFEU - Institute for Energy and Environmental Research Heidelberg GmbH

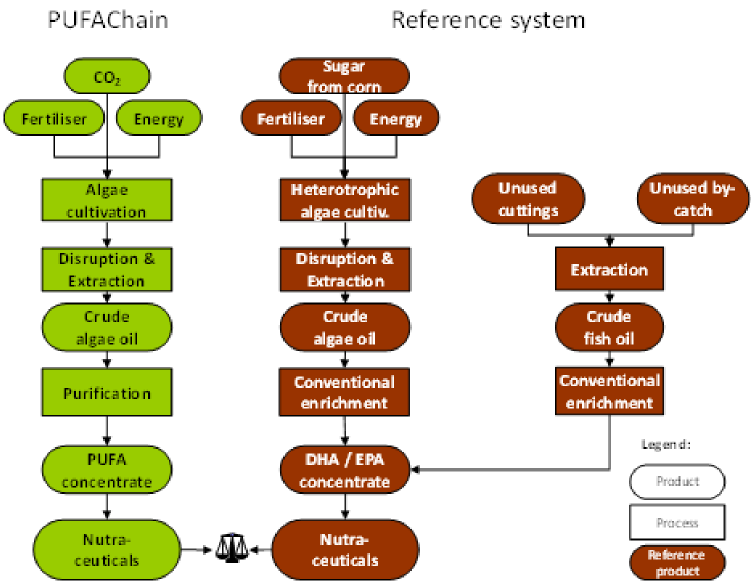

Figure 2 PUFAChain products and reference products (From: Keller et al, 2017a)

The project comprised 10 work packages (WPs) of which WP9 covers sustainability aspects (Figure 3).

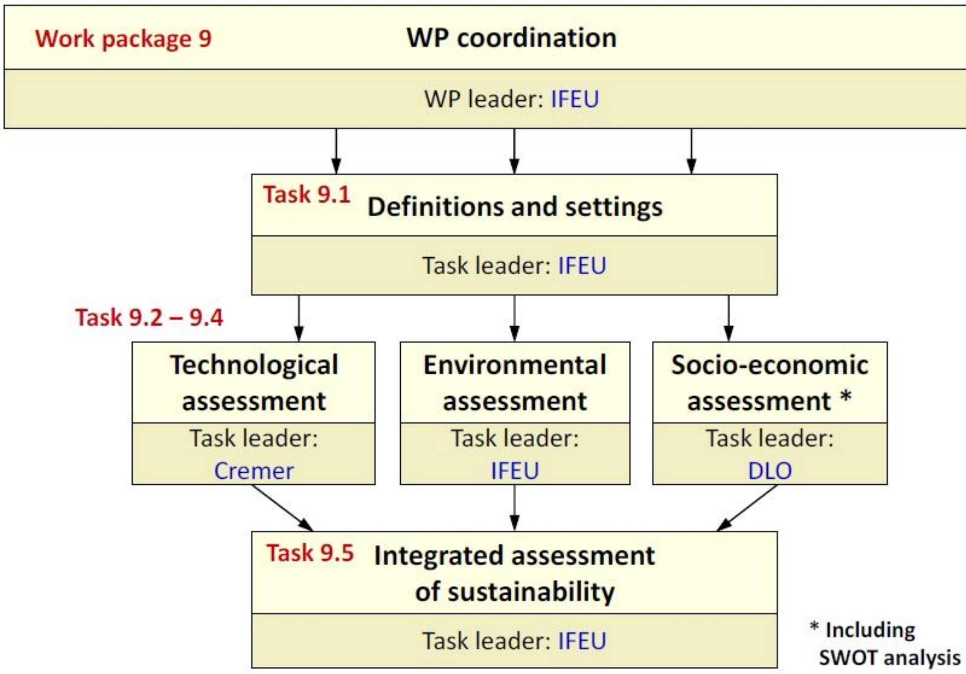

Figure 3 Structure of PUFAChain WP9 “Sustainability”

Within WP9, IFEU carried out the WP coordination, definitions and settings description (Task 9.1) the environmental assessment (LCA = Life Cycle Assessment, Task 9.3) and the integrated assessment of sustainability (Task 9.5). Cremer OLEO GmbH & Co. KG carried out the technological assessment (Task 9.2). Wageningen Research (former DLO) carried out the socio-economic assessment (Task 9.4), including a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis.

Several scenarios, based on geographic location, algae species, production area and end products were chosen to evaluate different supply chains (Table 1).

Table 1 Variables taken into account for the different supply chain scenarios

Parameter	Variables
Geographic location	Southern Europe (Lisbon), Central Europe (Munich) & Northern Europe (Oslo)
Algae species	*Prorocentrum cassubicum*, *Thalassiosira weissflogii* and a combination of *Chloridella simplex* and *Raphidonema nivale* Lagerheim
Production area	10 ha, 100 ha (net area)
End products	EPA, DHA, SDA

The different scenarios are explained in more detail in Chapter 3.3 (System Boundaries). Further detailed information can be found in PUFAChain deliverables 9.1 and 9.3.

1.2 Objectives and methods of Task 9.4: The socio-economic assessment

In Task 9.4 a socio-economic assessment of the systems defined in Task 9.1 was performed for the PUFAChain project by Wageningen Research. The socio-economic assessment includes a macro-economic assessment (Chapter 2), a LCC (Life Cycle Costing, micro-economic) analysis (Chapter 3), followed by an overall SWOT analysis taking into account the different parts with emphasis on the socio-economic aspects (Chapter 4).
The **macro-economic assessment** focuses on market analysis and competiveness and provides information about market and price developments. Both peer-reviewed and generic data sources were used. The **LCC (micro-economic) analysis** uses both existing PUFAChain project information and tools in development from the Interreg project EnAlgae, combined with data from Task 9.1 and the project partners. UNEP/SETAC guidelines for LCC were taken into account. The macro- and micro-economic analyses both identify profitability and market competiveness of the systems. The **SWOT analysis** has been updated during the project and takes into account the results of the other three analyses. When useful, reference systems/products were assessed as well. The integrated **socio-economic analysis**, presented in a data table (Chapter 5), includes all major social and micro-economic aspects, such as impacts on employment and public acceptance of new technologies. Institutional, legislative and political aspects are included if applicable. UNEP/SETAC guidelines for sLCA (social life cycle assessment) and recent methodological literature are taken into account. The results are used as input for Task 9.5.

2 Market Analysis and Competitiveness of the PUFAChain

By Joanneke Spruijt

2.1 Introduction

This chapter focuses on markets and competitiveness of the PUFAChain process. The algae in the PUFAChain process will be produced in industrial-scale photo bioreactors. After oil and polyunsaturated fatty acids (PUFA) extraction from the phototrophic algae the extraction cake can possibly be sold on various markets (Table 2). Main focus of the PUFAChain process is on purified eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) or EPA/DHA mixtures containing high EPA/DHA levels. The main product from the PUFAChain process is thus EPA/DHA oil from phototrophic algae and the coproduct is the extraction cake. In addition, after EPA/DHA purification other fatty acids (FAs) can be extracted and sold as coproducts, but this market is not included in the analysis.

The most obvious market for EPA/DHA oil from phototrophic algae is the growing EPA/DHA consumer market, which can be divided into the market segments dietary supplements, pet foods, functional foods, infant formulas, pharmaceuticals and clinical nutrition (Table 2). Fish oil and EPA/DHA from unicellular marine heterotrophic organisms are the main competitors in these markets. Also, the PUFAChain process offers good opportunities on the growing aquaculture feed (aqua feed) market, replacing fish oil by the main (algae EPA/DHA) product and fish meal by the coproduct (algae oil extraction cake). Furthermore, the livestock feed market offers opportunities for the protein-rich algae coproduct to replace fish meal or soybean meal.

Table 2 Products, markets and competing products of the PUFAChain process

Product	Markets	Competing products
EPA/DHA oil phototrophic algae (main product)	EPA/DHA consumer market - Dietary supplements - Pet foods - Functional foods - Infant formulas - Pharmaceuticals - Clinical nutrition Aquaculture feed market	EPA/DHA oil from heterotrophic microorganisms EPA/DHA in (concentrated) fish oil (FO)
Extraction cake (coproduct)	Aquaculture feed market Livestock feed market	Extraction cake from heterotrophic microorganisms Fish meal (FM) Soybean meal

In this report, current algae, algae oil and algae EPA/DHA production, usage and cost prices are described, followed by the description of fish oil and fish meal production, usage and prices. EPA/DHA consumer, aquaculture and livestock feed markets are analysed and market opportunities, prices and positioning are described for the PUFAChain process.

2.2 Algae production

2.2.1 Global production and usage

There are around 30,000 species of microalgae but only a small number of them are produced on an industrial scale since a few decades (Gouveia et al, 2008). The most important species for biotechnological reasons are green algae (Chlorophycea) *Chlorella vulgaris*, *Haematococcus pluvialis*, *Dunaliella salina* and cyanobacteria *Spirulina maxima*. They are produced on an industrial scale mostly as human nutritional supplement and additives for animal feed (Table 3). According to Kovač et al (2013) *Spirulina* is the most produced species, followed by *Chlorella* sp., *Crypthecodinium cohnii* and *Schizochytrium* sp. The latter two unicellular heterotrophic marine organisms are cultivated for DHA oil.

Table 3 Annual production, country of production, applications and products of algae for important species in descending production volume (Kovač et al, 2013)

Algae species	Annual production (tonnes/year)	Producing countries	Applications and products
Spirulina (Arthrospira)	3000	China, India, USA, Myanmar, Japan	Human and animal nutrition, cosmetics (phycobiliproteins, powders, extracts, tablets, beverages, chips, pasta, liquid extract)
Chlorella sp.	2000	Taiwan, Germany, Japan	Human nutrition, aquaculture, cosmetics (tablets, powders, nectar, noodles)
Dunaliella salina	1200	Australia, Israel, USA, China	Human nutrition, cosmetics (ß-carotene, powders)
Aphanizomenon flos-aquae	500	USA	Human nutrition (capsules, crystals, powder)
Haematococcus pluvialis	300	USA, India, Israel	Aquaculture, astaxanthin
Crypthecodinium cohnii	240 (DHA oil)	USA	DHA oil
Schizochytrium sp.	10 (DHA oil)	USA	DHA oil

2.2.2 North-West European algae initiatives

In 2012 an inventory of North-West European algae initiatives was carried out to get an overview of the market and research initiatives on algae production and refinery (Spruijt, 2015). Most of the 117 reported initiatives were found in Germany and the Netherlands, followed by France and the United Kingdom. The main focus is on microalgae, but especially in the UK also macro algae initiatives were mentioned. There is limited information about the used species. Most frequently mentioned for microalgae were *Chlorella*, cyanobacteria, *Nannochloropsis*, *Scenedesmus* and unspecified mixtures. Information about the production scale of algae is very limited. A lot of initiatives are at lab scale or in very small research pilots. In Germany and the Netherlands, only a few initiatives produce on an area larger than 250 m^2 or in a volume larger than 75 m^3. A broad range of production facilities is reported, of which the open raceway pond is the most frequently mentioned in an average 20 % of all cases (Table 4). In Germany (plastic) bag systems, flat panel bioreactors (FPBRs) and others are frequently used. In the Netherlands, algae are often cultured in open raceway ponds and in the United Kingdom mainly in tubular bioreactors or in the sea (Spruijt, 2015).

Table 4 Production modes as percentage of total North-West European algae initiatives (117) per country and as percentage of all initiatives (Spruijt, 2015). Some initiatives employ multiple production modes

	DE	**NL**	**FR**	**UK**	**All**
Open raceway pond	11	50	9	0	**20**
Tubular bioreactor	14	17	4	25	**15**
(Plastic) bag system	19	6	0	6	**9**
Flat panel bioreactor	16	0	0	6	**6**
Wild seaweed	0	0	0	19	**3**
Other	19	6	9	13	**13**
Unknown	22	31	87	31	**39**

Many initiatives are using waste or residual streams to produce algae for one or more algae markets. Examples of these streams are CO_2, manure and industrial or municipal waste streams. Since production costs are lowered by using these waste streams, waste stream handling can be seen as a market sector. Waste stream and energy markets are most frequently mentioned. These markets have the lowest added value (Figure 4). High value molecules constitute the top of the market in added value. A lot of initiatives are focussed on this market (Spruijt, 2015) (Table 5).

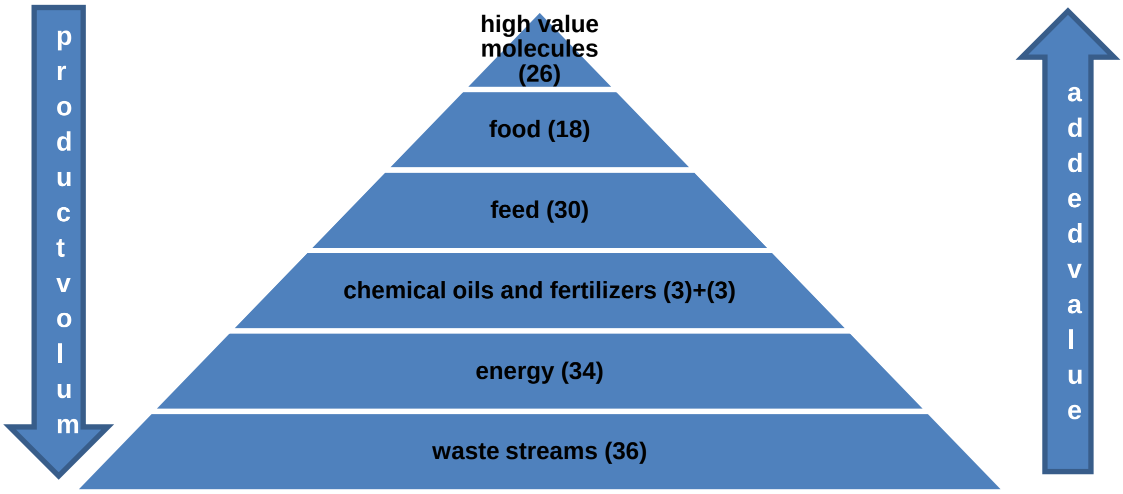

Figure 4 Number of North-West European algae initiatives in the algae market value pyramid (Spruijt, 2015)

Table 5 **Market focuses as percentage of total North-West European algae initiatives per country and as percentage of all initiatives (Spruijt, 2015). Some initiatives focus on multiple markets**

	DE	NL	FR	UK	All
Waste stream	43	42	4	19	**31**
Energy	51	6	48	0	**29**
Feed	16	42	9	31	**26**
High value molecules	16	8	48	19	**22**
Food	24	6	13	13	**15**
Technology provider	14	3	9	0	**8**
Chemical oils	8	0	0	0	**3**
Fertilizers	0	0	4	19	**3**
Provider of culture material	3	0	4	0	**2**
Others	0	0	0	6	**2**
Unknown	8	33	13	31	**20**

In Germany the majority of the initiatives are pilots or research projects. The research is very diverse, from screening algae species, research on cyanobacteria and optimizing photo bioreactors (PBRs) to the production of high value molecules, biogas and hydrogen. Only a minor share of the initiatives are assumed to be commercially active selling algae products or services. Three of them are technology providers, from which two also serve algae product markets. German initiatives mainly handle waste streams and/or produce feed/food products. Two of them produce high value molecules. Also in the Netherlands most of the initiatives are pilots or research projects. Scientific organisations are less often involved than in Germany. Pilots often concern waste stream handling from agricultural, industrial, domestic/municipal and transport sectors. Four initiatives are producing (shell) fish feed, two of them are pilots. Only about five organisations are commercially selling algae products or technologies. French companies are mainly active in the high value molecule market (especially in France: cosmetic products) or in the low value energy market. There is hardly any information available on the status or scale of these initiatives. In French research projects the energy market is also important. In the United Kingdom and Ireland, more activities involve macro algae (7 out of 17 initiatives). All of them are private companies. Microalgae are used to produce fertilizers, feed additives, food, cosmetics, and high value molecules or to filter out microalgae from ecologically sensitive areas. Two Belgian projects were reported on pilot-scale. They are producing for the high value market or other markets. One project in Belgium covers a hectare. In this project CO_2 is captured from the lime and glass industry to produce biofuel for industrial furnaces and reduction of fuel energy consumption (Spruijt, 2015).

2.2.3 Cultivation systems

2.2.3.1 Phototrophic algae production systems

Large-scale cultivation of microalgae for human and animal nutrition takes place since decades in open ponds/raceways[4]. For producing more specific products, closed PBRs are used increasingly. PBRs come as simple or complex transparent tubes, panels and bags in different configurations. They make controlled and reproducible high-density growth of microalgae possible. Economic aspects concerning micro-algae production systems were studied on the basis of bio-economic models by Spruijt et al (2014a). Three types of micro-algae production systems were studied: open ponds, tubular and flat panel bioreactors (FPBs).

The yearly algae biomass production in a 1,000 m^2 open pond located in the Netherlands is 1,538 kg of dry matter (DM) according to the model, equalling 15 tonnes DM per ha. Biomass productions per area in tubular and flat panel PBRs are twice and more than three times higher than in an open pond respectively (Figure 5). Differences in production between production systems could be attributed fully to differences in photosynthetic efficiency (PE) on daylight (1.5 %/3 %/ 5 % respectively for the three systems) dependent on system configuration (light path) according to Spruijt et al (2014a).

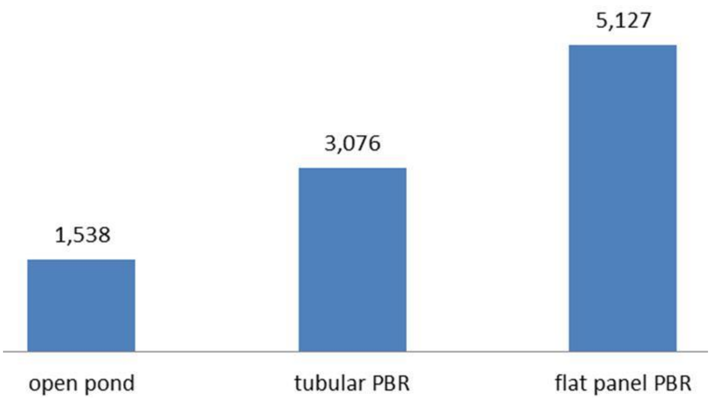

Figure 5 Yearly biomass production in kg DM for three algae production systems (1,000 m^2 scale) (Spruijt et al, 2014a)

2.2.3.2 Unicellular marine heterotrophic organisms production systems

The unicellular marine heterotrophic organism production in fermenters results in higher biomass growth rates, higher cell densities and as a result improved harvesting compared to phototrophic algae production. In these systems, organic carbon is the energy source and O_2 is a limiting factor for growth. Fermenter sizes range from 1 to 500,000 litres[5]. The technology is decade's old and commercial fermenters are readily available. A typical fermenter size is 200,000 L (Lee Chang et al, 2015). Glucose is the most widely used source of organic carbon and is relatively inexpensive, around 0.50 € per kg. However, 2-3 kg glucose is needed to produce one kg of algae biomass (DM) (Orfield et al, 2015). Zheng (2013) shows a comparison of microalgae production in phototrophic and heterotrophic systems (Table 6).

[4] http://www.enalgae.eu/growth-and-harvesting.htm
[5] www.bbi-biotech.com

Table 6 Comparison of phototrophic and heterotrophic microalgae biomass production methods (Zheng, 2013)

Variable	Raceway pond	PBR	Heterotrophy
Microalgae biomass (tonnes DM)	100	100	100
Volumetric productivity (kg/m^3/day)	0.08	1.5	24.2
Area (m^2)	12,121	6,313	200
CO_2 (tonnes)	183	183	-129
Sugar (tonnes)	-	-	213
Water (MM gal)	7.3	2.2	0.2

2.2.4 Cost price algae biomass

2.2.4.1 Phototrophic algae

According to Spruijt et al (2014a) the cost price for algae biomass produced on the reference scale of 1,000 m^2 is much lower in PBRs than in open ponds, mainly because of the lower costs for capital goods and labour (Figure 6). Only electricity costs were slightly higher for PBRs. The use of flat panel PBRs resulted in the lowest algae biomass cost price. It should be noted that CO_2 and heat supply were supposed to be available at no costs in their model. Norsker et al (2011) calculated an ascending cost price for tubular PBRs, open ponds and flat panel PBRs of 4.15, 4.95, and 5.96 € per kg DM respectively on 100 ha scale, including dewatering. On 1 ha scale the cost prices were 9.90, 17.72, and 10.49 € per kg DM respectively, which means their calculations for open ponds were significantly different from the model by Spruijt et al (2014a).

Figure 6 Algae cost price per kg DM for three algae production systems at 1,000 m^2 scale. Productivities for the three systems are estimated at 15, 31 and 51 tonnes DM per ha respectively for open ponds, tubular PBRs and flat panel PBRs (Spruijt et al, 2014a)

Economies of scale of algae production for tubular PBRs were explored as well by Spruijt et al (2014a) (Figure 7). The cost price for algae biomass in these systems ranges from 19.07 €/kg DM at small scale (Figure 6, this equals around 3 tonnes DM per year) to 4.57 €/kg DM at large scale (Figure 7, this equals around 3,000 tonnes DM per year). Even at the largest scale costs remained high due to electricity costs.

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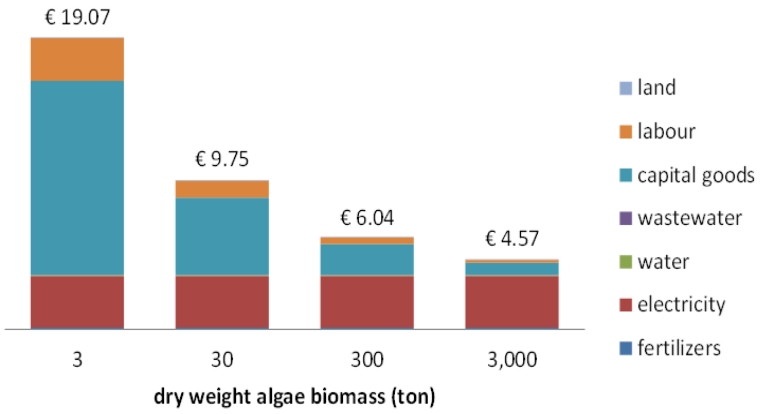

Figure 7 Algae cost price per kg DM in tubular PBRs at ascending scale (Spruijt et al, 2014a)

More recently, Ruiz et al (2016) calculated the cost price for 100 ha facilities in six locations. The lowest price was found for the south of Spain (3.40 €/kg DM) in flat panel photo bioreactors. They expect prices to go down to around 0.50 €/kg DM for that location in ten years.

2.2.4.2 Unicellular marine heterotrophic organisms

The heterotrophic microorganism production has advantages compared to phototrophic production like the use of (relatively) proven technology (fermenters have been used for decades in biotechnological industries), higher biomass growth rates and higher oil and PUFA contents of the cells. As mentioned, glucose represents a major share of the costs: 1 kg of algae DM biomass requires input of 2-3 kg of glucose (Orfield et al, 2015). In addition, cooling costs (fermentation of sugar leads to heat production) and electricity costs (aeration, stirring, sterilization etc.) represent important costs. The use of alternative low-cost carbon sources may lead to decreases in cost price (Zheng, 2013), but this technology is not used on an industrial scale as the major algae producers use sugar from cane or corn. Zheng (2013) calculated a cost price of 0.39 € per kg DM in a system with a yearly production of 100 tonnes DM with lignocellulose materials as the feedstock. He did not include costs for electricity as they were assumed to be compensated for by the provided energy from burning organic by-product streams from the process in an ethanol plant. In addition, their yearly capital depreciation of 5,800 € for a plant that can produce 100 tonnes of DM seems extremely low.

Sijtsma calculated that DHA from heterotrophic microorganism *C. cohnii*, grown on ethanol, was 3-5 times more expensive than DHA from fish oil. Perez-Garcia and Bashan (2015) present conservative and optimized cost prices of 4.50 and 0.45 €/kg for phototrophic and 1.25 and 1.05 €/kg for heterotrophic production respectively based on Wijffels et al (2010) and Tabernero et al (2012). The prices for phototrophic production are based on a production area of 100 ha flat panel PBRs, while those for heterotrophic production are based on 465 fermenters of 150,000 L each. As a kg of glucose costs about 0.71 €/kg (Zhao et al, 2015), the minimum substrate cost price for a kg DM microalga is at least 1.42 €. Equipment costs of fermenters are assumed to be cheaper than those of PBRs (Perez-Garcia and Bashan, 2015), but equipment costs for comparable systems are high (Table 7). Depreciation times influence equipment costs to a large extent. Tabernero et al (2012) for example assumed a depreciation time of 35 years, which can explain the low resulting cost price.

Estimates by Huurman and Elissen (personal communication, 2017) on heterotrophic biomass cost price considered energy consumption, glucose and mineral nutrients consumption and the use of comparable reactor systems. This resulted in a cost price range of 3.14-9.15 €/kg DM heterotrophic microorganisms (Table 7).

Table 7 Optimized and conservative cost prices for heterotrophic microorganism biomass and EPA/DHA oil (Huurman and Elissen, personal communication, 2017)

	Optimized		**Conservative**	
	Per kg DM	Per kg*** EPA/DHA oil	Per kg DM	Per kg*** EPA/DHA oil
Energy	0.89	3.54*	0.89	5.53*
Glucose	1.42*	5.68*	2.13*	13.31*
Mineral nutrients	0.17	0.70*	0.17	1.09*
Equipment (USP and DSP)	0.66	2.66**	5.96	23.83**
Total	**3.14**	**12.57**	**9.15**	**43.76**

*Assuming 50 % oil/ 50 % EPA/DHA/ 2:1 glucose to biomass conversion and 40 % oil / 40 % EPA/DHA/ 3:1 glucose biomass conversion respectively in optimized and conservative scenarios
** Assuming only 50 % oil/ 50 % EPA/DHA scenario, as equipment costs are highly variable
*** The density of EPA/DHA is 0.943 g/cm^3

The main variable (due to system complexity and requirements and surrounding logistics) is the price of equipment, including production facilities and centrifuging equipment (USP and DSP) (Petrides, 2000; Meyer et al, 2017). A depreciation time of 10 years was assumed. The calculations were based on seven fermenters of each 260,000 L total volume (filling volume of each reactor is 200,000 L), producing 8,400 tonnes DM heterotrophic microorganisms biomass per year. Overall, equipment costs and glucose seem to be the most important drivers of heterotrophic cost price, followed by energy (e.g. for mixing, aerating, sterilization and cooling) and mineral nutrients. Of course, energy and glucose costs could be lowered by the use of waste streams with co-generation of energy.

2.2.4.3 Cost price comparison

Based on the optimized rough cost price estimate (Table 7) and Figure 7 at comparable production scales, heterotrophic production seems cheaper than phototrophic production in tubular PBRs (€3.14 vs. €4.57 per kg DM Biomass). Considering the higher oil and EPA/DHA content of heterotrophic microorganisms, the difference in cost price per kg of EPA/DHA oil even increases in favour of heterotrophic production. With improving technologies and efficiency and increased use of low-cost substrates, cost prices for both types of microorganism/-algae are expected to decrease further. According to Chauton et al (2015) optimized costs for EPA or DHA production can be €10.41 per kg PUFA from flat panel PBRs (assuming optimized photosynthetic efficiency and doubling of the EPA and DHA yield of phototrophic algae).

2.3 Algae oil production

2.3.1 Global production and usage

Algae oil is almost exclusively produced for PUFAs. In 2014, global production of omega-3 algae oils was approximately 7,280 tonnes[6]. Many pilot systems have been built to produce biodiesel from algae, but they were not economically viable.

2.3.2 Downstream processing of algae into oil

Downstream processing (DSP) of algae into oil in the EnAlgae model (Spruijt et al, 2014a) involves the recovery of intracellular lipids, and the subsequent conversion to fatty acid methyl esters (FAME) via a transesterification reaction. Steps involved in this process are:

[6] https://www.naturalproductsinsider.com/articles/2015/03/omega-3-insights-magazine-algal-based-omega-3s.aspx

2.3.2.1 *Drying*

Dry biomass is preferable for supercritical CO_2 (sCO_2) extraction, as the presence of water can create a boundary layer, making it more difficult to extract lipids.

2.3.2.2 *Milling*

Breaking open cell walls will enhance extraction of intracellular contents such as neutral lipids. In this step, a ball mill is used for mechanical cell disruption.

2.3.2.3 *Supercritical CO_2 extraction (sCO_2)*

In the supercritical CO_2 process step CO_2 is passed through a sub-cooler to become liquid so it can be pumped towards the vessel containing the algae biomass. The temperature and pressure are raised to enable the CO_2 to become supercritical. CO_2 acts as a solvent to remove neutral lipids, such as triacylglycerides (TAG). A pressure drop is used to collect various fractions from the biomass. The model simplifies the process by examining the extraction of only one product (TAG) from the algae biomass. In practice, other products such as pigments could be extracted simultaneously, and a second depressurisation step added to collect a different fraction. Following sCO_2 extraction, the remaining (protein-rich) biomass can be sold for other purposes.

2.3.2.4 *Refining*

Lipid material extracted from algae biomass must be refined prior to transesterification, to exclude any membrane lipids and chlorophyll from the TAG. Lipids are refined using methanol and a catalyst. The use of methanol is taken from Spruijt et al, 2014a, which is not suitable for example for nutraceutical applications.

2.3.2.5 *Transesterification*

In the model (Spruijt et al, 2014a), base catalysed (using potassium hydroxide) transesterification is used. Methanol must be present in excess as the reaction between the alcohol and lipid is reversible. A 98 % conversion of TAG to FAME is assumed. Glycerol, which is a by-product of the transesterification reaction, could be purified and sold.

The main DSP costs are supercritical CO_2 extraction, drying and milling, although by-products (protein-rich biomass and glycerol) could generate some extra revenues. Economies of scale are also of interest, as shown in Figure 8.

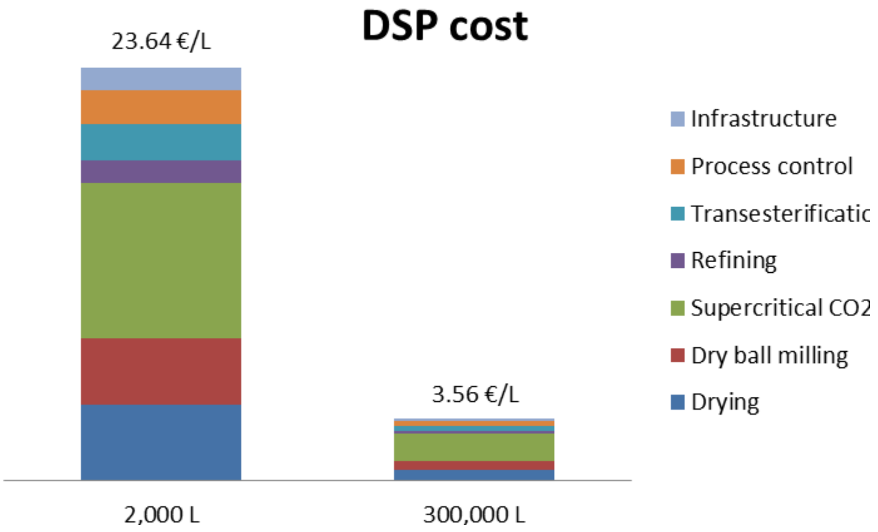

Figure 8 Downstream processing costs per litre algae oil at two scale levels (Spruijt et al, 2014a)

2.3.2.6 Revenues from DSP by-products

Protein-rich biomass

De-fatted biomass from sCO_2 extraction could have a number of applications. As a source of protein, it could be a substitute for soybean meal. According to the EnAlgae DSP model (Spruijt et al, 2014a) every litre algae oil results in around 3.8 kg de-fatted protein rich algae biomass, with a 62.5 % protein content. Soybean meal prices are 250-450 € per tonne. Based on an average soybean meal price of 0.35 €/kg (50 % protein content) the selling price for defatted algae biomass is assumed to be 0.44 €/kg (Spruijt et al, 2014a). Algae biomass with a residual amount of omega-3 lipids could be more valuable, with a market price more similar to fish meal (currently priced at >1 €/kg[7]). In Chapter 3.4.3 also a polysaccharide-rich by-product is described, but this is not taken into account in the calculations shown in Table 8.

Glycerol

Glycerol is a by-product of the transesterification reaction. The crude product may contain water, free fatty acids and residual salts. Distillation may be carried out to produce a purer product, and as such increase the value. Pure glycerol has applications in the pharmaceutical and personal care industries. A crude glycerol product may be used as an additive to anaerobic digestion to enhance biogas yield. In the EnAlgae DSP model, subsequent refining of the glycerol is not considered. Every litre algae oil results in the production of 91 grams glycerol with a price similar to that of crude glycerol (0.50 € /kg) (Spruijt et al, 2014a). Revenues from DSP by-products protein-rich biomass and glycerol are thus assumed to be 1.68 and 0.05 €/l algae oil respectively (Table 8) (Spruijt et al, 2014a).

Table 8 Revenues from DSP by-products per litre algae oil (Spruijt et al, 2014a)

By-product	Amount		Unit price		Revenues
Protein-rich biomass	3.844	kg DM	0.44	€/kg DM	€ 1.68
Glycerol	0.091	kg	0.50	€/kg	€ 0.05
Total					**€ 1.73**

When subtracting these revenues from the costs (Figure 8) this leads to net cost prices for algae oil of 21.91 and 1.83 € at small and large scale respectively.

2.3.3 Cost price algae oil

The calculated cost price for algae oil in the EnAlgae bio-economic production models ranges from 69 €/L at small scale to 26 €/L at large scale (Spruijt et al, 2014a). Small scale is based on yearly production of 2,107 L algae oil from 10 tonnes DM algae at an assumed cost price of €10 per kg DM with DSP costs of 21.91 €/L. Large scale is based on yearly production of 300,000 L algae oil from 1,500 tonnes DM algae at decreased cost price of €5 per kg DM with DSP costs of 1.83 €/L. The algae biomass cost is the main driver for the production price. For heterotrophic microorganisms, lipid content is about 2.5 times as high as for phototrophic algae (50 % vs. 20 %) (Spruijt et al, 2014a; Orfield et al, 2015). This possibly affects DSP costs.

[7] www.indexmundi.com

2.4 EPA/DHA production from microalgae

The lipid content of microalgae varies between 1 and 85 % of DM with typical contents of higher than 40 % under environmental stress conditions (Chisti, 2007). PUFAs like EPA and DHA have beneficial health effects, comparable to the effects of fish oil (Becker, 2013).

2.4.1 EPA/DHA global production and usage

The global market value for omega-3 oils was around 320 million € in 2014[8]. Infant formula applications represent the most important end application for DHA oil (about 49 % of the volume in 2012), followed by dietary supplements (28 %), food and beverage (19 %) and animal feed (about 4 %) (Figure 9)[9].

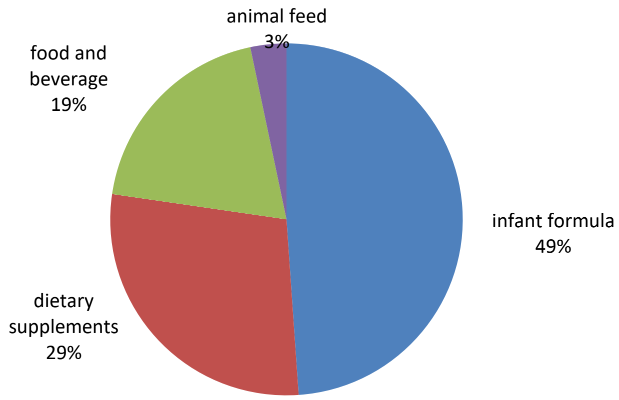

Figure 9 Global algae DHA market volume by end application in 2012[6]

2.4.2 EPA/DHA producers

DSM/Evonik

The former Martek Biosciences Corporation, now part of DSM, is a major producer of PUFA from algae[6]. They produce algae oils from heterotrophic microorganism *Schizochytrium* sp., for example Life'sDHA™ and Life'sOMEGA™ (Figure 10). The algae oil contains 50 % EPA/DHA (DSM/Evonik, 2017). This PUFA source will be aimed at initial applications in salmon aquaculture and pet food and is produced in the US[10].

[8] https://www.naturalproductsinsider.com/articles/2015/03/omega-3-insights-magazine-algal-based-omega-3s.aspx
[9] http://www.algaeindustrymagazine.com/the-global-algae-oil-omega-3-market-in-2014/
[10] http://www.feednavigator.com/R-D/Skretting-gets-behind-algal-oil-breakthrough-from-Evonik-and-DSM?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright

Figure 10 Martek Biosciences Corporations fermentation vessels for heterotrophic microorganism production (Ismail, 2013)

Lonza

Lonza is an ingredient manufacturer like DSM. The company lost a patent dispute with Martek/DSM about algae DHA and DSM currently supplies Lonza[11]. They sell DHA ('DHAid') as oil and powder ingredient for the food industry from the same heterotrophic microorganism source as DSM[12]. DHAid is a refined triacylglycerol oil (>95% TAG), derived from *Ulkenia sp*., a marine protist, with a total DHA content of 38 to 50 %. The remaining fatty acids of *Ulkenia* DHA oil are comprised mainly of saturated palmitic acid (C16:0) (28 to 37 %) and a lesser amount (8 to 14 %) of the omega-6 fatty acid docosapentaenoic acid (DPA) (C22:5) (GRAS Notice 319).

Source-Omega

Source-Omega uses heterotrophic technology and water extraction to produce its DHA algae oil from *Schizochytrium* algae[13].

Qualitas Health

Qualitas Health has 'Almega PL' on the market, an EPA-rich algae strain for dietary supplements, photographically grown in open ponds[14] (Figure 11). It is an omega-3 oil from *Nannochloropsis oculata* marketed as an alternative to krill oil. The strain has a polar lipid structure, including glycolipids and phospholipids, which enhances bioavailability.

[11] http://www.nutraingredients.com/Suppliers2/Lonza-and-DSM-settle-omega-3-patent-dispute
[12] http://www.nutritionaloutlook.com/delivery-systems/everywhere-omega-fatty-acids
[13] www.source-omega.com
[14] www.qualitas-health.com

Figure 11 Open pond system Qualitas Health[10]

SB oils

Solazyme Bunge Renewable Oils (SB oils) is a joint venture between TerraVia and Bunge, which produce 'AlgaPrime DHA', a whole algae ingredient for the aquaculture feed market (Figure 12). Table 9 shows the basic nutritional and fatty acid profile of AlgaPrima DHA[11]. The facility is based in Brazil and the *Schizochytrium* algae producing DHA rich oil are grown on sugar cane. The sugarcane waste is a renewable source of energy for the facility[15].

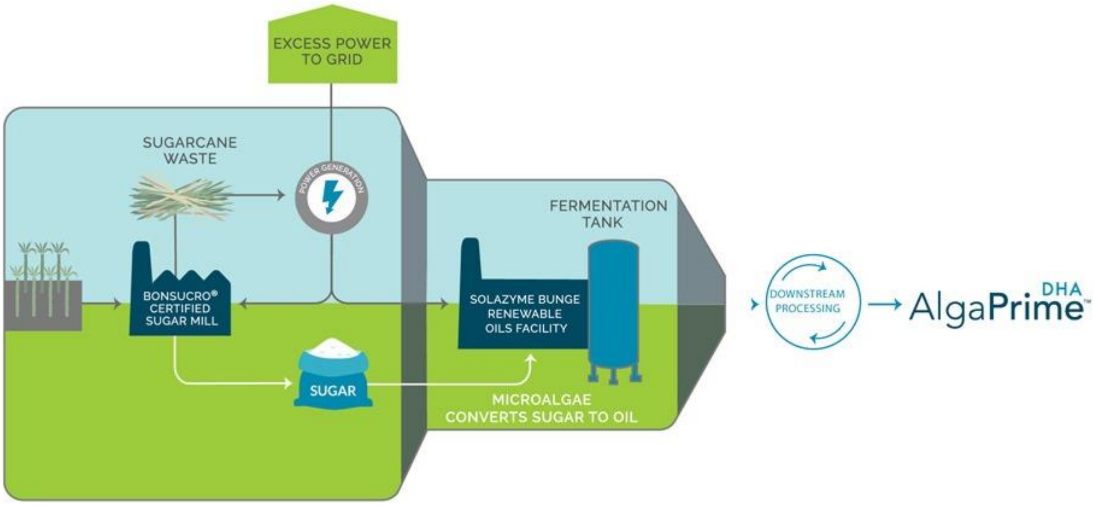

Figure 12 Scheme of the SB Oils facility[11]

[15] www.algaprime.com

Table 9 Basic nutritional and fatty acid profile of AlgaPrime DHA[11]

Basic nutritional profile	Content (g/100g)	Fatty acid profile	FA as % of fat
Protein (crude)	12.6	C16:0 (Palmitic)	33.8
Moisture	3.0	C18:0 (Stearic)	1.5
Ash	14.0	C22:5 n6 (DPA)	12.6
Carbohydrates	12.0	C22:6 n3 (DHA)	48.2
Fat	53.0		
Fibre (crude)	5.4		

Cellana

This company patented their algae cultivation system 'ALDUO' whereby series of photo bioreactors are coupled with open ponds (Figure 13). Cellana has a pilot project in Hawaii where marine microalgae are grown and EPA and DHA containing products are sold. Cellana's 'ReNew' product line is focused on high value oils for human nutrition and whole algae enriched with EPA/DHA for animal and aquaculture feeds[16].

Figure 13 Cellana's ALDUO system: photo bioreactors coupled with open ponds[12]

Aurora Algae

Aurora (as the former Aurora Biofuels) tried to set up a large scale open pond algae project in Western-Australia to produce biodiesel, but the project proved unprofitable[17,18]. In 2014, Aurora (as Aurora Algae) bought land in South-Texas to cultivate phototrophic algae strains in open seawater ponds with a high EPA content (Figure 14). This project seems to have failed as well, because the company sold off the Texas-based land and the lab equipment in 2015.

[16] www.cellana.com

[17] http://www.biofuelsdigest.com/bdigest/2015/07/22/rip-aurora-algae-algae-and-the-never-never/

[18] http://www.biodieselmagazine.com/articles/8012/aurora-algae-lands-22-million-in-finance-round

Figure 14 Open pond system Aurora Algae in Western Australia[14]

Algae Biosciences

Algae Biosciences stated to use a closed PBR (Figure 15) and supercritical CO_2 extraction, as opposed to some competitors that employ hexane or other hydrocarbon-based solvents. They grew two different strains of marine algae separately, extracted the EPA and DHA separately, and blended them in one product, according to customer wishes[19]. However, there is no company website anymore.

Figure 15 PBR system (Ismail, 2013)

AlgaeCytes

The British company AlgaeCytes is developing and commercialising ingredients and focuses on EPA and high protein biomass from freshwater microalgae[20]. They produce EPA rich (30 % EPA of total FAs) algae oils from *Eustigamatophyte* freshwater microalgae (Figure 16).

[19] http://www.nutritionaloutlook.com/delivery-systems/everywhere-omega-fatty-acids

[20] www.nutramara.ie

Figure 16 AlgaeCytes pilot installations[16]

BASF and NPC

BASF and NPC started a partnership in 2013 to join forces on algae technology[21]. Their systems for marine algae are based on constructed lakes for prawn production in Saudi-Arabia.

Fraunhofer IGB

Researchers at the Fraunhofer IGB institute, Germany, grow the marine phototrophic microalgae *Phaeodactylum tricornutum* for EPA production in a PBR, flat-panel airlift (FPA) reactor[22].

Table 10 shows an overview of the different algae EPA/DHA producers mentioned.

[21] www.newtrition.basf.com

[22] http://publica.fraunhofer.de/documents/N-45331.html

Table 10 Overview of algae EPA/DHA producers, algae strains, technologies/activities and markets

Company	Algae strain	Cultivation system	Marketing or developing	Market focus
Algae Biosciences	One EPA and one DHA strain?	Phototrophic PBR's	Developing	DHA and EPA (separately) consumer market
AlgaeCytes	*Eustigamatophyte* freshwater microalgae	Phototrophic flat panel bioreactors?	Developing	EPA consumer market
Aurora Algae	High EPA marine strain?	Phototrophic open ponds	Stopped	EPA consumer market
BASF and NPC	Marine algae?	Phototrophic Open ponds?	Developing	Consumer and aquaculture feed market?
Cellana	Marine algae?	Phototrophic open pond/PBR combi	Marketing/developing	DHA and EPA consumer and animal/aquaculture feed market
DSM/Evonik	*Crypthecodinium cohnii* and *Schizochytrium* sp.	Heterotrophic on sugar	Market leader	DHA and EPA consumer market
Fraunhofer IGB	*Phaeodactylum tricornutum*	Phototrophic flat-panel PBR	Developing	EPA industrial market
Lonza	*Crypthecodinium cohnii* and *Schizochytrium* sp.?	Heterotrophic on sugar	Marketing	DHA consumer market
SB oils	*Schizochytrium* sp.	Heterotrophic on sugar	Marketing	Whole algae DHA aquaculture feed market
Source-Omega	*Schizochytrium* sp.	Heterotrophic on sugar	Marketing	DHA consumer market
Qualitas Health	*Nannochloropsis oculata*	Phototrophic open ponds	Marketing	EPA consumer market

2.4.3 EPA/DHA purification

Algal EPA/DHA purification is a complex process and depends on the algae strain used. The following techniques were found in literature. In PUFAChain short-path distillation is used in Work Packages 5 and 6.

2.4.3.1 Winterization and urea complexation

Mendes et al (2007) developed a simple and inexpensive procedure for concentrating DHA from *C. cohnii* biomass. This involved saponification and methylation in wet biomass, winterization and urea complexation. Temperature had a significant effect on DHA concentration and they found the most concentrated DHA fraction (99.2 % of total FAs) at a urea/fatty acid ratio of 3.5 and crystallization temperatures of 4 and 8 °C. The highest DHA recovery (49.9 %) was found at a urea/fatty acid ratio of 4.0 and a crystallization temperature of 24 °C, which corresponds to 89.4 % DHA of total FAs.

2.4.3.2 SMB Technology

Orochem developed the Simulated Moving Bed technology[23]. They can purify up to 97-99 % EPA, DHA and ALA (α-linoleic acid) from different feedstock with EPA and DHA percentages lower than 20 % by using an absorbent.

2.5 Fish meal and fish oil (FM and FO)

2.5.1 FM and FO production

According to IFFO, 75 % of fish meal and fish oil is produced from small fish species (anchovy, herring, capelin and menhaden) that are not often used for human consumption due to little demand or

[23] www.orochem.com

infrastructure[24]. The other 25 % is produced from fish offal, trimmings or cuttings, and other wastes from processing of edible fish. In 2010 fish oil and fish meal production were respectively 888 and 4,166 thousand tonnes (Figure 17) (Shepherd & Jackson, 2012). The raw fish are cooked, pressed, dried and ground. From pressing a liquor is produced, that contains fish oil, water and soluble protein. The oil is recovered by centrifugation and further refined. The solid fraction after drying and grounding is fishmeal with on average 6-10 % fish oil. The largest fish meal producers are Peru and Chile, followed by Thailand, China, USA, Japan, Denmark, Norway and Iceland[20].

Figure 17 Mass balance of marine ingredients production in 2010 (From: Shepherd & Jackson, 2012)

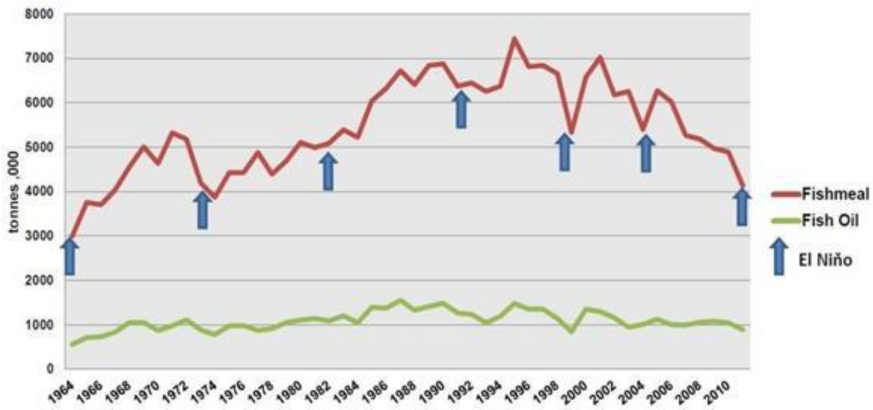

Figure 18 Global fish meal and fish oil production 1964-2010 (From: Shepherd & Jackson, 2012)

The fish meal and fish oil production varies from year to year and decreases during the El Niño phenomenon every couple of years (Figure 18) (Shepherd & Jackson, 2012). In addition, due to limited fish supplies and increasing demand, the sector is vulnerable. It is estimated by FAO that 90 % of the world's fisheries are fully exploited or facing collapse[25]. Both fish meal and fish oil supplies have been decreasing the last years

24 http://www.iffo.net/production
25 https://www.nytimes.com/2017/04/30/world/asia/chinas-appetite-pushes-fisheries-to-the-brink.html

[26]. Possible alternatives are trimmings from processing factories, vegetable oil and meal, insects, single-cell protein, recycled waste and algae. It is expected that alternatives are becoming more and more important [27].

2.5.2 FM and FO usage

In the 1960s fish meal (68-72 % protein and 6-12 % oil) was almost exclusively used as a high protein ingredient in nutritionally demanding periods in the life cycles of pigs and poultry (Figure 19)[28]. Currently the main use is high protein feed ingredient in aquaculture (Shepherd & Jackson, 2012).

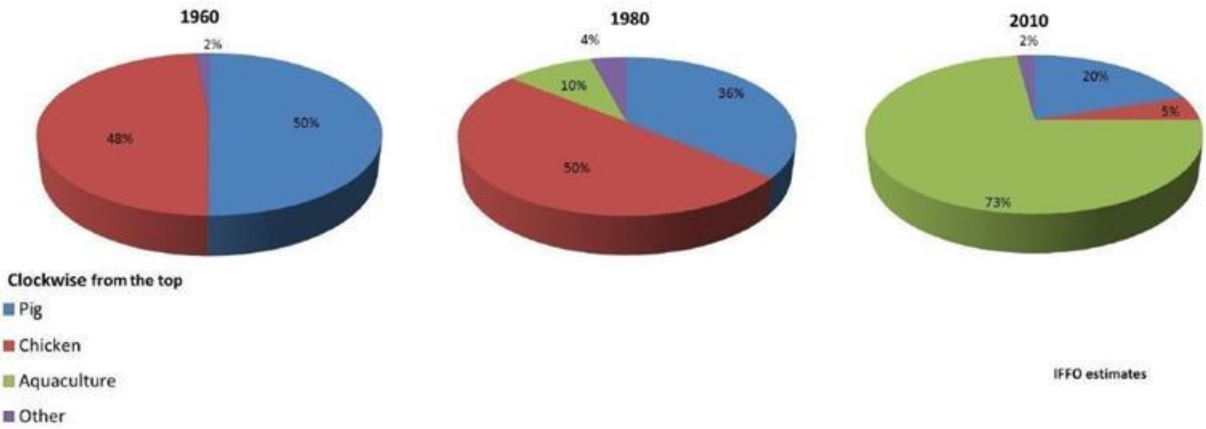

Figure 19 Changing uses of fish meal from 1960 to 2010 (From: Shepherd & Jackson, 2012)

In the 1960s fish oil was mainly used as hardened edible oil and for industrial uses. Currently most fish oil is used aquaculture feeds and increasingly for human nutritional supplements and functional foods (Figure 20) (Shepherd & Jackson, 2012).

[26] https://www.undercurrentnews.com/2015/03/09/iffo-global-fishmeal-fish-oil-supply-could-return-to-normal-levels-in-2015/
[27] http://www.luxresearchinc.com/news-and-events/press-releases/read/alternative-proteins-claim-third-market-2054
[28] www.iffo.net

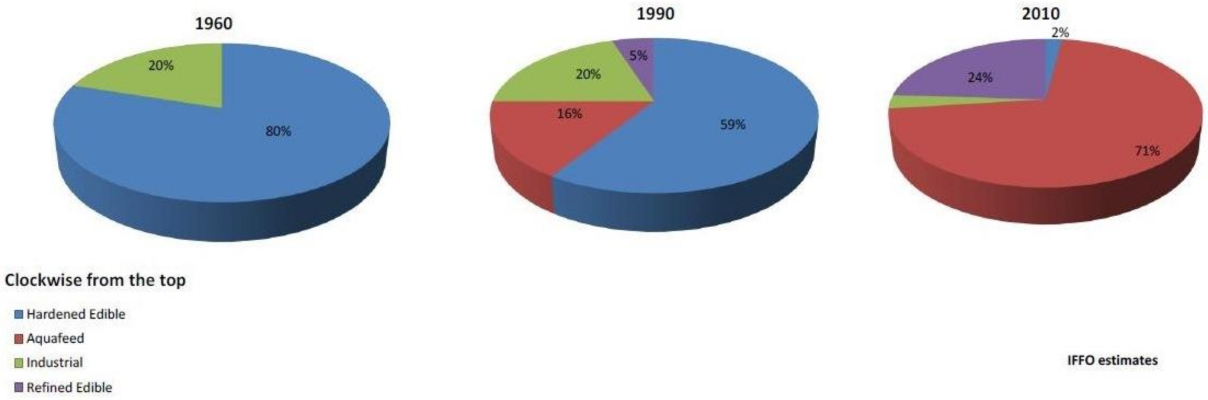

Figure 20 Changing uses of fish oil from 1960 to 2010 (From: Shepherd & Jackson, 2012)

2.5.3 FM and FO price

Because of the limited supply sources, the fish meal and oil sector remains vulnerable. Prices are, as mentioned, influenced by the El Niño seasons and the extent to which alternative sources are available. From 2011-2015 (Figure 21) fish oil prices varied from €1.07 to €2.14 per kg (€1.21 to €2.43). Nikolik and de Jong (2017) expect the fish meal and fish oil prices to stabilize the coming years due to a stabilizing supply.

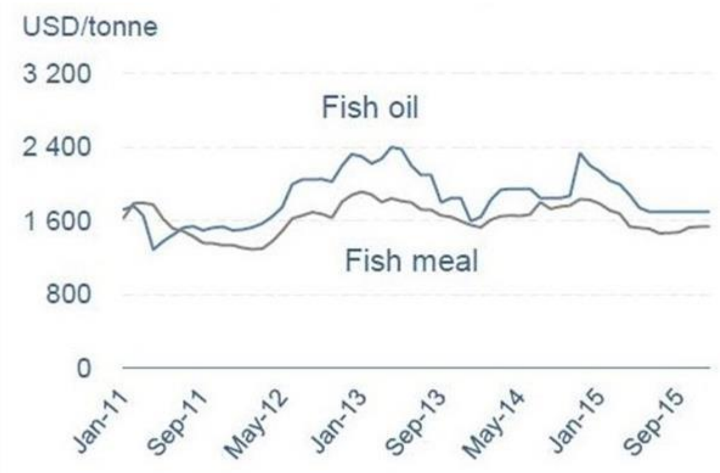

Figure 21 Fish oil and fish meal price developments in Europe, 2011-2015 (FAO, 2016)

2.5.4 FO EPA/DHA purification

Fish oil can contain environmental pollutants (Tocher, 2009) and ingredients with a fishy smell/taste, which are difficult to remove as each step reduces the quality of EHA/DPA. Purification of PUFA from fish oil can for example be done by multicolumn counter current solvent gradient purification (MCSGP) or silver-thiolate chromatographic material and high-performance liquid chromatography (Dillon et al, 2013). No information has been found about the costs of these processes.

2.6 EPA/DHA consumer market

2.6.1 PUFA health claims

PUFAs (EPA, DHA and ALA) protect against heart disease and fit into a healthy diet[29, 30]. High levels of EPA and DHA are present in fatty fish, such as mackerel, herring and salmon. An average content of EPA and DHA is found in perch, shrimp, cod, mussels, lobster and haddock. Fish cannot make their own DHA and EPA, but obtain them from algae. ALA is a vegetable fatty acid, found in (wal)nut, linseed oil and other vegetable oils. The human body can also make EPA and DHA to a small extent itself from ALA. The European Food Safety Authority (EFSA) has approved health claims on omega-3 fatty acids[31]. DHA/EPA are important for maintenance of normal cardiac function and normal (fasting) blood concentrations of triglycerides. DHA is important for maintenance of normal vision and normal brain function, ALA for contribution to brain development (Table 11). In contrast, there are also concerns about an increased risk for prostate cancer[32].

Table 11 EFSA approved health claims for DHA, EPA and ALA[25]

Claims	DHA/EPA	DHA	ALA
Maintenance of normal cardiac function	X		
Maintenance of normal (fasting) blood concentrations of triglycerides	X		
Maintenance of normal vision		X	
Maintenance of normal brain function		X	
Contribution to brain development			X

2.6.2 Global EPA/DHA market development

The global EPA/DHA market is growing fast[33]. In 2013, the market was estimated to be 124 thousand tonnes worth almost 2 billion € and is predicted to be 241 thousand tonnes valued at 4.2 billion € by 2020. Positive results on health effects combined with approved health claims, increased health awareness and a higher living standard are important drivers for this market. Negative impacts on the market growth (of fish oil) are fear of overfishing/depleting fish supplies and concerns about contaminations or negative health effects.

2.6.3 Market developments by (oil) source

The largest part of the EPA/DHA oil market volume and value is from fish and only a minor part from algae (Figure 22A). Algae oils have a relatively larger share in market value (18 %) than in market volume (Figure 22B). Because of the depleting fish supplies (mainly anchovy: see below), krill and algae are expected to be the most promising sources of raw material in the near future [34]. As mentioned in chapter 2.5.1, due to limited fish supplies and increasing demand, the sector is vulnerable. It is expected that fisheries cannot be sustainably extended to a substantial degree to meet additional market demand. It is even concluded that both fish meal and fish oil supplies have been decreasing the last few years.

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29 https://www.hartstichting.nl/gezond-leven/vetten
30 www.voedingscentrum.nl/encyclopedie/omega-3
31 https://www.efsa.europa.eu/en/press/news/120727
32 http://www.harvardprostateknowledge.org/high-intake-of-omega-3-fats-linked-to-increased-prostate-cancer-risk
33 http://www.reportlinker.com/p02029889/Omega-3-Polyunsaturated-Fatty-Acids-PUFAs-A-Global-Market-Overview.html
34 https://www.gminsights.com/industry-analysis/EPA-DHA-omega-3-ingredients-market

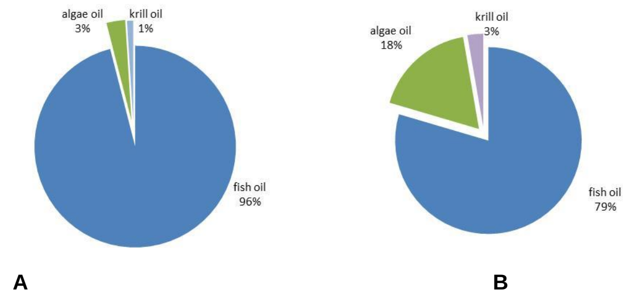

Figure 22 EPA/DHA market volume (A) and value in 2011 (B) by source ([35]; Ismail, 2013)

2.6.3.1 Fish oil

Most fish oil is produced in Peru, Chile, Scandinavia and other European countries, adding up to 85 % of the global production in 2014[36]. Due to its high EPA and DHA content and well-regulated fisheries, anchovy oil is the most used[29]. In 2014 however, there was a reduced capture of anchovy due to concerns over remaining stocks (Bernasconi, 2014). As mentioned, concerns over declining fish stocks, contaminations and taste aspects make alternative oils more attractive. Technological advances allow better (micro)encapsulation (taste masking) of omega-3 ingredients, resulting in a broader usage scope in the food and beverage industries. This however doubles the price of the product (D. Lochmann, personal communication, 2016).

Fish oil concentrates, because of their high prices in pharmaceutical applications, have the highest market share: 48 % of the EPA/DHA market value in 2014. In the three largest markets (US, Europe and China) increasingly consumers prefer concentrates over refined anchovy oils. As a result, the global demand increased with 3 % but a concomitant sharp decline in prices resulting from increased competition led to an overall decrease in the value of the concentrate market of 7 % (Bernasconi, 2014). Concentrates are increasingly popular because they result in a lower daily intake in number of pills and avoidance of extra calories. Suppliers like DSM Nutritional Products, BASF Human Nutrition and FMC's Epax division produce concentrates with EPA/DHA concentrations of up to 90 % (Bernasconi, 2014; [37, 38]). According to Ismail (2013) improvements in concentration could lead to a much lower fish oil demand in the near future.

2.6.3.2 Krill oil

The high-end krill oil market has grown fastest. Krill oil is naturally high in the antioxidant astaxanthin and phospholipids. Marketers emphasize that EPA/DHA in krill oil have improved bioavailability as they are bound primarily to these phospholipids, in contrast to EPA/DHA in fish and algae oil that are primarily bound to triglycerides ([29, 39]; Ismail, 2013; Bernasconi, 2014).

2.6.3.3 Algae oil

Algae oil accounts for 3 % of the EPA/DHA market volume and 18 % of the value (Figure 22). Algae oil has some advantages over fish oil in smell/taste, oxidative stability, higher DHA vs. EPA concentrations, sustainability and suitability for vegetarians. Some of these disadvantages can be overcome by technological solutions like microencapsulation. Labelling as "vegetarian", "kosher" and "organic" have

[35] http://en.siriopharm.com/o-mega3/
[36] https://www.gminsights.com/industry-analysis/EPA-DHA-omega-3-ingredients-market
[37] http://www.omega3.basf.com/web/global/omega3/en_GB/index
[38] http://www.nutritionaloutlook.com/omega-3/ultra-high-concentrates-are-next-omega-3-supplyside-west-report
[39] http://www.nutritionaloutlook.com/delivery-systems/everywhere-omega-fatty-acids

strengthened the demand for algae oils [40, 41, 42]. EPA/DHA products from fish oil are however much lower in price compared these products from alternative oils. This, accompanied by a high price sensitivity in end consumers, has led to a slower than expected market introduction. Other challenges for algae producers include small market volumes per supplier, a monopolistic market nature and high costs for algae processing [43].

2.6.3.4 Plant oil

Flaxseed, canola oil, walnuts, etc. contain ALA, for which there is a big market since it is an essential omega-3 in human diet. Plants can produce EPA/DHA as well after insertion of algae genes. Several multinationals are developing genetically modified EPA/DHA rich canola oil, but for the European and Japanese markets only non-GMO (genetically modified organisms) products are allowed.

2.6.4 Market regions

North America is traditionally the largest market region for EPA/DHA (Figure 23), but the supplement market is becoming saturated. The Asia Pacific region, especially China, is growing fastest, while growth in the European market is steadier. Demand in the rest of the world (Middle East, Africa and Latin America) is rising as well.

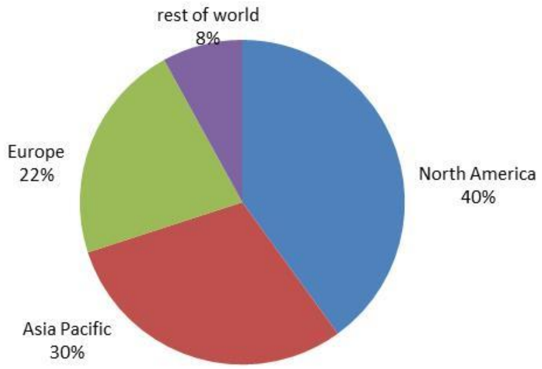

Figure 23 Global EPA/DHA market volume distribution[44]

2.6.5 EPA/DHA market segmentation (applications)

Most of the EPA/DHA oil is used for dietary supplements, followed by pet foods, food and beverage, infant formula, pharmaceuticals and clinical nutrition (Figure 24). In terms of value, the segmentation changes with higher shares of pharmaceuticals, infant formula and clinical nutrition (Figure 25).

40 http://www.reportlinker.com/p02029889/Omega-3-Polyunsaturated-Fatty-Acids-PUFAs-A-Global-Market-Overview.html
41 https://www.gminsights.com/industry-analysis/EPA-DHA-omega-3-ingredients-market
42 http://www.algaeindustrymagazine.com/the-global-algae-oil-omega-3-market-in-2014/
43 http://www.algaeindustrymagazine.com/the-global-algae-oil-omega-3-market-in-2014/
44 http://en.siriopharm.com/o-mega3/

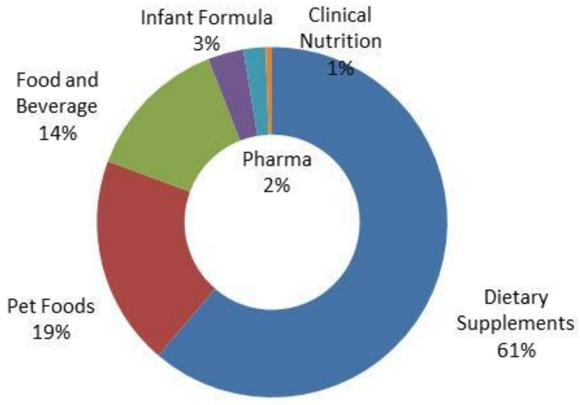

Figure 24 Market segmentation global EPA/DHA market end user application by volume[45]

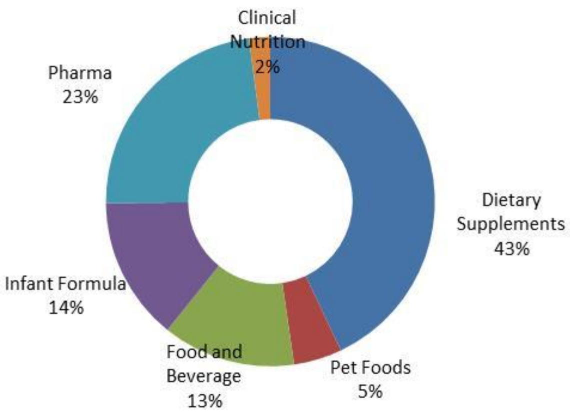

Figure 25 Market segmentation global EPA/DHA market end user application by value[39]

2.6.5.1 Dietary supplements

The market for dietary supplements is still growing, with a small decrease in 2014. The North American market was exposed to negative media and is almost saturated. However, BRIC countries and Eastern Europe show an increasing demand. There is movement to krill and high concentrated fish oil, whereby the strong competition in the concentrates market causes price pressure ([46, 47, 48]; Bernasconi, 2014).

2.6.5.2 Pet and animal feeds

The second market (in volume) are animal feeds with added EPA/DHA, which is an average growing sector. The humanization of pets and demand for high quality feeds are strong drivers. Key products are puppy/ kitten feeds, premium food formulas and products to improve skin and coat [40, 41].

2.6.5.3 Functional food

There is an increasing focus on/interest in personal health and lifestyle, changing diets, functional foods and health benefits of omega-3. EPA/DHA fortified foods and drinks are a strong growing market. Health and wellness are large markets for the world's largest food and drink companies like Nestlé. Their product development and marketing efforts are driving forces for market growth [40, 41].

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45 http://www.reportlinker.com/p02029889/Omega-3-Polyunsaturated-Fatty-Acids-PUFAs-A-Global-Market-Overview.html
46 https://www.packagedfacts.com/Global-EPA-DHA-7145087/
47 https://www.gminsights.com/industry-analysis/EPA-DHA-omega-3-ingredients-market
48 http://www.nutritionaloutlook.com/delivery-systems/everywhere-omega-fatty-acids

2.6.5.4 Infant formula

Infant formula is one the fastest growing markets for omega-3[49]. This is linked with the economic growth in Asia (mainly China, with an annual growth rate of almost 20 %), Eastern Europe, and, to a lesser extent, the Middle East and Latin America and the growing number of working women. United Nations FAO/WHO (Food and Agriculture Organization/World Health Organization) recommend that all infant formula should contain DHA and ARA and in 2011 this was the case in 87 % (Packaged Facts, 2012).
Important players in the market like Nestlé and Abbott Laboratories developed new products [40], [41]. As algae oils have a high DHA content they are important in this market segment. However, only DSM's life'sDHA™ from algae oil is currently used in US infant formulas[50].

2.6.5.5 Pharmaceuticals

Pharmaceuticals based on omega-3 represent a small volume, but a high value. Only Lovaza/Omacor and Epadel are approved yet in the US/Europe and Japan respectively and are both based on fish oil (Packaged Facts, 2012). The patent for Lovaza/Omacor expires within two years, so similar products will likely be made by other companies (D. Lochmann, personal communication, 2016). The pharmaceutical market is expected to grow fast due to the growing importance and application scope of cholesterol reducing pharmaceuticals[51]. Many new companies are expected to enter this market, since several drugs are in advanced clinical trials phases ([52]; Packaged Facts, 2012).

2.6.5.6 Clinical nutrition

The application of omega-3 in clinical nutrition has increased because of anti-inflammatory properties and beneficial effects for patients with trauma and chronic wounds. Clinical trials and strict regulations result in limited market access. Societal changes (aging populations, higher incidences of chronic diseases, increasing home care of patients) lead to market growth. Demand stagnates in the US and Japan, but increases significantly in less developed regions of Europe, Asia Pacific and Latin America (Packaged Facts, 2012).

2.6.6 European market segmentation

The European EPA/DHA market is expected to grow from about 25,000 at current to about 30,000 tonnes in 2020 (Figure 26) (for comparison: the global market was 124,000 tonnes in 2013). European market segmentation is comparable to global segmentation and every segment is likely to grow.

49 http://www.persistencemarketresearch.com/market-research/fatty-acids-supplements-market.asp
50 http://www.dsm.com/markets/foodandbeverages/en_US/products/nutritional-lipids.html
51 https://www.gminsights.com/industry-analysis/EPA-DHA-omega-3-ingredients-market
52 http://www.reportlinker.com/p02029889/Omega-3-Polyunsaturated-Fatty-Acids-PUFAs-A-Global-Market-Overview.html

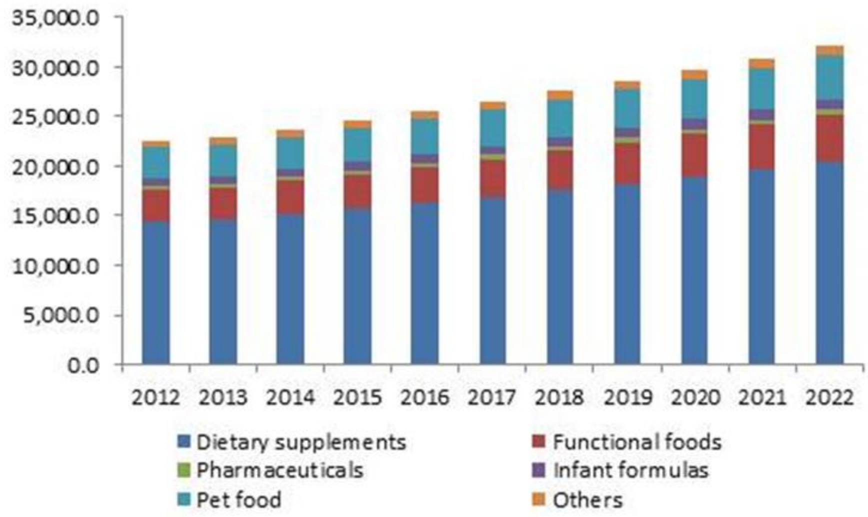

Figure 26 European EPA/DHA ingredients market size by application, 2012-2022 (tonnes)[46]

2.6.7 Key players EPA/DHA market

Five companies represent about 75 % of the total EPA/DHA market. DSM leads the market, followed by Epax and Croda Health Care[53].

DSM

DSM sells life'sDHA™, life'sOMEGA™ and MEG-3® fish oil[54]

- Life'sDHA™ is an algal source of DHA as mentioned before. DSM is also developing a high-concentrate omega-3 DHA (85 %) algae oil
- Life'sOMEGA™ is also an algal source of EPA/DHA. It was the first vegetarian EPA/DHA product available as an alternative to fish sources
- MEG-3® fish oil is an EPA/DHA omega-3 from fish oil, without fishy taste or smell

Epax (part of FMC)

Epax is part of the FMC Corporation[55]. Epax product lines are EPA/DHA fish oil concentrates or ultra concentrates (min. 700 mg/g EPA/DHA) as ethyl esters and triglycerides. Triglycerides are the natural form of lipids in fish. The product Epax 4535 TGN is a triglyceride oil with a minimum of 450 mg/g EPA and 350 mg/g DHA in a total minimum of 860 mg/g.

Croda Health Care

Incromega™ products from Croda Health Care are EPA or DHA rich fish oil concentrates in various compositions in ethyl ester or triglyceride form[56].

BASF

BASF[57] is a key player in the market through its acquisition of Pronova. Pronova Pure® is sold as a supplement and Lovaza/Omacor (See Pharmaceuticals) as a prescription drug. They contain up to 90 % omega-3 fish oil content in an EPA:DHA ratio 46:38 as ethyl esters. BASF announced the acquisition of

53 http://www.persistencemarketresearch.com/market-research/fatty-acids-supplements-market.asp
54 http://www.dsm.com/markets/foodandbeverages/en_US/products/nutritional-lipids.html
55 http://www.epax.com/
56 http://www.crodahealthcare.com
57 http://www.omega3.basf.com/web/global/omega3/en_GB/index

Equateq, a manufacturer of high-concentrate omega-3s based in Scotland. With the acquisition, BASF extends its portfolio of omega-3 products for the pharmaceutical and dietary supplement industries with concentrates with variable ratios of EPA and DHA at concentration levels of up to 99 % purity[58].

Cargill

Cargill is selling IngreVita EPA/DHA Omega-3 oil. Ingrevita is a food and beverage ingredient containing both canola and fish oil[59].

2.6.8 PUFA share in end product cost

Because of the proximity of the European market and because supplements are the largest and most transparent market segment a rough price analysis was made for online purchases of (algae or fish based) supplements in May 2016. Supplements offered contained 150 to 600 mg DHA/EPA and 40 mg DHA only (for kids). Consumer end prices ranged from € 0.15 to € 0.50 per softgel/capsule (Figure 27).

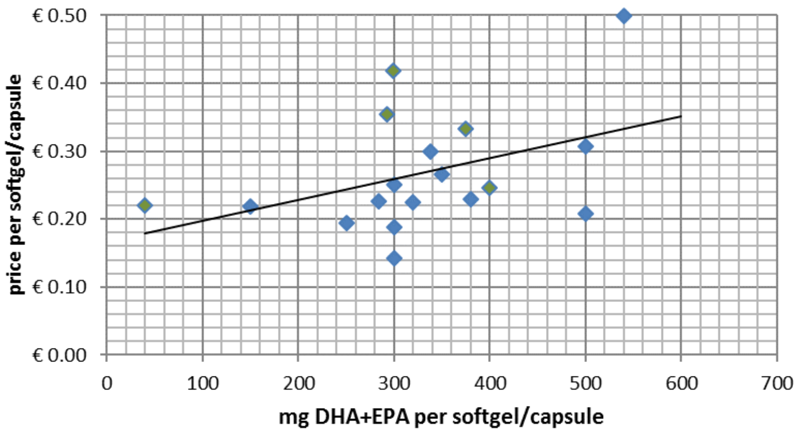

Figure 27 Calculated DHA/EPA supplement consumer prices offered for online purchase per softgel/capsule, May 2016 (green=algae products, blue=fish products)

Raw materials added in the supplements with algae/fish oil (concentrates) are mostly gelling agents (glycerine, gelatine), starch and antioxidants. Calculated from the amount of EPA/DHA, supplements based on algae or fish oil are sold for about €400 – €1,500 per kg EPA/DHA and algae DHA supplements for about € 5,500 per kg DHA.

2.7 Aquaculture feed market

2.7.1 Global aquafeed market development

Global fish production has grown steadily over the last 50 years with an average annual growth rate of 3.2 % (FAO, 2014). Growth is mainly caused by increasing aquaculture production as capture production is limited (Figure 28). At current, more than half of the fish we consume is from aquaculture (FAO, 2016a).

58 http://www.nutritionaloutlook.com/delivery-systems/everywhere-omega-fatty-acids

59 https://www.cargill.com/news/releases/2014/NA31659460.jsp

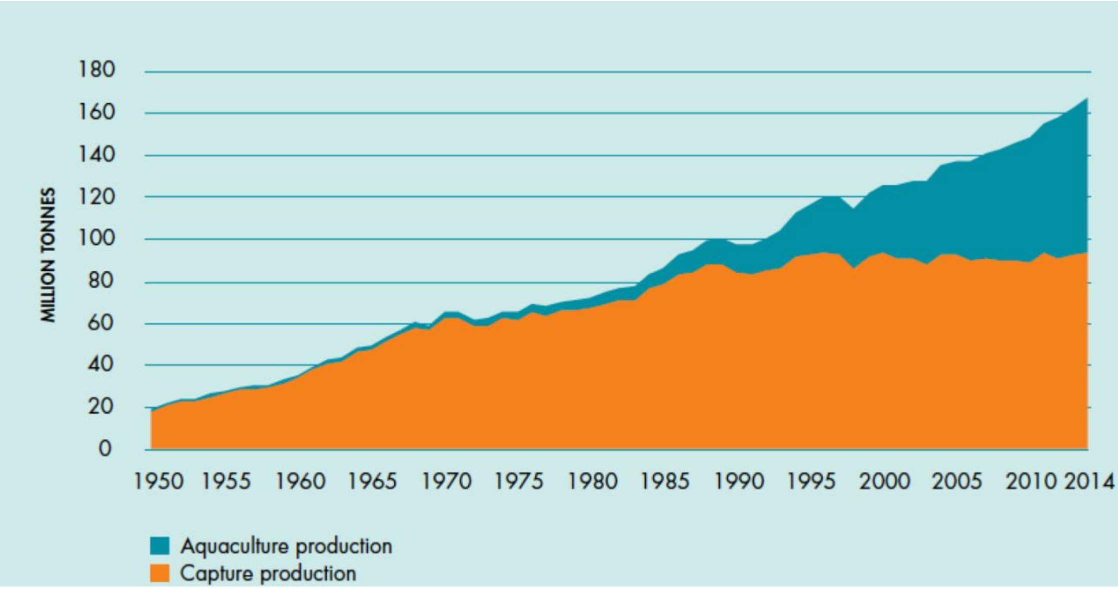

Figure 28 World capture fisheries and aquaculture production in million tonnes from 1950-2014 (FAO, 2016b)

Aquafeed constitutes 40-50 % of aquaculture production costs[60]. Aquafeeds are compound feeds consisting of various raw materials and additives (e.g. corn, soy, fish meal, fish oil, wheat). As a result of the growing aquaculture sector and advances in feed production technologies, the aquafeed market is growing accordingly. The market was valued at 52,589 million € in 2013 and is projected to be 104,448 million € by 2019 [61]. In volume the market was estimated to be 53,824 thousand metric tonnes in 2014 with a projected CAGR (Compound Annual Growth Rate) of 10.7 % from 2014-2019.

Important drivers for the growing aquaculture sector are expanding populations, increasing incomes, changes in diet and increased seafood consumption, increasing consumer concerns and high-quality standards[62]. In addition, low-cost production technologies and alternative feed ingredients are continuously developed, especially in Europe[56]. The Asia-Pacific region has the largest aquafeed market share. Key players in the aquafeed market are AllerAqua A/S, Cargill, Inc., Beneo GmbH, Biomar A/S, Avanti Feeds Ltd, Alltech Inc., Biomin GmbH, Charoen Pokphand Foods Public Company Limited, Nutreco N.V. and Coppens International B.V.[63].

2.7.2 Aquatic animal type

The largest aquafeed demand is for carp production, followed by molluscs[64]. Also, salmon production accounts for a considerable part of the aquafeed demand[65]. Together with demand for carp this accounted for 50 % of the total aquafeed consumption in 2015. In addition, aquafeed for crustaceans is expected to grow at the fastest rate the coming years.

[60] http://www.thefishsite.com/fishnews/20396/fish-feed-market-forecasted-to-grow-117-per-cent-by-2018/
[61] http://www.allaboutfeed.net/Feed-Additives/Articles/2015/11/Aquafeed-market-Global-trends-and-forecasts-2705131W/?dossier=23678&widgetid=1
[62] http://www.prnewswire.com/news-releases/global-aquafeed-market-is-expected-to-reach-155-billion-by-2022-575690951.html
[63] http://www.acutemarketreports.com/report/world-aquafeed-market
[64] http://www.grandviewresearch.com/industry-analysis/aquafeed-and-aquaculture-additive-market
[65] http://www.thefishsite.com/fishnews/27439/global-aquafeed-market-expected-to-reach-156-billion-by-2022/

2.7.3 Aquaculture feed ingredients

Feeds for fish and crustaceans are similar in composition while feeds for molluscs consist for the major part of algae[66]. Soy is the most important ingredient in aquafeeds, followed by fish meal, but as a plant protein source, corn is expected to grow faster the coming years[67]. Fish meal and fish oil are important diet components for farmed carnivorous fish, as they supply essential amino acids and fatty acids.
Atlantic salmon is an omnivorous fish whose feed ingredient composition in intensive farming systems is dependent on its life stage, but the composition is roughly shown in Figure 29. Fish meal and fish oil constitute a large part of the farmed salmon feed.

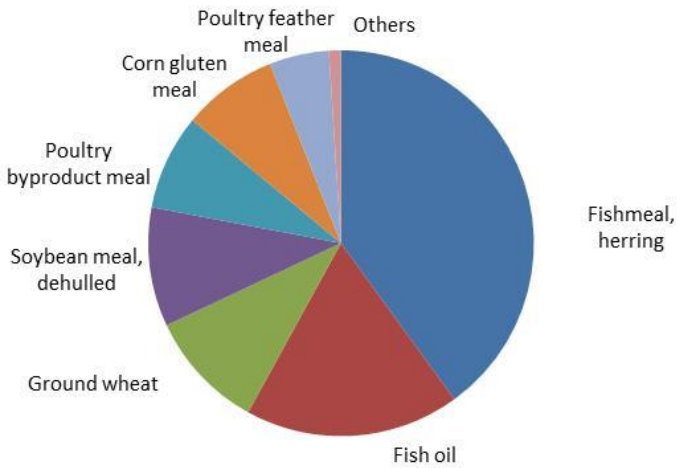

Figure 29 Atlantic salmon feed ingredient composition in intensive farming systems, roughly based on Tacon et al (2011)

To reduce aquafeed dependence on fish meal and fish oil, different alternatives are investigated and/or already used. Alternative ingredients include algae, insects, plants, SCP (single cell proteins) etc (Figure 30) (Schalekamp et al, 2016). Essential fatty acid content and digestibility are important characteristics for these alternatives for fish oil and fish meal respectively.

[66] http://www.prnewswire.com/news-releases/aqua-feed-market-by-end-consumption-fish-crustaceans-mollusks-others-by-additives-antibiotics-vitamins-antioxidants-amino-acids-feed-enzymes-feed-acidifiers-others-by-geography-global-trends--forecasts-to-2018-209321601.html
[67] http://www.marketwatch.com/story/aquafeed-market-worth-16823-billion-usd-by-2021-2016-04-08-92033059

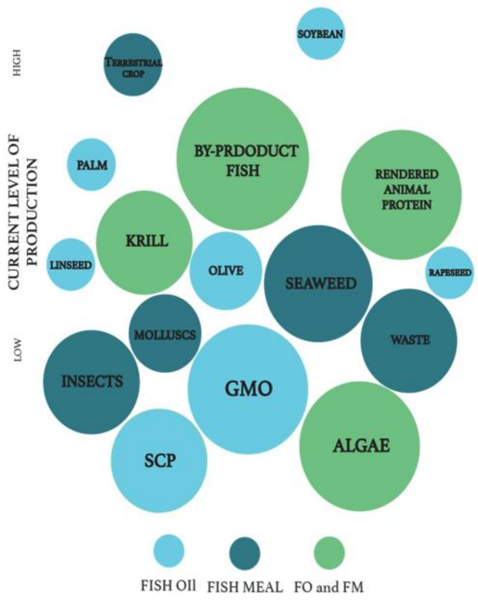

Figure 30 Overview of alternative ingredients for fishmeal and fish oil, ranked by current level of production and its potential (From: Schalekamp et al, 2016)

Many ingredients can partially replace fish meal with minor or no effects on fish growth, e.g. insects in the diets of farmed seabass[68]. However, fish meal prices are expected to stabilize the coming years, and this makes investments in alternatives more difficult[69]. In addition, some alternatives can lead to decreased growth due to lack of certain minerals/amino acids (animal by-products) or are difficult to apply due to logistics (fish trimmings). At the moment, insects, single cell proteins and algae are regarded as the most promising alternatives.

2.7.4 Algae for aquaculture feed

As mentioned, mollusc feeds consist for a large part of microalgae. In addition, they are used as (mostly live) food for larvae and juveniles of molluscs, shrimps, crustaceans and fish (freshwater and marine) and the culture of zooplankton for food in aquaculture. Mature fish are usually not fed on feeds containing microalgae, although for example Coppens recently launched Neogreen for trout, a fish meal and fish oil free fish feed containing omega-3 rich algae[70] and Lerøy/Biomar launched a salmon feed with reduced marine sources and AlgaPrime DHA from *Schizochytrium* sp. produced by TerraVia and Bunge[71]. DSMs algae oil has been recently approved for use in aquafeed. Skretting tested the digestion of the algae oil and the EPA/DHA absorption with good results and they can provide feed formulations with different EPA/DHA ratios from algae[72.]

Traditionally, the most commonly used species in aquaculture are *Chlorella, Nannochloropsis, Tetraselmis, Isochrysis, Phaeodactylum, Thalassiosira, Pavlova, Chaetoceros* and *Skeletonema* in several

[68] http://www.feednavigator.com/Sectors/Aquaculture/European-seabass-production-sustained-when-insects-partially-replace-fishmeal-in-diets
[69] http://www.feednavigator.com/Sectors/Aquaculture/Stable-fishmeal-prices-forecast-alternative-protein-players-could-face-choppy-waters
[70] https://www.coppens.com/en/feed-programs/industrial/trout/466343-neogreen4663-67
[71] http://www.biomar.com/en/denmark/articles/news/wholehearted-focus-on-salmon-fed-with-microalgae-by-leroy/
[72] http://www.feednavigator.com/R-D/Skretting-gets-behind-algal-oil-breakthrough-from-Evonik-and-DSM?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright

combinations to provide a well-balanced diet. Mixed algae species lead to better growth and survival rates than feeds composed of only one algae species. In 1999 about 1,000 tonnes microalgae were produced for aquaculture (62 % for molluscs, 21 % for shrimps and 16 % for fish) (Voort, van der et al, 2015). Other sources (Neori, 2013) however mentioned that 240 million tonnes (!) of greenwater algae are yearly cultured in polyculture fish farming systems, where fish (especially carp), bivalves and shrimp feed directly on them or via small herbivorous protozoans and zooplankton. An equal amount of naturally occurring microalgae is ingested by bivalves in coastal marine farms.

The PUFAFEED project focused on the production of DHA rich *C. cohnii* as alternative for fish oil (Sijtsma). Novel cultivation technologies with acetate or ethanol as carbon source enhanced DHA productivity with a factor 2-3. The biomass was used as feed ingredient for fish larvae after centrifugation, homogenisation and spray drying. *Nitzschia laevis* was evaluated for EPA production under heterotrophic conditions, but EPA production was still much lower than that of DHA. In comparison, EPA production by phototrophic *Phaeodactylum tricornutum* was not interesting due to lower lipid and EPA levels. Short term feeding trials with *C. cohnii* biomass containing feeds with salmon and sea bream did not affect growth parameters. Longer term experiments with salmon fed on *C. cohnii* and *P. tricornutum* led however to slightly reduced body weight, but no adverse effects on health. The inclusion of DHA from *C. cohnii* instead of fish oil would lead to 10 % higher production costs of salmon feed (Sijtsma, personal communication).

Rabobank International expects aquafeed to become one of the first markets for algae products in which they will be competitive, because of decreasing marine sources and increasing prices[73]. Aquafeed companies, for example in the salmon sector, where 350,000 MT of fish oil is consumed yearly, are increasingly looking into algae and other alternative products. Technological improvements and lower production prices for microalgae will benefit this market.

2.8 Livestock feed market

2.8.1 Global livestock feed market development

Compound feed production globally approaches an estimated 1 billion tonnes per year. Global annual turnover of the feed manufacturing sector is more than 337 billion € yearly. FAO estimates that by 2050 60 % more food has to be produced with an even higher percentage increase (almost triple) in animal protein production[74]. Four of the global top 20 feed producers are located in Europe: ForFarmers, Agrifirm Group, De Heus and Nutreco (all in the Netherlands)[75]. In 2015, soy products and palm kernel expeller (imported into the EU) accounted for 31 % and 20% of the Dutch livestock feed respectively. Only 0.1% of Dutch feed is fish meal (

[73] https://www.seafoodsource.com/news/supply-trade/algae-becoming-increasingly-relevant-due-to-soaring-fishmeal-and-fish-oil-demand-prices
[74] www.ifif.org
[75] www.wattagnet.com

Table 12, based on Cormont and Van Krimpen, 2016). Fishmeal is not allowed as ruminant feed in the EU, but only for non-ruminants (Jedrejek et al, 2016) as a result of the spongiform encephalopathy crisis.

Table 12 Protein-rich feedstock volumes in Dutch livestock (poultry, pigs and cattle) feeds in 2015 (based on Cormont and Van Krimpen, 2016)

Protein-rich feedstock	Volume in Dutch feed in 2015	
	(1.000 tonnes)	**(%)**
Soy products	1,353	30.8
Palm kernel expeller	879	20.0
Sunflower expeller	745	16.9
Rapeseed products	587	13.3
Whey powder	361	8.2
Corn products	225	5.1
Vinasse	154	3.5
Lupine	27	0.6
Alfalfa	23	0.5
Peas	21	0.5
Potato protein	14	0.3
Milk powder	6	0.1
Fish meal	3	0.1
Linseed	2	0.0
Total	**4,398**	**100.0**

Sustainability issues surrounding livestock feeds are important in the Netherlands, and alternatives for substitution of imported soy are looked into, such as locally produced algae (Spruijt et al, 2014b). Prices for soybean meal and fish meal have increased over the last 10 years. Price fluctuations in fish meal are higher than in soybean meal because of fluctuations in the supply influenced by the El Niño seasons (Figure 31)[76].

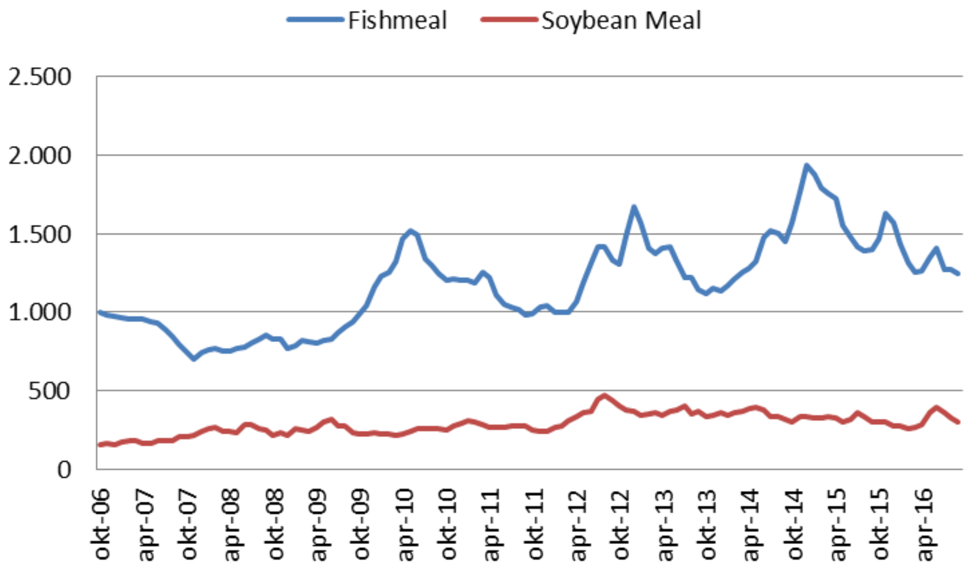

Figure 31 Fish meal and soybean meal prices in euro per metric tonne 2006-2016[77]

[76] www.indexmundi.com
[77] www.indexmundi.com

2.8.2 Algae for livestock feed

Based on dry matter content, algae contain comparable or even higher levels of protein, carbohydrates and lipids than conventional ingredients for livestock feeds. Nutrient composition between the different micro-algae is variable, but most algae have a high protein content (Table 13). Research shows that algae can be added in diets of pigs up to a percentage of 14 % and possibly even up to 33 % without adverse effects on performance. In laying hens and broilers addition of 12 and 17 % algae respectively did not affect performance. Based on chemical composition and in vitro digestibility of dried algae the nutritional value was deducted, after which optimizations with these algae in pig diets were made. This showed that algae at a maximum cost price of € 0,30 per kg DM can compete well with other livestock feed resources. At this price level about 5 % dried algae are incorporated in the diet. However, the minimum cost-price for large-scale production of algae still is still € 5 per kg DM (Spruijt et al, 2014b).

Table 13 Nutrient composition of conventional feedstuffs and various algae (as % DM) (From: Lum et al, 2013)

Feedstuff/algae	Protein	Carbohydrate	Lipid
Soybean	37	30	20
Corn	10	85	4
Wheat	14	84	2
Anabaena cylindrica	43-56	25-30	4-7
Arthrospira maxima (Spirulina)	60-71	13-16	6-7
Chlorella vulgaris	51-58	12-16	14-22
Spirogyra sp.	6-20	33-64	11-21
Synechococcus sp.	73	15	11

Different microalgae species have high lipid and PUFA contents, such as EPA and DHA (Spruijt et al, 2014b). Feeding hens with *Schizochytrium* sp. resp. *C. cohnii* to produce ”OMEGA” eggs has proven to be profitable (Pulz & Gross, 2004). In addition, studies in dairy cows have focused on producing PUFA fortified milk, which increased PUFA concentrations in milk, with a mixed effect on the milk fat content (Lum et al, 2013). To be able to compete with soybeans as protein source, with fish oil as PUFA source and with other livestock feed additives the cost price of algae must be decreased. Development of innovative, more productive algae cultivation systems, with limited installation and energy costs should enable this (Spruijt et al, 2014b).

2.9 Regulations

2.9.1 Regulations in the EU

Food supplements

Food supplements are concentrated sources of nutrients (or other substances) with a nutritional or physiological effect, marketed as an addition to a normal diet in “dose” form, such as pills, tablets, capsules, liquids in measured doses, etc. Directive 2002/46/EC contains harmonised rules to protect consumers against potential health risks from food supplements and misleading information (ec.europa.eu/food/safety/labelling_nutrition/supplements/index_en.htm).

Novel foods and food ingredients

Novel food is food not consumed to a significant degree in the European Union prior to 15 May 1997 and which falls under one of the categories listed in the Regulation (e.g. food consisting of or isolated from micro-organisms, fungi or algae). Authorisation and use of novel foods and food ingredients have been harmonised in the European Union by Regulation (EC) No 258/97. Novel food will only be approved for use in the EU if they do not present a risk to public health, are not nutritionally disadvantageous when replacing a similar food and are not misleading to the consumer. They must undergo a scientific assessment prior to authorisation to ensure their safety. The authorisation sets out, as appropriate, the conditions for their use, their designation as a food/food ingredient and labelling requirements. A novel food or ingredient may be marketed through a simplified procedure called "notification" (Article 5 of Regulation (EC) No 258/97). The company notifies the Commission about their intention to place on the market a novel food or ingredient based on the opinion of a Member State food assessment body that has established "substantial equivalence" to an already authorised novel food. Novel food is subject to the general labelling requirements (Regulation 1169/2011). Specific additional requirements for the labelling of novel food may also apply, if necessary to properly inform the consumer. The label must mention the name of the food, and, where appropriate, specify the conditions of use. Any nutrition and health claim should only be made in accordance with the Health and Nutrition Claims Regulation 1924/2006 (ec.europa.eu/food/safety/novel_food/authorisations/index_en.htm).

Feed additives
Feed additives are products used in animal nutrition for purposes of improving the quality of feed and the quality of food from animal origin, or to improve the animals' performance and health, e.g. providing enhanced digestibility of the feed materials. According to Regulation (EC) No 1831/2003 feed additives may not be put on the market unless authorisation has been given following a scientific evaluation demonstrating that the additive has no harmful effects, on human and animal health and on the environment (ec.europa.eu/food/safety/animal-feed/feed-additives/eu-rules/index_en.htm).

Infant formula
Infant formula and follow-on formula are products designed to satisfy the specific nutritional requirements of healthy infants (children under the age of 12 months). These products are specifically covered by Commission Directive 2006/141/EC. The Directive lays down the requirements for the composition and labelling of infant formula and follow-on formula. The annexes of the Directive give criteria for the composition (protein, carbohydrate, fat, mineral substances, vitamins and certain other ingredients) of infant formulae and follow-on formulae including, where necessary, minimum and maximum levels (ec.europa.eu/food/safety/labelling_nutrition/special_groups_food/children/index_en.htm).

Nutrition and Health Claims on Food
European Union rules on nutrition and health claims have been established by Regulation (EC) No 1924/2006. This regulation is the legal framework used by food business operators when they want to highlight the particular beneficial effects of their products - in relation to health and nutrition - on the product label or in its advertising. The rules of the Regulation apply to nutrition claims (such as "low fat", "high fibre") and to health claims (such as "Vitamin D is needed for the normal growth and development of bone in children"). The objective of those rules is to ensure that any claim made on a food's labelling, presentation or advertising in the European Union is clear, accurate and based on scientific evidence. Food bearing claims that could mislead consumers are prohibited on the EU market. This not only protects consumers, but also promotes innovation and ensures fair competition. The rules ensure the free circulation of foods bearing claims, as any food company may use the same claims on its products anywhere in the European Union. A public EU Register of Nutrition and Health Claims lists all permitted nutrition claims and all authorised and non-authorised health claims, as a source of reference and so that full transparency for consumers and food business operators is ensured (ec.europa.eu/food/safety/labelling_nutrition/claims/index_en.htm).

Medicinal products

The European system offers several routes for the authorisation of medicinal products:

- The centralised procedure, which is compulsory for products derived from biotechnology, for orphan medicinal products and for medicinal products for human use which contain an active substance authorised in the Community after 20 May 2004 (date of entry into force of Regulation (EC) No 726/2004) and which are intended for the treatment of AIDS, cancer, neurodegenerative disorders or diabetes. The centralised procedure is also mandatory for veterinary medicinal products intended primarily for use as performance enhancers in order to promote growth or to increase yields from treated animals. Applications for the centralised procedure are made directly to the European Medicines Agency (EMA) and lead to the granting of a European marketing authorisation by the Commission which is binding in all Member States.
- The mutual recognition procedure, which is applicable to the majority of conventional medicinal products, is based on the principle of recognition of an already existing national marketing authorisation by one or more Member States.
- The decentralised procedure, which was introduced with the legislative review of 2004, is also applicable to the majority of conventional medicinal products. Through this procedure an application for the marketing authorisation of a medicinal product is submitted simultaneously in several Member States, one of them being chosen as the "Reference Member State". At the end of the procedure national marketing authorisations are granted in the reference and in the concerned Member States.

Purely national authorisations are still available for medicinal products to be marketed in one Member State only. European Medicines Agency's (EMA) main task is to co-ordinate the scientific evaluation of the safety, efficacy and quality of medicinal products which undergo either procedure. All scientific questions arising in these procedures are dealt with by the EMA (ec.europa.eu/health/authorisation-procedures_en.htm).

2.9.2 Regulations in the US

Dietary Supplements and dietary ingredients

FDA regulates both finished dietary supplement products and dietary ingredients. FDA regulates dietary supplements under a different set of regulations than those covering "conventional" foods and drug products. Under the Dietary Supplement Health and Education Act of 1994 (DSHEA):

- Manufacturers and distributors of dietary supplements and dietary ingredients are prohibited from marketing products that are adulterated or misbranded. That means that these firms are responsible for evaluating the safety and labelling of their products before marketing to ensure that they meet all the requirements of DSHEA and FDA regulations.
- FDA is responsible for taking action against any adulterated or misbranded dietary supplement product after it reaches the market.

Unlike drugs, supplements are not intended to treat, diagnose, prevent, or cure diseases. That means supplements should not make claims, such as "reduces pain" or "treats heart disease." Claims like these can only legitimately be made for drugs, not dietary supplements. Under existing law, including the Dietary Supplement Health and Education Act passed by Congress in 1994, the FDA can take action to remove products from the market, but the agency must first establish that such products are adulterated (e.g., that the product is unsafe) or misbranded (e.g., that the labelling is false or misleading) (www.fda.gov/Food/DietarySupplements/).

Pet food

There is no requirement that pet food products have pre-market approval by the FDA. However, FDA ensures that the ingredients used in pet food are safe and have an appropriate function in the pet food. Many ingredients such as meat, poultry and grains are considered safe and do not require pre-market approval. Other substances such as sources of minerals, vitamins or other nutrients, flavourings, preservatives, or processing aids may be generally recognized as safe (GRAS) for an intended use (21 CFR 582 and 584) or must have approval as food additives (21 CFR 570, 571 and 573) (www.fda.gov/AnimalVeterinary/Products/AnimalFoodFeeds/PetFood/default.htm).

Food additives

Any substance that is reasonably expected to become a component of food is a food additive that is subject to premarket approval by FDA, unless the substance is generally recognized as safe (GRAS) among experts qualified by scientific training and experience to evaluate its safety under the conditions of its intended use, or meets one of the other exclusions from the food additive definition in section 201(s) of the Federal Food, Drug, and Cosmetic Act (FFDCA). Any food additive that is intended to have a technical effect in the food is deemed unsafe unless it either conforms to the terms of a regulation prescribing its use or to an exemption for investigational use. Otherwise, in accordance with section 409 of the Act, the substance is deemed an unsafe food additive. Any food that contains an unsafe food additive is adulterated under section 402(a)(2)(C) of the FFDCA (www.fda.gov/Food/IngredientsPackagingLabeling/FoodAdditivesIngredients/ucm228269.htm).

Infant formulas

Because infant formula is a food, the laws and regulations governing foods apply to infant formula. Additional statutory and regulatory requirements apply to infant formula, which is often used as the sole source of nutrition by a vulnerable population during a critical period of growth and development. These additional requirements are found in section 412 of the FFDCA and FDA's implementing regulations in 21 CFR 106 and 107. FDA does not approve infant formulas before they can be marketed. However, all formulas marketed in the United States must meet federal nutrient requirements and infant formula manufacturers must notify the FDA prior to marketing a new formula. If an infant formula manufacturer does not provide the elements and assurances required in the notification for a new or reformulated infant formula, the formula is defined as adulterated under section 412(a)(1) of the FFDCA and FDA has the authority to take compliance action if the new infant formula is marketed. FDA has requirements for nutrients in infant formulas, which are located in section 412(i) of the FFDCA and 21 CFR 107.100 (www.fda.gov/food/guidanceregulation/guidancedocumentsregulatoryinformation/infantformula/ucm056524.htm#q2).

Nutrient Content Claims

The Nutrition Labelling and Education Act of 1990 (NLEA) permits the use of label claims that characterize the level of a nutrient in a food (i.e., nutrient content claims) if they have been authorized by FDA and are made in accordance with FDA's authorizing regulations. Nutrient content claims describe the level of a nutrient in the product, using terms such as free, high, and low, or they compare the level of a nutrient in a food to that of another food, using terms such as more, reduced, and light. A summary of the rules for use of nutrient content claims can be found in Chapter VI of The Food Labelling Guide. Examples of nutrient content claims can be found in Appendices A and B (www.fda.gov/Food/IngredientsPackagingLabeling/LabelingNutrition/ucm111447.htm).

Health Claims on Food

Health claims describe a relationship between a food substance (a food, food component, or dietary supplement ingredient), and reduced risk of a disease or health-related condition. Appendix C of The Food Labelling Guide contains a summary of those health claims that have been approved for use on food and dietary supplement labels (www.fda.gov/Food/IngredientsPackagingLabeling/LabelingNutrition/ucm111447.htm).

GOED is still waiting to hear back from FDA on whether or not DHA/EPA will be granted a qualified health claim for reduction of blood pressure. Although FDA has postponed its decision three times and could postpone again, it would be surprising if the agency does not come back with a final decision in 2016.

GOED also continues to hope that EPA/DHA will be selected to undergo an Institute of Medicine (IOM) Dietary Reference Intake (DRI) review (www.nutritionaloutlook.com).

Drug registration

The Federal Food, Drug, and Cosmetic Act requires firms that manufacture, prepare, propagate, compound, or process drugs in the U.S. or that are offered for import into the U.S. to register with the FDA. These domestic and foreign firms must at the time of registration, list all drugs manufactured, prepared, propagated, compounded, or processed for commercial distribution in the U.S. Additionally, foreign establishments must identify a U.S. agent and importers at the time of their registration. Registration information must be renewed annually
(www.fda.gov/Drugs/GuidanceComplianceRegulatoryInformation/DrugRegistrationandListing/default.htm)

Regulation and control of new drugs in the United States has been based on the New Drug Application (NDA). The goals of the NDA are to provide enough information to permit FDA reviewer to reach the following key decisions:

- Whether the drug is safe and effective in its proposed use(s), and whether the benefits of the drug outweigh the risks.
- Whether the drugs proposed labelling (package insert) is appropriate, and what it should contain.
- Whether the methods used in manufacturing the drug and the controls used to maintain the drug's quality are adequate to preserve the drug's identity, strength, quality, and purity.

The documentation required in an NDA is supposed to tell the drug's whole story, including what happened during the clinical tests, what the ingredients of the drug are, the results of the animal studies, how the drug behaves in the body, and how it is manufactured, processed and packaged
(www.fda.gov/Drugs/DevelopmentApprovalProcess/HowDrugsareDevelopedandApproved/ApprovalApplications/NewDrugApplicationNDA/default.htm).

3 Life Cycle Costing (LCC) of Algae-based PUFA production

By Marcel van der Voort

3.1 Goals and scope

The PUFAChain project is aiming to develop and contribute to sustainable PUFA production based on phototrophic algae. The economic analysis consists out of a macro- (Chapter 2) and micro- (this Chapter) economic part. This micro-economic analysis, combined with the macro-economic analysis, should provide insight in the economic viability of a future mature production chain for PUFAs from phototrophic algae. The main goal is to provide insight into the economic sustainability, but there are a few secondary goals:

- Insight in the economic sustainability per scenario
- Insight in the effect of each production chain step on the overall cost price
- Recommendations towards a mature production chain in 2025

The results can be used by project partners of the PUFAChain project to research and implement (technological) improvements or market strategies.

Unlike the LCA part of the sustainability assessment (Keller et al, 2017a), the LCC part will not perform calculations on the competing supply chains (reference systems). Instead the market price of the competing products (reference products) will be used as guideline. The macro-economic analysis (Chapter 2) will provide the market price reference.

3.2 System boundaries

Task 9.1 describes the definitions, settings and system descriptions. More information can be found in the report on the definitions, settings and system descriptions. The Deliverable 9.1 and 9.3 reported in Keller et al, 2017a.

3.3 Methodology

For this micro-economic assessment, the Life Cycle Sustainability Assessment (LCSA) methodology of UNEP/SETAC is used as reference for the approach and methodology. The life cycle assessment (LCA) and life cycle costing (LCC) are related and share the same goals, definitions and settings. The partners within work package 9 (WP9) of the PUFAChain project organized a number of definition & settings meetings during the course of the project. The sustainability assessment in PUFAChain project is aiming for a mature industrial scale production plant by 2025. This plant will produce PUFAs from phototrophic algae: DHA (docosahexaenoic acid), EPA (eicosapentaenoic acid) and SDA (stearidonic acid). The WP9 meetings with partners lead to a set of seven scenarios.

Two main regions will be assessed in six scenarios (Table 14): Southern Europe (region around Lisbon) and Central Europe (region around Munich). In addition, one scenario for Northern Europe (region around Oslo) was added. Either a Conservative performance of 10-hectare (net) area or an Optimistic performance of 100 hectare (net) area is taken into account per regional scenario as size reference. All scenarios are for 2025. The following strains of algae were used for the calculations: *Prorocentrum cassubicum* (SAG 40.80), *Thalassiosira weissflogii* (CCAP 1085/18) and a combination of *Chloridella simplex* (SAG 51.91) and *Raphidonema nivale* Lagerheim (CCCryo 381-11). The potential algae strains were evaluated during the course of the project.

Table 14 Overview of seven scenarios investigated

Location	Algae	Season (days) per strain	Main products
Lisbon	*Prorocentrum*[1)]	All year (330 days)	EPA, DHA & SDA
Lisbon	*Thalassiosira*[1)]	All year (330 days)	EPA, DHA
Lisbon	*Chloridella*[2)]*/Raphidonema*[2)]	Summer (240), winter (90)	EPA
Munich	*Prorocentrum*	All year (330 days)	EPA, DHA & SDA
Munich	*Thalassiosira*	All year (330 days)	EPA, DHA
Munich	*Chloridella/Raphidonema*	Summer (120), winter (210)	EPA
Oslo (100 ha)	*Chloridella/Raphidonema*	Summer (80), winter (250)	EPA

[1)] Seawater strain [2)] Freshwater strain

The LCC is mainly assessing the influence of geography/climate, scale and algae strain on the costs of a potential mature production plant. This analysis leads to more insight whether a potential PUFA supply chain based on phototrophic algae can economically compete with other sources of EPA/DHA.

Within WP9 one common dataset was compiled. The WP9 dataset contains input of all the project partners, especially A4F, Mahle Innowa, NATEX, IOI Cremer and Fraunhofer IZI-BB. This data was either already available at the partners or based on research, pilot and demo tests during the course of the PUFAChain project. The data combined with commercial experience and knowledge of partners are used to make expert judgements on the potential supply chain for 2025, mainly for the 100 ha (Optimistic) scenario. The capital expenditure data were fine-tuned with the Business Case study in WP5 of the PUFA Chain project. The data used in the micro-economic assessment is based on the dataset of July 2017. The Oslo scenario was not part of the WP5 Business Case study. Therefore, the CAPEX values for Oslo are calculated separately and based on extrapolation and expert judgement of the data for Lisbon and Munich.

The micro-economic analysis follows the LCC approach, which assesses the costs within a supply chain related to the life cycle of the product (Swarr et al., 2011). The costs are modelled in a linear way. The capital and operational costs of all separate supply chain steps for producing EPA/DHA from different algae strains are taken into account. This results in a cost price per kg EPA/DHA (functional unit). The cost prices or costs used represent the actual market prices needed. Therefore, the final cost prices reflect the total (gross) value added throughout the supply chain (Hunkeler et al., 2008).

To create a common basis for all scenarios the following assumptions/starting points were decided on: All equipment needed, including the land, are purchased. No interest costs of the capital expenditures are included, except for the land needed. There is no life expectancy (no depreciation period) implemented on the land purchased for the production and processing site(s). This in accordance with IFRS guidelines (www.ifrs.org). Other capital expenditures have a linear depreciation for their life expectancies. All capital expenditures are depreciated to nil due to the large uncertainties and tailor-made solutions implemented.
The operational expenses are based on the values, e.g. for electricity, of the WP9 dataset and current market prices. Disposal costs of waste and waste water are included. For all relevant scenarios the required saltwater is produced by adding salt to freshwater. Therefore, no purified seawater is applied for the salt water algae strains.

Although the LCC is modelling an industrial scale production for 2025, current cost prices are used. Therefore, future increases in labour and other costs per region or scenario have not been taken into account. The same is applied on all operational expenditures.

As mentioned above a great deal of uncertainty is connected to the modelling of an industrial scale production for PUFAs based on phototrophic algae. New developments in for example technology, biology, economy, environment and social perceptions could influence the outcome significantly. The modelling is done with the research questions as starting point. This micro-economic assessment should not be interpreted as an actual business case.

3.4 Descriptions for the life cycle costing of PUFAChain

This paragraph highlights the most significant settings used for the LCC per process step.

3.4.1 Algae strains, crop rotation and cultivation process

The PUFAChain focuses on the phototrophic cultivation of microalgae in fresh or saltwater media. The algae cultivation system was assessed during the course of the PUFAChain project in WP3 and WP4. The cultivation system selected is an Unilayer Horizontal Tubular Photo BioReactor (UHT-PBR).
The algae cultivation process consists of the following steps:

- Culture medium preparation
- Inoculation of small flasks (with LED lighting)
- Green wall panels (several litres to m^3)
- Production in UHT-PBRs
- Semi-continuous cultivation with periodic partial harvests

For the *Chloridella*/*Raphidonema* option a rotation in algae strains between seasons is included based on their temperature optima. CAPEX values per installation and scenario are based on the WP5 data of partner A4F, dataset of July 2017. All CAPEX values are calculated per year, based on the life-expectancy. The OPEX and production values were also calculated per year.
The production and processing installations and equipment consists out of the following items.

- Offices, warehouse and workshop
- Laboratories
- Control and electrical systems
- Civil engineering
- Licencing, EPC and contractor costs
- Water treatment systems
- Nutritive medium preparation systems
- Production systems
- Thermo-regulation system
- Effluents and medium recycling

Land area needed for the production facilities is included in the calculations. The hectares mentioned in each scenario are net (photosynthetic) area. Per scenario the area needed is increased by 35 % to achieve a viable estimate of total production area needed. Additional/auxiliary processes at the production location, harvesting, drying and cell disruption also require space. Of the 35 % additional space 20 % is expected at the algae production site and 15 % for the extraction and oil processing site. The land prices used are based on current real estate prices for industrial area. The current price levels of real estate are taken. This approach simulates a project were an investor purchases industrial area for realizing PUFA production based on algae. Due to rising real-estate prices, this approach negatively influences the outcome. Other options could benefit the scenarios significantly, mainly due to the high share in CAPEX of land costs (see Table 15). These options could be brownfield sites, and/or an investor already has land available.

3.4.2 Calculated algae cultivation values

The production is the most significant supply chain step in costs. The calculated results specific for the algae production are stated below. The calculated values for the CAPEX are stated, including the share of the two most significant cost elements. For the OPEX the calculated values are stated, including the share of all cost elements.

Table 15 Calculated CAPEX values for infrastructure/installations (in EUR/year) used per scenario including the share of the two main cost items (EUR/year)

	Southern		Central		Northern
Value/Scenario	**10 ha**	**100 ha**	**10 ha**	**100 ha**	**100 ha**
CAPEX (EUR/year)	2,646,287	24,590,861	3,146,253	29,506,076	41,356,705
UHT-PHR installation (%)	17%	15%	15%	13%	10%
Land (%)	71%	76%	74%	79%	84%

The calculated OPEX costs are discussed in the following three paragraphs. This to highlight geographical differences.

3.4.2.1 Calculated OPEX values of algae cultivation for Southern Europe

The intermediate results for the OPEX give an insight in the most significant cost elements for PUFA production for Southern Europe. All Southern Europe scenarios give the same costs elements that contribute the most in the OPEX. These are labour, water, electricity and CO_2.

Table 16 Production values *Prorocentrum cassubicum, Thalassiosira weissflogii* and the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Southern Europe (Conservative and Optimistic performance) per year

Value for:	***Prorocentrum cassubicum***		***Thalassiosira weissflogii***		***Chloridella/ Raphidonema***	
Scenario	**10 ha**	**100 ha**	**10 ha**	**100 ha**	**10 ha**	**100 ha**
OPEX	2,830,200	35,227,500	2,302,000	25,866,600	2,456,700	31,523,100
Nutrients	3%	2%	3%	3%	1%	1%
CO_2	8%	7%	9%	9%	1%	1%
Water	23%	19%	29%	26%	26%	20%
Silicates	1%	0%	1%	1%	0%	0%
Salt	2%	2%	3%	3%	0%	0%
Electricity	9%	7%	15%	13%	10%	9%
Waste	1%	1%	2%	2%	2%	1%
O&M costs	4%	3%	5%	5%	5%	4%
Labour costs	49%	58%	33%	39%	57%	65%

3.4.2.2 Calculated OPEX values of algae cultivation for Central Europe

The intermediate results for the OPEX give an insight in the most significant cost elements for PUFA production for Central Europe. All Central Europe scenarios give the same costs elements that contribute the most in the OPEX. These are labour, water, electricity and CO_2. The production parameters for *Prorocentrum cassubicum* and *Thalassiosira weissflogii* were nearly identical. As a result, the calculated results are also identical for both algae strains.

Table 17 Production values *Prorocentrum cassubicum, Thalassiosira weissflogii* and the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Central Europe (Conservative and Optimistic performance)

Value for:	***Prorocentrum cassubicum***		***Thalassiosira weissflogii***		***Chloridella/ Raphidonema***	
Scenario	**10 ha**	**100 ha**	**10 ha**	**100 ha**	**10 ha**	**100 ha**
OPEX	2,009,950	27,332,700	2,009,950	27,332,700	1,714,950	24,198,450
Nutrients	3%	2%	3%	2%	3%	3%
CO_2	7%	6%	7%	6%	4%	3%
Water	2%	2%	2%	2%	3%	3%
Silicates	1%	0%	1%	0%	0%	0%
Salt	2%	2%	2%	2%	0%	0%
Electricity	18%	13%	18%	13%	15%	10%
Waste	6%	5%	6%	5%	2%	2%
O&M costs	6%	5%	6%	5%	7%	6%
Labour costs	56%	65%	56%	65%	65%	74%

3.4.2.3 Calculated OPEX values of algae cultivation for Northern Europe

The intermediate results for the OPEX give an insight in the most significant cost elements for PUFA production using the Optimistic ACR scenario for Northern Europe. The ACR option for *Chloridella/ Raphidonema* shows differences per scenario. The Southern Europe scenario shows a high water need compared to Central and Northern Europe. The Northern Europe scenario shows the lowest inputs except for the labour needed. The labour costs are more or less fixed. The inputs needed such as water, electricity and CO_2 are related to the algae biomass produced. The amounts of algae biomass produced change per scenario for all strains. For *Chloridella/Raphidonema* the difference between the Optimistic performance scenarios for Southern Europe (about 2,900 kg yield) and Central Europe (about 2,100 kg yield) were small compared to the other two strains. The Northern Europe scenario produced about 1,600 kg of algae biomass. Since inputs are strongly related to yields, this indicates the differences between the European regions.

Table 18 Production values for the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Northern Europe (Optimistic performance)

Value for:	***Chloridella/ Raphidonema***
Scenario	**100 ha**
OPEX	26,489,369
Nutrients	1%
CO_2	2%
Water	1%
Silicates	0%
Salt	0%
Electricity	7%
Waste	5%
O&M costs	7%
Labour costs	77%

3.4.3 Settings and descriptions further PUFA supply chain steps

The supply chain steps from production to oil processing are taken into account for this micro-economic assessment. After production the steps of harvesting, cell disruption, drying, extraction and oil processing are incorporated. Below the most significant settings and process descriptions are stated.

3.4.3.1 Algae harvesting, cell disruption and drying settings and description

The algae harvesting is done by membrane concentration including filtration. The osmotic shock method for cell disruption of the algae strains *Prorocentrum* and *Thalassiosira* is applied. The cell disruption method for *Chloridella* and *Raphidonema* is bead milling. Data on bead milling was not available within the PUFAChain project and were taken from the EnAlgae project (Kenny et al., 2015, derived from Balasundaram et al., 2012). There is no differentiation per algae strain in installation size.

All filtration, diafiltration and drying equipment is assumed to have a depreciation period of 10 years. The harvesting of the microalgae by membrane filtration (Mahle Innowa) has been tested in practice in WP 4 in a pilot scale set-up. The data on concentration and diafiltration are made available by project partners A4F and Mahle Innowa. All strains need cell disruption as mentioned above. The algae paste is dried by spray-drying in all scenarios. During data collection and initial calculations, the disruption efficiency proved to be a significant factor. Supercritical CO_2-extraction was able to extract nearly all algae oil from the biomass. The previous step of cell disruption determines the efficiency of successive steps. The yield in EPA/DHA is therefore influenced significantly by the efficiency of cell disruption and also by losses during drying and harvesting. The biomass produced is a starting point for the further supply chain steps. The biomass yield influences for example the energy demand for further processing. The difference in algae biomass yield per scenario/geographical location is therefore a significant factor for inputs needed further down in the supply chain.

3.4.4 Algae Biomass processing

Processing of the algae biomass is done in a two-step process. The first step is supercritical CO_2-extraction, followed by processing of the extracted oil to obtain the PUFAs. The production, harvesting, cell disruption and drying are all assumed to be at the production location of the algae. In the scenarios the geographical locations Southern Europe (Lisbon area), Central Europe (Munich area) and Northern Europe (Oslo area) were used as reference. Supercritical CO_2-extraction and further processing of the oil are assumed to take place at a central location in Germany for all locations/scenarios. As such, transportation is needed from the production location to the extraction and processing location.

As mentioned above cell disruption degree determines to a significant extent the efficiency of the supercritical CO_2-extraction. The same is true for losses during purification, since these parameters directly influence the yield in kilogram EPA/DHA/SDA (Functional Unit).

The data on extraction an oil processing is collected within WP9 and provided by project partners NATEX and IOI Oleochemical. The processes include extraction of oil from the algae biomass, PUFA concentration and separation and downstream processing. The IOI Oleochemical location In Central Germany is taken as reference for example for the land costs. The amount of land needed for processing is estimated at 20% of the net area of production per scenario. The location is the same for all scenarios, including the prices of land and installations. There is difference in CAPEX per scenario for extraction and oil processing. This difference is based on the expected produced amounts of algae biomass. The CAPEX is a static number in the modelling. The changes in volumes produced do not change the size of the installation.

Supercritical CO_2-extraction of algae biomass results in two main products: Algae oil containing the desired PUFAs and a dry powder high in polysaccharides. The by-products also contain protein. Potential uses of the by-product(s) have not been evaluated in WP9.4. An option is to use the by-products as feedstock for anaerobic digestion. Although it is expected that the by-product could be used higher up in the value pyramid, e.g. for food or feed (Chapter 2) in the near future.

3.4.4.1 Prices and price quotations

The CAPEX and OPEX costs are determined as specific as possible for each scenario/geographical location. Price quotations for the industrial area are taken from listings of real estate agents. Hourly wages for labour are primarily based on statistical data combined with labour market reports per geographical location. All other operational costs are provided by price quotations of potential suppliers.

3.4.5 Calculated costs of the total supply chain

The calculations give an indication on the economic viability of a potential supply chain of PUFAs based on phototrophic algae. The figures included below state the relation between the supply chain steps. The CAPEX and OPEX are separated for clarity per supply chain step. The production is for all strains, Conservative or Optimistic performance and region the most significant element in costs. The CAPEX and OPEX are stated below for the whole supply chain. The next paragraph will the results per Functional Unit.

The calculated results of the Southern Europe Optimistic scenarios are taken as example. This to visualise the share of each of the supply chain step within the total costs. The proportions of other scenarios/geographical locations are not identical, but do show much similarity. Therefore, only the Southern Europe Optimistic scenarios are taken as example. The results for all scenarios per Functional Unit are stated in the next Chapter 3.5.

These results signal a few important aspects in consideration of realising a PUFA supply chain of phototrophic algae. The CAPEX and OPEX of production of algae are strongly influencing the competitiveness of the overall supply chain. The figures below provide insight for business partners to focus improvements on relevant supply chain steps.

The figures show that the CAPEX is mainly determined by the cultivation/production CAPEX. The OPEX is mainly production, but also the costs for drying are a significant cost element in the OPEX. The concentration/filtration and cell disruption combined are for *Chloridella* and *Raphidonema* a significant cost element in OPEX. The additional need for bead milling adds to the cost for this supply chain step. Another capital-intensive supply chain step is the Oil Processing. The CAPEX is, as mentioned, fixed to the size determined per scenario. The difference per strain are therefore limited.

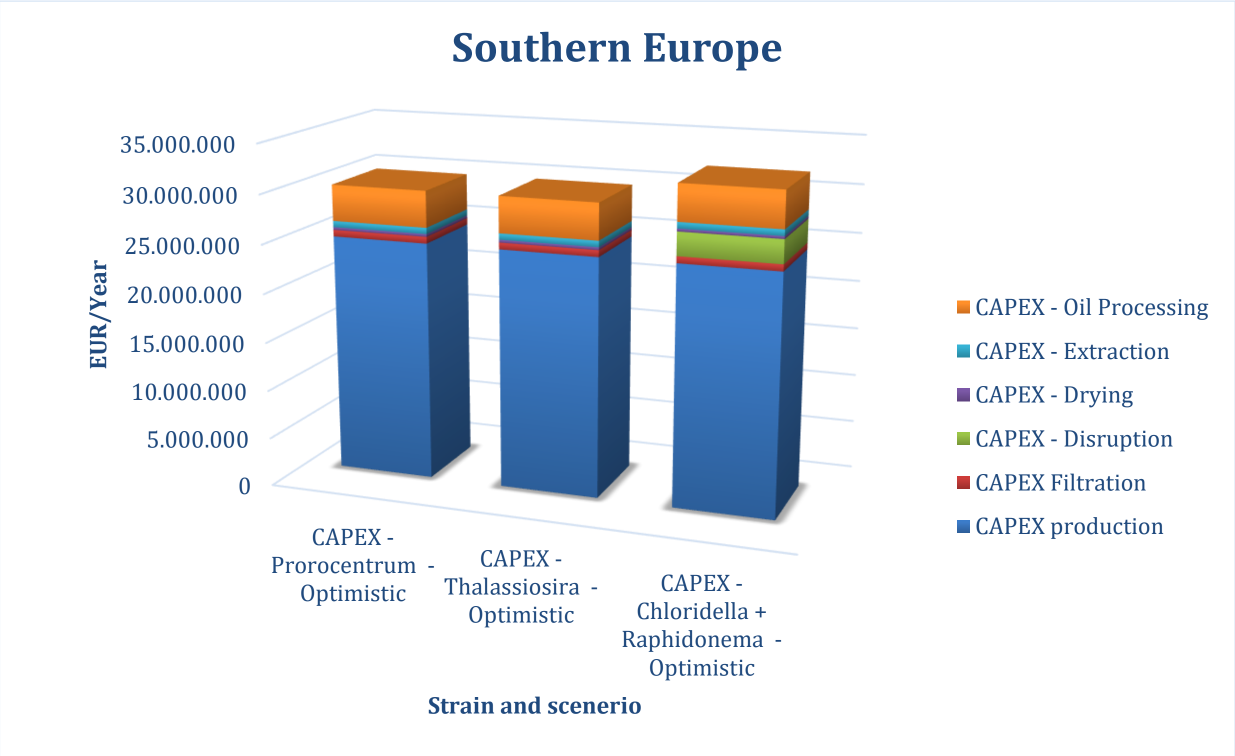

Figure 32 CAPEX for each of the three strains of the Optimistic performance scenario for Southern Europe

The OPEX varies per strain. In the Optimistic performance for Southern Europe the Thalassiosira strain has the lowest inputs and therefore costs. The Prorocentrum strain has higher OPEX cost, but a significantly higher yield. The next paragraph will state results based on the Functional Unit of kilogram EPA/DHA.

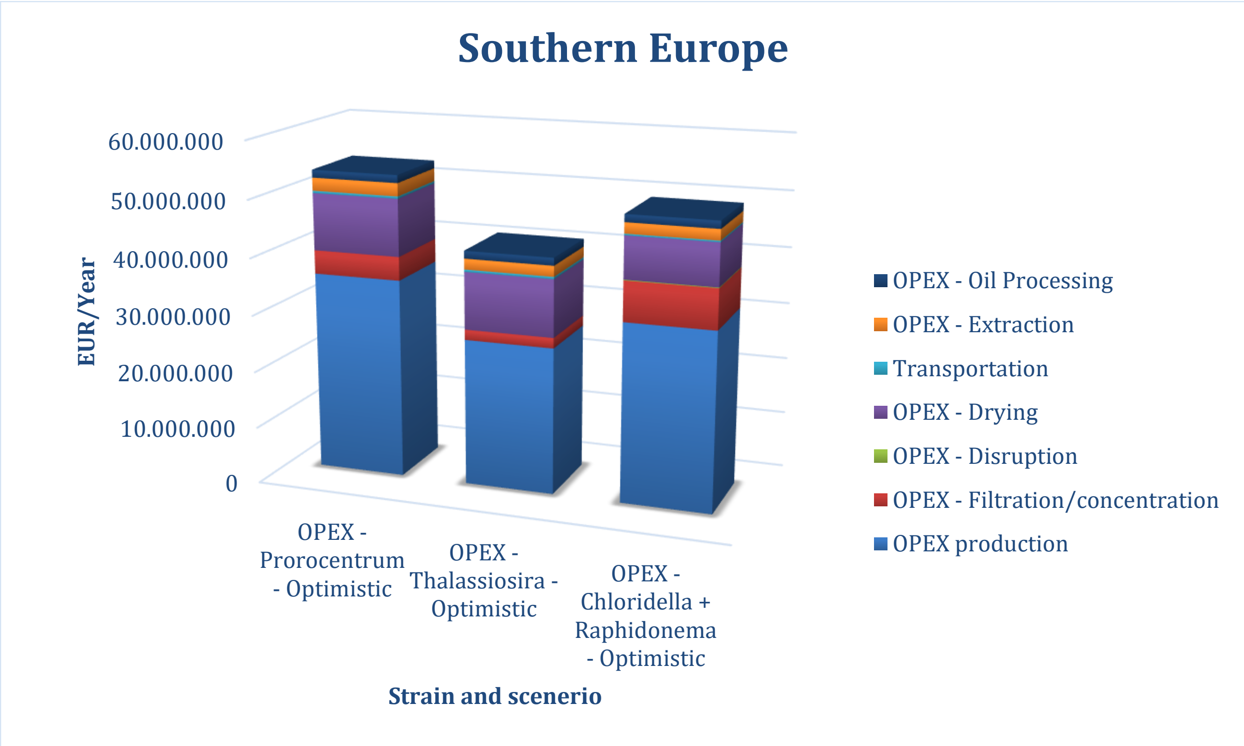

Figure 33 OPEX for each of the three strains of the Optimistic performance scenario for Southern Europe

3.5 Life Cycle Costs Assessment

3.5.1 General remarks

The CAPEX is based on a fixed set of installations per area size/scenario. The same approach was used for a number of OPEX cost units, such as Operation and Maintenance costs and labour. An actual supply chain in 2025 would probably be designed more specific for each type of algae strain used. As such the modelling is a prediction based on current knowledge, experience and data. A secondary goal of the LCC modelling was to inform the partners within the PUFAChain project on the most relevant costs and their influence on the overall PUFA supply chain performance.

The costs of land are incorporated in the model. The current real-estate prices of industrial area for Lisbon, Munich and Oslo were used. The reason for this remark is that all regions are (the most) expensive regions per country concerned. The costs for industrial land are therefore high compared to other regions within the same country. The location in alternative areas/locations in the vicinity of these cities could provide better options for an economically viable PUFA supply chain in 2025.

3.5.2 Results of the Life Cycle Costing

The algae supply chain is calculated from production of resources to end product (algae production and processing, algae harvesting, cell disruption and drying and algae biomass processing by supercritical CO_2-extraction and oil processing). This results in a cost price per kg EPA/DHA (functional unit) for each production scenario. As reference the market values of competing products ('reference products') are taken. The global market volume for omega-3 PUFA was around 115,000 MT in 2012 (Industry Experts, 2014). Market segments are dietary supplements, pet food, food & beverages, infant nutrition, pharmaceuticals and clinical nutrition (Table 2). Price ranges for dietary supplements based on algae or fish oil are around €400 – €1,500 per kg EPA/DHA and up to € 5,500 per kg for pure DHA (Industry Experts, 2014) (Chapter 2.6.8). This price range represents an end-user price. The actual business to business price range is expected to be lower.

3.5.2.1 Overall results of scenarios

A number of scenarios fall within the stated price range of €400 – €1,500 per kg EPA/DHA. Only four scenarios fall outside this range. A number of potential improvements are discussed in Chapter 3.7.

Table 19 Cost price EPA/DHA/SDA (€/kg) per scenario

Scenario	Conservative (10 ha)	Optimistic (100 ha)
South (Prorocentrum)	848	704
South (Thalassiosira)	1359	468
South (Chloridella + Raphidonema)	1156	932
Central (Prorocentrum)	1196	997
Central (Thalassiosira)	2058	753
Central (Chloridella + Raphidonema)	2344	1915
North (Chloridella + Raphidonema)		3903

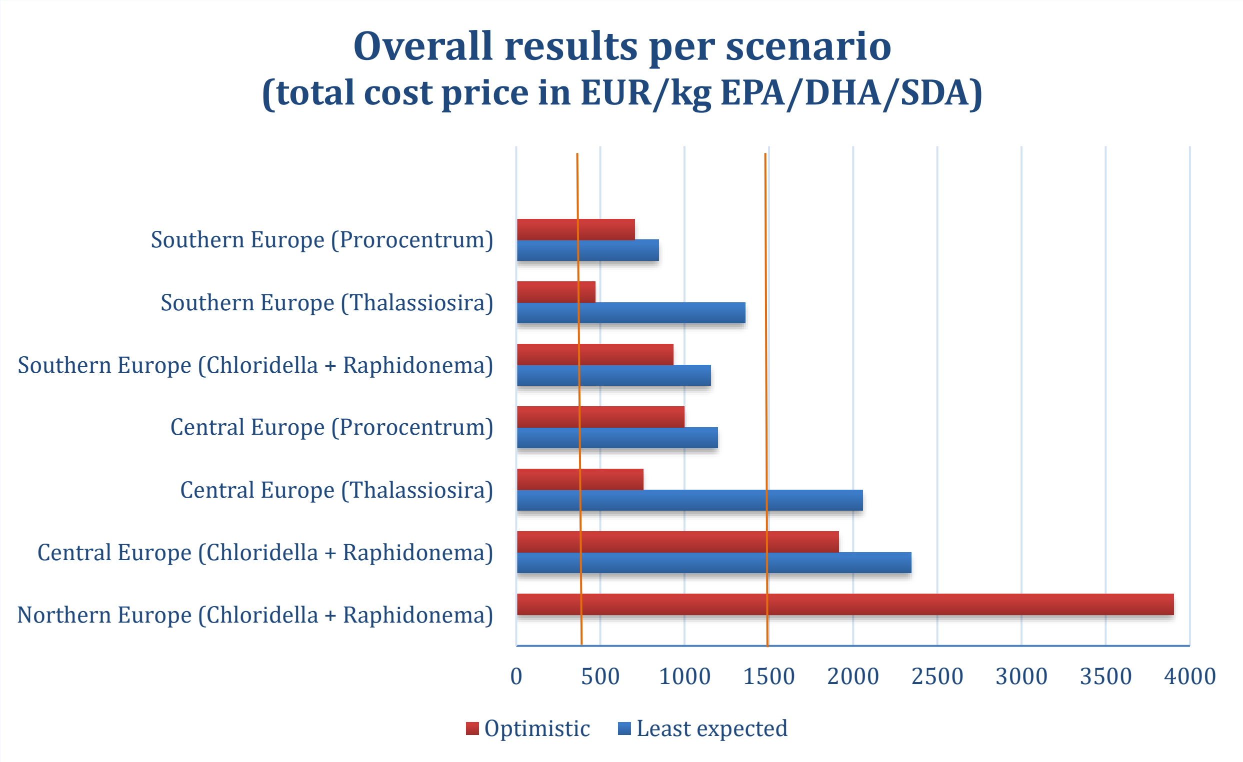

Figure 34 Overall results in cost price EPA/DHA/SDA (€/kg) per region, algae strain for the Conservative and Optimistic performance scenarios (including market price range)

3.5.2.2 Results for Southern Europe

All costs were calculated per Functional Unit (FU) per year. The FU in this case is the amount of EPA/DHA/SDA produced in kilogram. All calculations combined give an overall result for the whole supply chain per algae strain, scenario and location. In addition to the overall results, the share of each step in the supply chain in the overall costs is given.

The *Prorocentrum cassubicum* strain is a supplier of EPA, DHA and SDA. This saltwater algae is produced all year (330 days). The *Prorocentrum cassubicum* is an interesting algae strain, especially in the Conservative scenario for Southern Europe. The lower performance of *Prorocentrum cassubicum* for the Optimistic performance scenarios for Southern Europe is due to the lower oil content compared to *Thalassiosira weissflogii*. This combined with the scale of production results in significant differences.
The *Prorocentrum cassubicum* strain has the best results of this study for the Conservative performance scenario for Southern Europe.

Table 20 LCC outcome for production of *Prorocentrum* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*	
Scenario	**10 ha**	**100 ha**
Cost price EPA/DHA/SDA (€/kg)	848	704
Total costs of supply chain (€/year)	8,237,089	83,449,152
Total CAPEX (€/year)	*3,278,520*	*29,917,094*
Total OPEX (€/year)	*4,958,569*	*53,532,058*

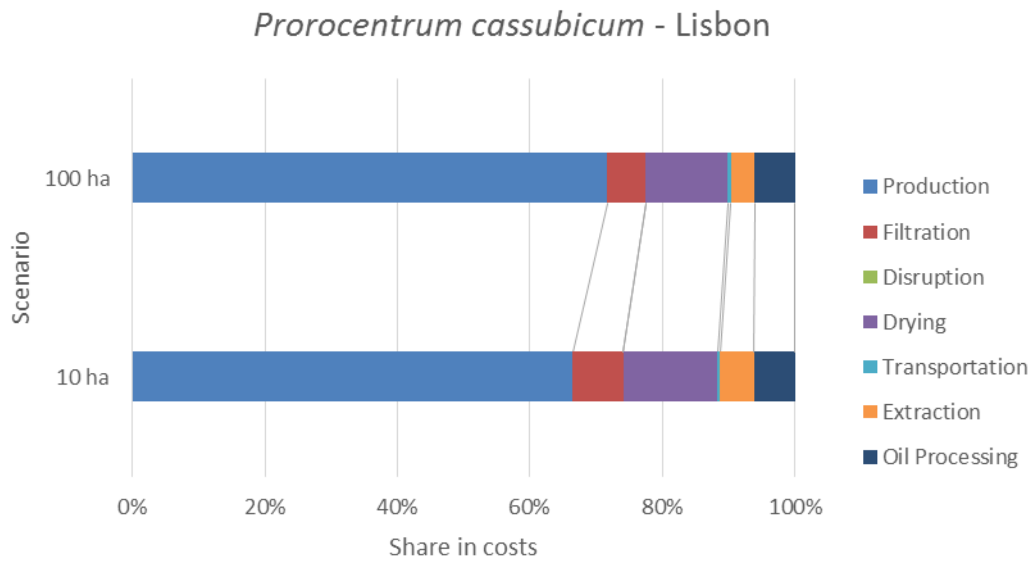

Figure 35 Cost components of PUFA production from *Prorocentrum cassubicum* in Southern Europe (Conservative and Optimistic performance scenario)

The *Thalassiosira weissflogii* strain is a supplier of EPA and DHA. This saltwater algae is produced all year (330 days). As mentioned above *Thalassiosira weissflogii* performs well in the Optimistic performance scenario for Southern Europe. The scale of production and higher oil content favour the *Thalassiosira* strain. The lower inputs and thus lower OPEX needed complement the results of *Thalassiosira* further.
The *Thalassiosira* strain in the Optimistic performance scenario for Southern Europe has the best results of this study. Even so the Thalassiosira in the Conservative performance scenario (10 ha) fall also within the market price range. Although it is on the high end of the price range.

Table 21 LCC outcome for production of *Thalassiosira* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Thalassiosira weissflogii*	
Scenario	**10 ha**	**100 ha**
Cost price EPA/DHA (€/kg)	1,359	468
Total costs of supply chain (€/year)	7,454,621	71,327,122
Total CAPEX (€/year)	*3,278,520*	*29,917,094*
Total OPEX (€/year)	*4,176,101*	*41,410,028*

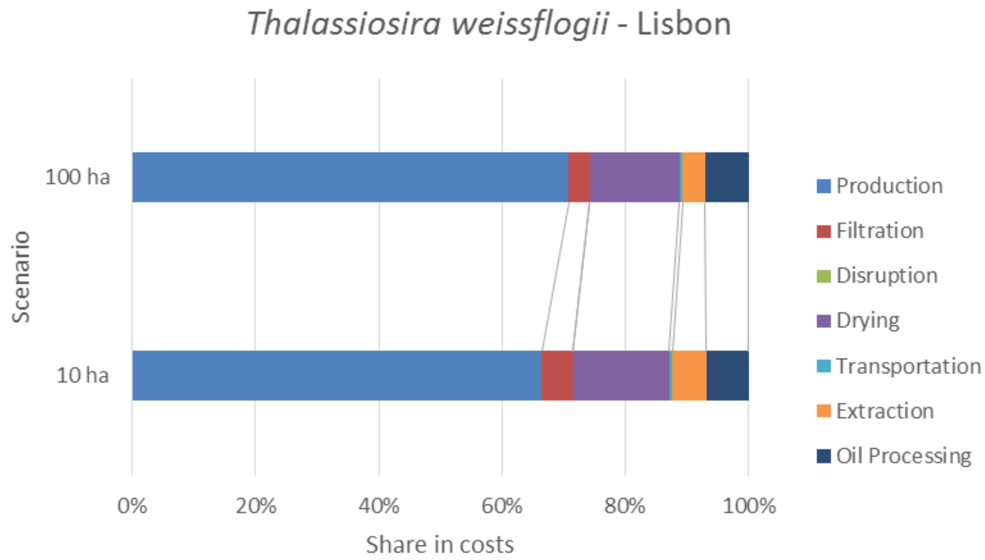

Figure 36 Cost components of PUFA production from *Thalassiosira weissflogii* in Southern Europe (Conservative and Optimistic performance scenario)

The *Chloridella/Raphidonema* strains are suppliers of EPA. These are freshwater algae and are produced as ACR option. For Southern Europe *Chloridella* is produced during summer (240 days) and *Raphidonema* during winter (90 days). The ACR option was research to assess for example effects of cultivation of strains during suitable conditions regarding light, temperature, etc. The *Chloridella/ Raphidonema* strains fall within the market price range reference. Although the *Chloridella/Raphidonema* strains are out-performed by the *Prorocentrum* and *Thalassiosira* strains for Southern Europe in both performance scenarios.

Table 22 LCC outcome for production of *Chloridella/Raphidonema* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Chloridella/Raphidonema*	
Scenario	**10 ha**	**100 ha**
Cost price EPA (€/kg)	1,156	932
Total costs of supply chain (€/year)	8,212,784	81,887,957
Total CAPEX (€/year)	*3,495,880*	*32,299,694*
Total OPEX (€/year)	*4,716,904*	*49,588,264*

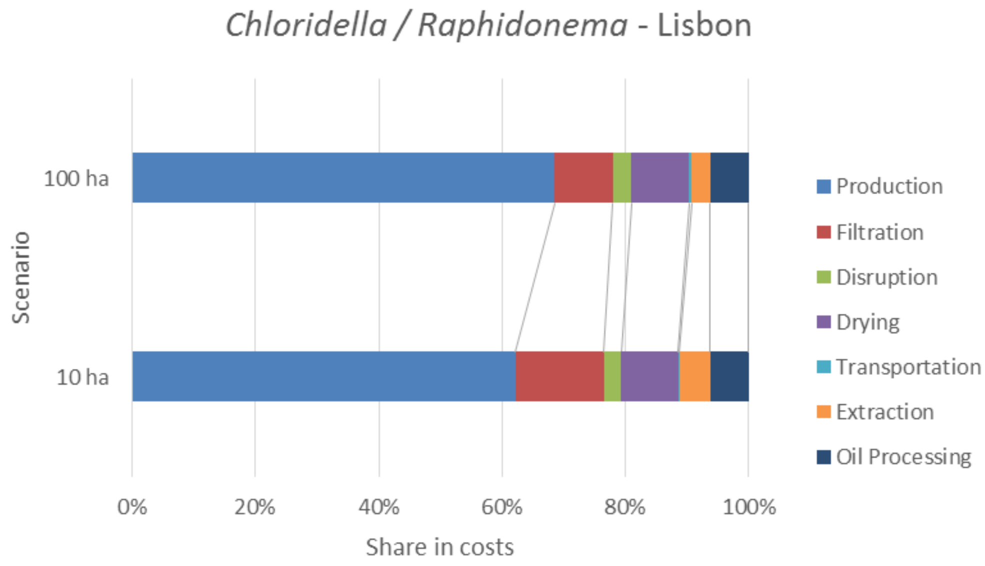

Figure 37 Cost components of PUFA production from *Chloridella/Raphidonema* in Southern Europe (Conservative and Optimistic performance scenario)

3.5.2.3 Results for Central Europe

All costs were calculated per Functional Unit (FU) per year. The FU in this case is the amount of EPA/DHA produced in kilogram. All calculations combined give an overall result for the whole supply chain per algae strain, scenario and location. The results for Central Europe are calculated in a similar way with scenario specific data for the region and production. All data combined result in costs for the whole supply chain per algae strain, scenario and location. The share of each step in the overall supply chain costs is also shown.

Due to higher costs and lower production all performance scenarios and strain for Central Europe perform less than the Southern Europe scenarios. Although a number of Central Europe scenarios do perform within the market price range used. The both performance scenarios for *Prorocentrum* for Central Europe are within the market price range. This is also the case for *Thalassiosira* in the Optimistic Performance scenario for Central Europe.

Table 23 LCC outcome for production of *Prorocentrum* in Central Europe (Conservative and Optimistic performance scenario)

	Values for ***Prorocentrum cassubicum***	
Scenario	**10 ha**	**100 ha**
Cost price EPA/DHA/SDA (€/kg)	1,196	997
Total costs of the supply chain (€/year)	7,747,592	78,797,255
Total CAPEX (€/year)	*3,637,655*	*33,256,119*
Total OPEX (€/year)	*4,109,936*	*45,541,136*

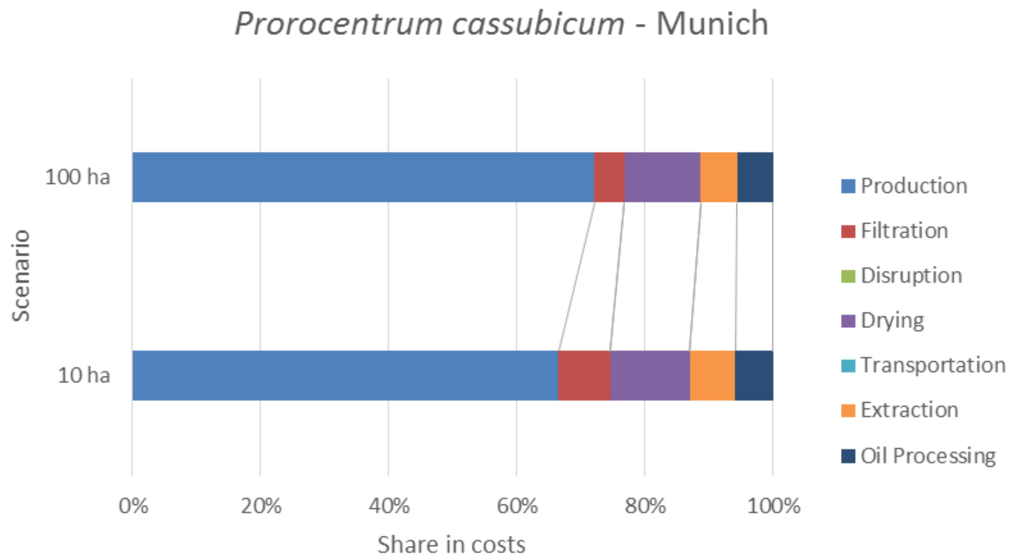

Figure 38 Cost components of PUFA production from *Prorocentrum cassubicum* in Central Europe (Conservative and Optimistic performance scenario)

The *Thalassiosira weissflogii* strain is a supplier of EPA and DHA. This saltwater algae is produced all year (330 days). As mentioned above the *Thalassiosira* in the Optimistic Performance scenario for Central Europe falls within the market price range.

Table 24 LCC outcome for production of *Thalassiosira* in Central Europe (Conservative and Optimistic performance scenario)

	Values for *Thalassiosira weissflogii*	
Scenario	**10 ha**	**100 ha**
Cost price EPA/DHA (€/kg)	2,058	753
Total costs of the supply chain (€/year)	7,523,964	76,549,562
Total CAPEX (€/year)	*3,637,655*	*33,256,119*
Total OPEX (€/year)	*3,886,308*	*43,293,443*

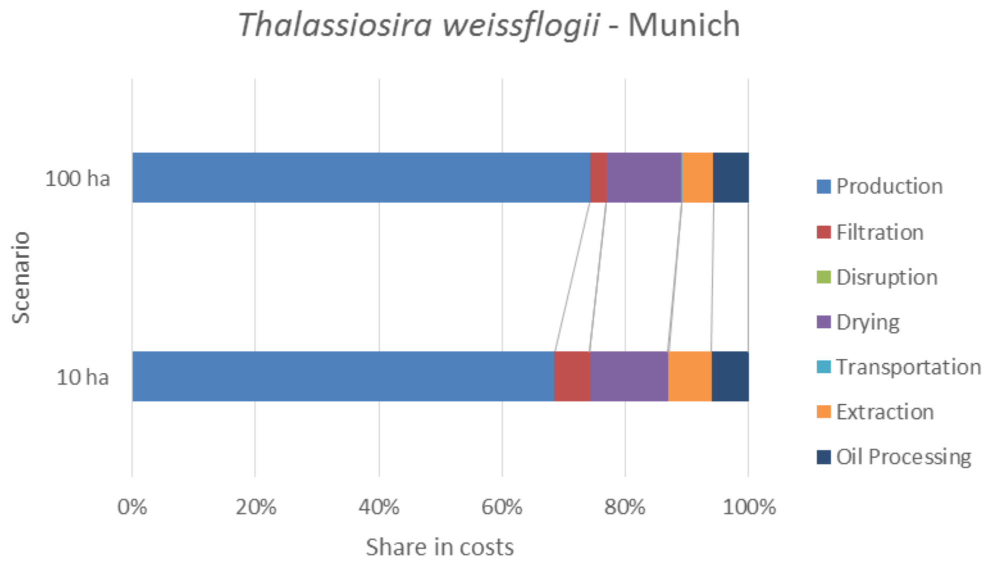

Figure 39 Cost components of PUFA production from *Thalassiosira weissflogii* in Central Europe (Conservative and Optimistic performance scenario)

The *Chloridella/Raphidonema* strains are suppliers of EPA. These are freshwater algae and are produced as ACR option. For Central Europe *Chloridella* is produced during summer (140 days) and *Raphidonema* during winter (190 days). This is based on the temperature and light intensity for Central Europe in regard to the strains cultivated.

The *Chloridella/Raphidonema* strains fall outside the market price range reference. The *Chloridella/Raphidonema* strains are for Central Europe out-performed by the *Prorocentrum* and *Thalassiosira* strains in both performance scenarios. This is mainly due to a lower biomass yield.

Table 25 LCC outcome for production of *Chloridella/Raphidonema* in Central Europe (Conservative and Optimistic performance scenario)

	Values for ***Chloridella/Raphidonema***	
Scenario	**10 ha**	**100 ha**
Cost price EPA (€/kg)	2,344	1,915
Total costs of the supply chain (€/year)	7,651,590	77,246,371
Total CAPEX (€/year)	*3,804,855*	*34,986,639*
Total OPEX (€/year)	*3,846,734*	*42,259,732*

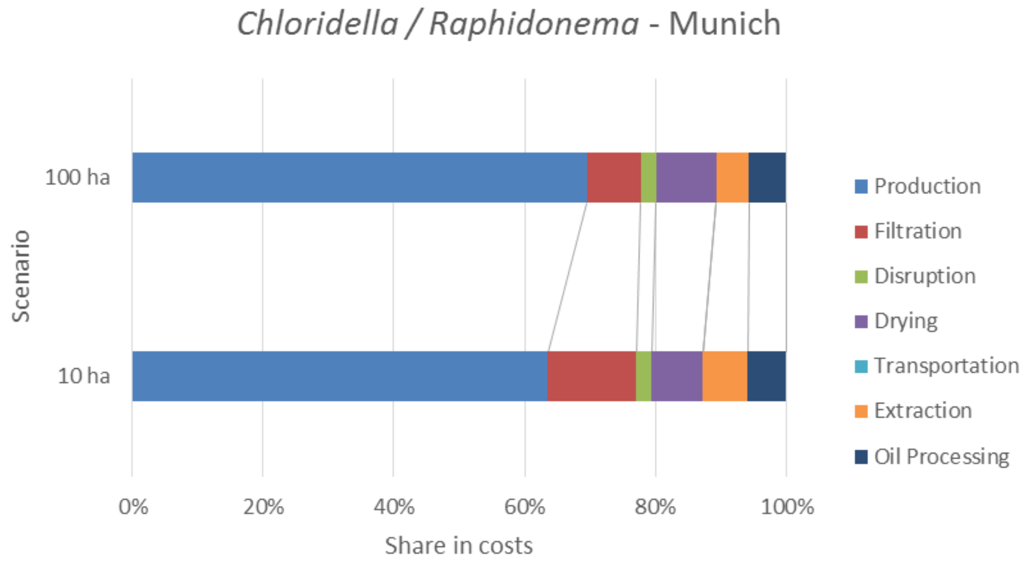

Figure 40 Cost components of PUFA production from *Chloridella/Raphidonema* in Central Europe (Conservative and Optimistic performance scenario)

3.5.2.4 Results for Northern Europe

The scenario for the Northern Europe (Oslo region) was only calculated for *Chloridella/Raphidonema* in the Optimistic performance scenario (100 hectare). The results for Oslo region are calculated in a similar way with scenario specific data for the region and production. All calculations combined result in costs for the whole supply chain. The share of each step in the overall supply chain costs is also shown.

The Northern Europe scenario was added to the Southern and Central Europe scenarios. As mentioned in the settings the *Chloridella/Raphidonema* strain could perform well in colder temperature and lower light intensity conditions. The *Chloridella/Raphidonema* strains are suppliers of EPA. These are freshwater algae and they are produced as ACR option. For Northern Europe *Chloridella* is produced during summer (80 days) and *Raphidonema* during winter (250 days). This is based on the temperature and light intensity for Northern Europe in regard to the strains cultivated.

Table 26 LCC outcome for production of *Chloridella/Raphidonema* in Northern Europe (Optimistic performance)

	Values for *Chloridella/Raphidonema*
Scenario	**100 ha**
Cost price EPA (€/kg)	4,017
Total costs of the supply chain (€/year)	85,825,759
Total CAPEX (€/year)	*45,351,967*
Total OPEX (€/year)	*40,473,792*

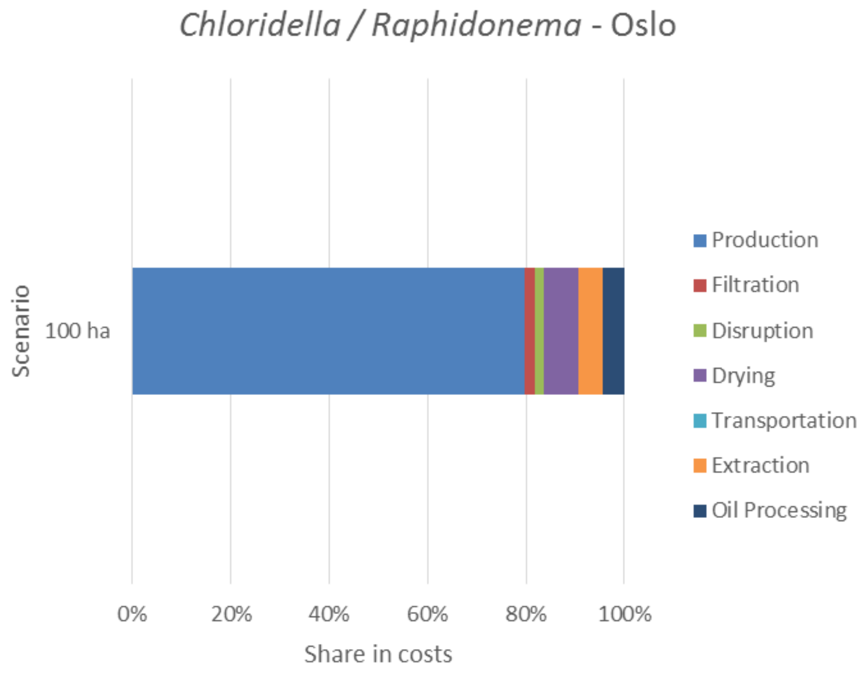

Figure 41 Cost components of PUFA production from *Chloridella/Raphidonema* in Northern Europe (Optimistic performance)

3.5.3 The results of biomass cultivation as cost price

To assess the performance per scenario the results of the cost price per kilogram dry weight biomass are calculated. The cultivation/production of algae is the most significant cost element, for CAPEX and OPEX. The dry weight biomass is not the Functional Unit within this research. The assessment is mainly related to the performance of the strains, performance scenarios and region for the cultivation/production.

3.5.3.1 Assessment of biomass cost price in Southern Europe

In table 27 the total costs (CAPEX and OPEX) combined with the produced dried algae biomass results in a potential cost price for algae biomass in Southern Europe. The results are based on the settings mentioned above for a potential mature supply chain for 2025.

Table 27 Biomass cost price for *Prorocentrum cassubicum, Thalassiosira weissflogii* and the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Southern Europe (Conservative and Optimistic performance)

Value for:	***Prorocentrum cassubicum***		***Thalassiosira weissflogii***		***Chloridella/ Raphidonema***	
Scenario	**10 ha**	**100 ha**	**10 ha**	**100 ha**	**10 ha**	**100 ha**
CAPEX (EUR/year)	2,770,720	25,558,004	2,770,720	25,558,004	2,988,080	27,940,604
OPEX (EUR/year)	4,500,615	49,458,927	3,726,830	37,757,253	4,283,106	46,067,119
Total Costs year (Production - drying)	7,271,334	75,016,931	6,497,550	63,315,257	7,271,186	74,007,722
Algae dried biomass (DW kg/year)	356,307	4,086,052	356,307	4,086,052	228,131	2,671,290
Algae biomass cost price (€/kg)	20.41	18.36	18.24	15.50	31.87	27.70

The algae cultivation costs make up a significant part of the overall supply chain. The assessment of the cost price for cultivation of algae could provide valuable insight in economic effects of improvement options. This specifically for cultivation of algae biomass.

3.5.3.2 Assessment of biomass cost price in Central Europe

In table 28 the total costs (CAPEX and OPEX) combined with the produced dried algae biomass results in a potential cost price for algae biomass in Central Europe. The results are based on the parameter mentioned above for a potential mature supply chain for 2025.

Table 28 Biomass cost price for *Prorocentrum cassubicum, Thalassiosira weissflogii* and the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Central Europe (Conservative and Optimistic performance)

Value for:	***Prorocentrum cassubicum***		***Thalassiosira weissflogii***		***Chloridella/ Raphidonema***	
Scenario	**10 ha**	**100 ha**	**10 ha**	**100 ha**	**10 ha**	**100 ha**
CAPEX (EUR/year)	3,262,375	30,212,389	3,262,375	30,212,389	3,429,575	31,942,909
OPEX (EUR/year)	3,478,202	39,683,358	3,277,921	38,010,785	3,242,314	36,996,756
Total Costs year (Production - drying)	6,740,577	69,895,747	6,540,297	68,223,174	6,671,890	68,939,665
Algae dried biomass (DW kg/year)	237,533	2,724,034	237,533	2,724,034	165,399	1,936,735
Algae biomass cost price (€/kg)	28.38	25.66	27.53	25.04	40.34	35.60

The algae cultivation costs make up a significant part of the overall supply chain. The assessment of the cost price for cultivation of algae could provide valuable insight in economic effects of improvement options. This specifically for cultivation of algae biomass.

3.5.3.3 Assessment of biomass cost price in Northern Europe

In table 47 the total costs (CAPEX and OPEX) combined with the produced dried algae biomass results in a potential cost price for algae biomass in Northern Europe. The results are based on the parameter mentioned above for a potential mature supply chain for 2025.

Table 29 Biomass cost price for the ACR option (*Chloridella simplex* and *Raphidonema nivale* Lagerheim) for Northern Europe (Optimistic performance)

Value for:	***Chloridella/ Raphidonema***
Scenario	**100 ha**
CAPEX (EUR/year)	43,201,787
OPEX (EUR/year)	34,380,892
Total Costs year (Production - drying)	77,582,679
Algae dried biomass (DW kg/year)	1,488,570
Algae biomass cost price (€/kg)	52.12

3.6 Life Cycle Costing Analysis

The goal of this analysis below is to determine the impact of improvement strategies. The strategies that could improve the overall cost price. The calculations result in a cost price for EPA/DHA/SDA in € per kilogram (Functional Unit). The production (cultivation) costs are the most significant cost aspect in all scenarios. Depending on scenario, production costs vary between 62 % and 80 % of the total costs. Therefore, three options are analysed to determine sensitivity of the cost prices to changes in the following components:

- Increasing biomass production yield
- Decreasing CAPEX
- Decreasing OPEX

The cultivation of algae is the most significant cost element. The biomass yield influences the overall results. The analysis below could give an indication on the effect of such an increase. The algae strains could potentially achieve higher yields. This analysis also could provide input for strain selection in the future.

The CAPEX is based on current price quotations. The costs could be lowered due to the scale of the scenarios chosen, Conservative performance (10 ha) and Optimistic performance (100 ha). This economy of scale is not fully incorporated into the current price quotations. This justifies the analysis of a decrease in CAPEX costs.

The OPEX is also based on current knowledge and price quotations. A large-scale production of algae is expected to lead to multiple improvement in the operation of algae cultivation and further downstream processing. A number of improvements combined is expected to at least 5 % till 10 %.

The algae strain *Prorocentrum cassubicum* was chosen as example for the analysis. CAPEX and OPEX are based on multiple costs elements. The most significant CAPEX is for land and production equipment (UHT-PBR). The most significant OPEX are labour, water and electricity. For both CAPEX and OPEX a fixed percentage is used to determine the effect on cost price. The overall CAPEX or OPEX is lowered based on this percentage.

Additionally, two specific elements, land and electricity costs, are analysed. The reason is the high share in CAPEX cost of cultivation/production and the sustainability option to used renewable energy. In this case an additional solar park as energy source for the algae cultivation site.

3.6.1 Analysis for Southern Europe

The analysis for Southern Europe (Lisbon) results in the following changes in cost price:

Table 30 LCC sensitivity analysis for increased biomass production yield of *Prorocentrum* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 848		€ 704	
Increased production strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% extra	€ 807	95%	€ 671	95%
Cost price EPA/DHA/SDA (€/kg) at 10% extra	€ 770	91%	€ 640	91%
Cost price EPA/DHA/SDA (€/kg) at 15% extra	€ 737	87%	€ 612	87%

Table 31 LCC sensitivity analysis for decreased CAPEX for *Prorocentrum* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 848		€ 704	
Decreased production CAPEX strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% less	€ 834	98%	€ 694	99%
Cost price EPA/DHA/SDA (€/kg) at 10% less	€ 820	97%	€ 683	97%
Cost price EPA/DHA/SDA (€/kg) at 15% less	€ 807	95%	€ 673	96%

Table 32 LCC sensitivity analysis for decreased OPEX for *Prorocentrum* in Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 848		€ 704	
Decreased production OPEX strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% less	€ 833	98%	€ 689	98%
Cost price EPA/DHA/SDA (€/kg) at 10% less	€ 818	97%	€ 674	96%
Cost price EPA/DHA/SDA (€/kg) at 15% less	€ 804	95%	€ 660	94%

The analysis for Southern Europe indicates the potential priorities for businesses to improve the overall performance of the PUFA supply chain. The increase in yield a strong effect on the overall performance. This for the Conservative and Optimistic performance scenarios. For Southern Europe a second focus could be lowering the OPEX. As mentioned before labour, water and electricity are the main costs elements in algae cultivation. A focus on reducing input or cost of inputs would improve the overall performance of the supply chain. The lowering of cost of CAPEX is the third option. The algae cultivation is a logical option, since the CAPEX of algae production is the main cost element. The focus on all three options analysed is expected. The analysis could provide insight in the decision-making process in aspects were links between CAPEX and OPEX exist. For example, a higher investment in installations to save energy input.

3.6.2 Analysis for Central Europe

The same analysis was performed for Central Europe (Munich) since yield and overall costs for Munich are slightly different. For example, labour and land costs quotations used are higher than for Southern Europe (Lisbon).

Table 33 LCC sensitivity analysis for increased biomass production yield of *Prorocentrum* in Central Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 1,196		€ 997	
Increased production strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% extra	€ 1,139	95%	€ 950	95%
Cost price EPA/DHA/SDA (€/kg) at 10% extra	€ 1,087	91%	€ 907	91%
Cost price EPA/DHA/SDA (€/kg) at 15% extra	€ 1,040	87%	€ 867	87%

Table 34 LCC sensitivity analysis for decreased CAPEX for *Prorocentrum* in Central Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 1,196		€ 997	
Decreased production CAPEX strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% less	€ 1,172	98%	€ 979	98%
Cost price EPA/DHA/SDA (€/kg) at 10% less	€ 1,147	96%	€ 960	96%
Cost price EPA/DHA/SDA (€/kg) at 15% less	€ 1,123	94%	€ 941	94%

Table 35 LCC sensitivity analysis for decreased OPEX for *Prorocentrum* in Central Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 1,196		€ 997	
Decreased production OPEX strategies				
Cost price EPA/DHA/SDA (€/kg) at 5% less	€ 1,180	99%	€ 980	98%
Cost price EPA/DHA/SDA (€/kg) at 10% less	€ 1,165	97%	€ 963	97%
Cost price EPA/DHA/SDA (€/kg) at 15% less	€ 1,149	96%	€ 945	95%

Similar to Southern Europe an increased biomass production yield is also for Central Europe the most viable option for improvement of overall performance. The changes in OPEX are less significant for improvement for Central Europe (Munich) than for Southern Europe (Lisbon). CAPEX on the other hand are more significant for Central than for Southern Europe. An improved scenario for Central Europe could be advised that it should first focus on increased biomass production yield, followed by cost reductions of the CAPEX and finally OPEX. As mentioned for Southern Europe the focus on all three options analysed is expected. The analysis could provide insight in the decision-making process in aspects were links between Yield, CAPEX and OPEX exist.

3.6.3 Land and electricity costs

Land costs are the most significant CAPEX while electricity costs are the most significant OPEX. Land costs constitute between 70 % and 79 % of CAPEX depending on scenario or location. Therefore, the effects of decreased land costs are calculated. The land costs for the alternative locations are based on price listings of real estate agents.

Table 36 Decreased land cost effects for Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 848		€ 704	
Decreased land costs (€20/m^2)				
Cost price EPA/DHA/SDA (€/kg)	€ 670	79%	€ 558	79%

Table 37 Decreased land cost effects for Central Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 1,229		€ 1,022	
Decreased land costs (€25/m^2)				
Cost price EPA/DHA/SDA (€/kg)	€ 864	72%	€ 725	73%

As mentioned in the general observations current scenarios are all located in the vicinity of big cities/capitals of each country. As such, the land prices of more urban areas are used. A shift towards a more rural area

would have a significant effect on cost prices. Due to the higher land price for Munich region lowering them has a more significant impact on the Central Europe scenario.
A number of alternative options addressed as recommendations in Keller et al., 2017a. The option addressed have the potential to reduce costs of land needed for algae cultivation, including the environmental impact. This would directly and positively influence the economic viability of the whole PUFA supply chain.

The use of renewable energy is an option that potentially could improve both economic and environmental performance. The substantial need for electricity in algae cultivation and further processing and the reported drop in investment costs for solar parks was a reason to research this option. The lower electricity costs are based on a market report with solar power plant installations bids for Europe (SolarPowerEurope, 2016), which mentioned electricity prices for Portugal and for Germany of € 0.05/kWh and € 0.08/kWh respectively. The effect of the reduced electricity price was calculated on the electricity use of the supply chain except the extraction and oil processing.

Table 38 Decreased electricity cost effects for Southern Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 870		€ 722	
Lower electricity costs (€ 0.05/kWh)				
Cost price EPA/DHA/SDA (€/kg)	€ 770	91%	€ 650	92%

Table 39 Electricity cost effects for Central Europe (Conservative and Optimistic performance scenario)

	Values for *Prorocentrum cassubicum*			
Scenario	**10 ha**		**100 ha**	
Cost price EPA/DHA/SDA (€/kg)	€ 1,229		€ 1,022	
Lower electricity costs (€ 0.08/kWh)				
Cost price EPA/DHA/SDA (€/kg)	€ 1,107	93%	€ 932	93%

A local renewable energy power plant, especially solar based, could thus provide cheaper electricity and could also reduce the CO_2-emissions related to electricity use. Similar to alternative land options, the solar park option could potentially improve the economic viability and the environmental impact.

3.7 Recommendations

The LCC offers insights and options for improvements for a mature supply chain for 2025. Further recommendations on the overall sustainability can be found in Keller et al, 2017b. The following recommendations can be made and are related to the micro-economic assessment.

3.7.1 General aspects

Costs of land

A general recommendation is that the scenarios were based on the geographical locations Lisbon, Munich and Oslo, relatively expensive regions in terms of land costs. The land costs were taken into account for the calculations and thus constitute a significant part of CAPEX. One of the recommendations is to investigate alternative locations with similar geographical settings, but with a lower land costs. As mentioned in Keller et al. 2017a, options as brownfield sites and restored opencast mining sites could provide economic and sustainable alternatives to existing industrial area used in the economic modelling. A well-chosen location could significantly improve the economic viability of a mature PUFA supply chain.

Renewable energy

As part of the integrated sustainability analysis the option of solar power as source of electricity was investigated (Keller et al., 2017a). Price reductions in recent years for realisation of solar parks lead to a positive outcome of this option. This option could improve the economic outcome, but also reduce CO_2-emissions per FU.

The productivity of algae and the production of solar based electricity shows similarities in production profile. An additional recommendation is to research potential benefits of these matching production profiles.

3.7.2 Supply chain specific aspects

Yields and algae strain selection

The most important recommendation is to focus efforts for improvement of or increasing biomass production yields. For both Southern and Central Europe an increase in production led to nearly 1-to-1 improvement of the overall cost price. Another element is EPA/DHA/SDA yield during processing steps. Efficiency in cell disruption and losses during purification for example have significant impacts on overall EPA/DHA/SDA yield. An ideal algae strain combines a high biomass yield in biomass and EPA/DHA/SDA and good processing properties. The recommendation is to further research suitable algae strains for PUFA production.

CAPEX and OPEX reduction

Two other aspects influencing overall cost price are CAPEX and OPEX. Both showed an improvement in cost reductions. There are similarities in results between Southern (Lisbon) and Central Europe (Munich) for changes in CAPEX and OPEX. For Southern Europe the improvement of OPEX has a slightly bigger effect than for Central Europe. For Central Europe the improvement of CAPEX has a slightly bigger effect than for Southern Europe. All in all, efforts should be made on all aspects of the supply chain for PUFAs from phototrophic algae. Both scenarios, Conservative (10 ha) and Optimistic (100 ha) performance, are significantly bigger than any algae production facilities build based on Photo BioReactors (PBR). A certain economy of scale could be expected. As well as technological advances that also reduce CAPEX and/or OPEX.

By-products and waste streams

In the economic modelling the by-product of supercritical CO_2-extraction is expected to be used as input for anaerobic digestion. This is a low value option. The by-product(s) of oil processing are discarded. It is recommended that all by-products and waste stream should be assessed to achieve their full economic potential. This in order to achieve a mature PUFA supply chain.

4 SWOT for the mature PUFAChain

By: Jorieke Potters

Figure 42 shows a SWOT analysis for the mature PUFAChain. Explanations of the different strengths, weaknesses, opportunities and threats can be found in the text below.

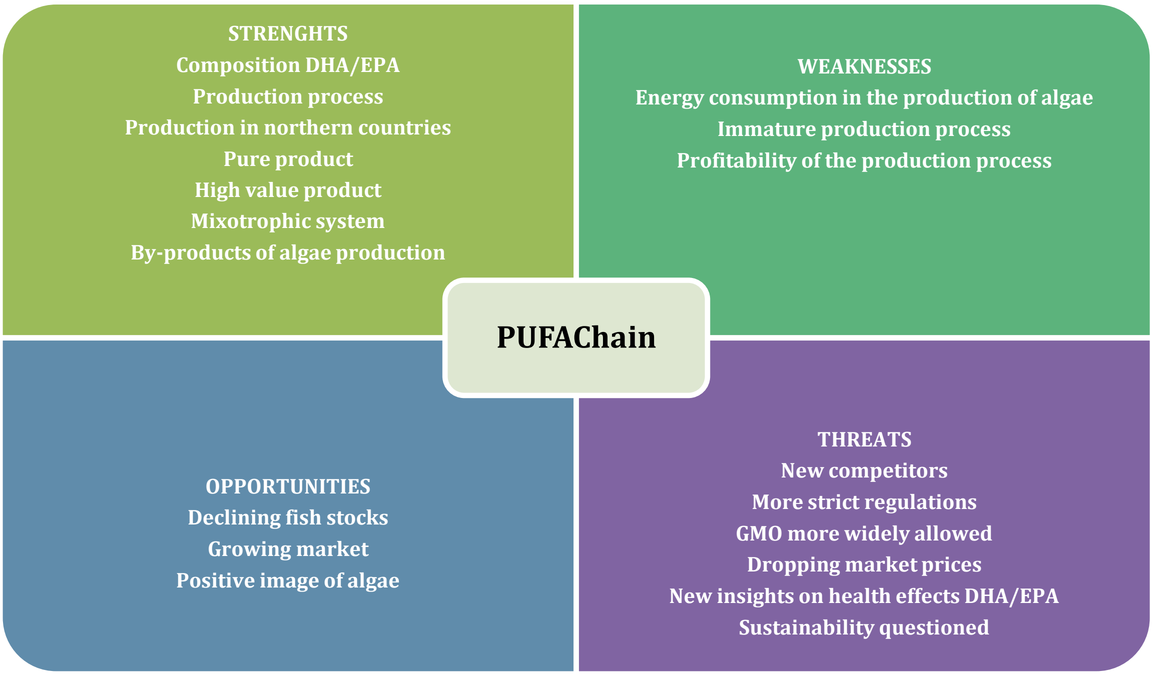

Figure 42 SWOT analysis for PUFAChain

4.1 Strengths

The production of omega-3 from phototrophic algae has several strong advantages compared to other sources of omega-3. These are relevant depending on the type of product and the mode of production that are being developed. Each one of them will be explained briefly also indicating the circumstances under which these strengths are most relevant.

Composition DHA/EPA

The selection of specific algae strains for DHA and EPA holds the promise of producing pure DHA and EPA. This is an important feature since it enables precise dosing for specific purposes. It is possible to obtain pure EPA and DHA from fish oil, but this requires an expensive separation process. Heterotrophic microorganisms mainly produce DHA. The question whether it is possible to obtain pure EPA or DHA economically on an industrial scale out of phototrophic algae is still to be answered. It depends on the strain used, the production, the extraction and purification process.

Production process

The production process of omega-3 from algae has the following features that positively resonate with societal demands and concerns.

Pressure on wild fish stocks: As compared to fish and krill based omega-3, algal omega-3 has the advantage of not contributing to the pressure on oceanic resources. When omega-3 is made out of cuttings, by-catch and left overs of consumption fish, the advantage is less demarcated.
Environmentally friendly: Potentially the cultivation of phototrophic algae could be environmental friendly, since it uses (instead of produces) CO_2. However, the production chain causes substantial CO2 emissions elsewhere and should therefore should be substantially optimized for other aspects will this aspect be of high importance (Keller et al, 2017a). An in-depth analysis whether the whole life cycle saves CO2 or causes additional CO2 emissions is needed.
Reduced pressure on arable land: For the production of phototrophic algae no arable land is needed. Even though land area is needed for the production units, this can be on industrial or marginal lands. This is an advantage compared to the production of heterotrophic microorganisms, where arable land is needed for the production of sugar. However, input of limited resources is currently still a requirement (Keller et al, 2017).
Origin and characteristics of the product: Omega-3 from phototrophic algae stems from a plant source and it can be labelled a vegan/vegetarian, biobased, halal and kosher product. Furthermore, it is a non-GM source. These are arguments that gain power in recent years since consumers have become more concerned about the origin of their food.

Production in northern countries

It is a specific aim of the PUFAChain to select algae strains that can be produced in northern European countries. This strength is relative since heterotrophic microorganisms depend less on climatic circumstances, thus can be produced anywhere. Whether it is possible to create a suitable production line for phototrophic algae under cold circumstances is to be seen.

Pure product

Fish and fish oil as a source of omega-3 have an important disadvantage of contamination with heavy metals and dioxin. This presents a health risk or requires an expensive purification processes. The production of omega-3 from algae source enables a pure product. Besides the absence of contaminants, algal oil from the PUFAChain process also does not contain organic solvents.

High value product

The PUFAChain aims at producing pure EPA and DHA. Especially pure EPA is very scarce and in high demand at the higher end of the market. This strengthens the chances for creating a profitable production chain.

Combination with heterotrophic microorganism production (mixotrophic system)

A combination of phototrophic algae and heterotrophic microorganism production, in two separate production installations, can result in several advantages. The heterotrophic system is specialised in DHA whereas in the phototrophic system EPA could be produced. The combination of both types of omega-3 presents interesting opportunities for blending specific recipes for the pharma market. The CO_2 that is produced in the heterotrophic system can be used as input in the phototrophic system. In winter production the heat from the heterotrophic system can be used for warming the phototrophic system. In this way the efficiency and profitability of the PUFAChain can be increased.

By-products of algae production

The protein-rich algae cake that results after extracting the PUFA provides opportunity to raise profitability by selling it for feed.

4.2 Weaknesses

Opposite the strengths are some weaknesses. These consist of risks on one hand and insecurities in the development of the PUFAChain on the other. Each one of them will be explained briefly also indicating the circumstances under which these weaknesses are most relevant:

Energy consumption in the production of algae

The production of phototrophic algae requires a constant mixing of the liquid in order to optimise exposure to light and to CO_2. This requires a constant pumping of the liquid in the tubes and causes high energy consumption. This could be reduced by adding solar panels to the plant (4.7.3), however this is more a means to compensate for energy use than to reduce the energy footprint of the phototrophic production process.

Immature production process

Omega-3 production from fish oil and heterotrophic microorganisms is already in business at commercial levels. The production process for PUFA from phototrophic algae is still in development and leaves a lot of questions to be answered and technical details to be investigated. The challenge is to produce a DHA and EPA in a profitable matter. The main challenges lie in the selection of the algae strains, optimise the algae production process, and finally the extraction of the oil and DHA/EPA, purification and storage. These challenges are further described in the technical assessment. Below for each production step the main questions and weaknesses that come with it are described:

Selection of algae: Despite the large collection of phototrophic algae, little is known about the characteristics and potential of the available algae strains. Since also the characteristics depend very much on the production circumstances, a lot of experimentation time is needed to select the most promising strains for different purposes and determine the optimum production circumstances. In the PUFAChain project important steps have been made in learning about production and processing.

Production: Once the strains are selected it is necessary to optimise the production process. This is not just a question of maximising dry matter production, since the content of EPA/DHA/SDA depend on the growing circumstances. For each alga strain the optimum growing conditions should be determined.

Extraction: the different algae strains have different types of cell membranes which differ in the ease of rupture. Furthermore, algae strains differ in the way they store their oil; in phospholipids, triglycerides or ethyl esters, each require a different extraction process with each its own challenges. The question is how to get the most omega-3 out of the different algae strains.

Purification: Once the oil is extracted from the algae, the effort needed to purify the algal oil depends for example on the lipid concentration and lipid class in the algae (e.g. Robles Medina et al, 1998). A lot of experimentation and investigation is needed to optimise the purification process.

Shelf life: Stability and storage of the product (shelf life), is another step where experimentation and experience are needed.

Profitability of the production process

In the present state of development, the profitability of the PUFAChain is a weakness. The profitability is weak at four levels.

Productivity of phototrophic production: Since phototrophic production of algae is still under development, the productivity is not optimal yet. Improvements can be expected in increased lipid yield and productivity (2-8 fold, by exploiting the physiological potential, improving strains by selection, breeding and genetic modification; Chauton et al, 2015).

Difficulty to patent: Many systems and methods related to the production of omega-3 from phototrophic algae have been patented already.

Business plan uncertain: At this stage it is possible to formulate a lucrative business case for the production of omega-3 from phototrophic production process at competitive cost prices compared to other omega-3 sources, but this is still an optimized scenario for 2025 (Chapter 4).
Extensive authorization procedure: The use of omega-3 (rich oils) from fish products and certain unicellular marine heterotrophic organisms is already authorised for different market segments, e.g. from *Schizochytrium* sp. None of such authorization seems to exist for pure omega-3 from phototrophic algae, only for complete algae like *Nannochloropsis gaditana*. This means before being able to market it, an application for authorisation of use in food, feed or pharma needs to be made presenting the scientific information and safety assessment report. A shorter route could be to apply for a 'notification' arguing that substantial equivalence exists to the already authorized omega-3 from unicellular marine heterotrophic organisms.

4.3 Opportunities

The present situation holds a number of opportunities for the production and marketing of omega-3 from phototrophic algae. Various opportunities result from the specific characteristics of the production process or from developments in the market through pricing or consumers' interest.

Declining fish stocks

The fact that the main source of omega-3 is declining, creates momentum for alternatives, thus giving alternatives such as omega-3 from phototrophic algae room for entering the market.

Growing market

In general, the market for EPA and DHA steadily increases due to a growing interest in health and food. There is quit a strong lobby to create more awareness on the positive effects of DHA/EPA for human health. Within this general growing market for omega-3, the potential market for vegan/vegetarian DHA/EPA is increasing since veganism is slowly growing and environmental awareness follows the same trend. The existing pharma market provides interesting sales opportunities for pure DHA and EPA.

Positive image of algae

Regardless of the specific production process or end products, the green colour in combination with clean production on the basis of sunlight using CO_2, provides good opportunities for marketing algae as a sustainable alternative.

4.4 Threats

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

New competitors

Since the market for PUFA is growing new producers of omega-3 from algae or yeast could enter this market as competitors. This could be either on cost price or on the quality of the product.

More strict regulations

When the rules for the use of algae products for pharma, food and feed become stricter this will reduce the market share for PUFA from algae.

GMO more widely allowed

In the US GM yeasts are being developed as vegan source for PUFA. This presents an important competitor in the US market. In case the use of GMO will be allowed in Europe this poses a serious threat that could compete on cost price. It can however be expected that the vegan/vegetarian consumer will not accept GM PUFA production.

Dropping market prices

The market price for PUFA may drop due to higher availability of PUFAs from other sources, increased production or decreased demand for example due to reasons mentioned below.

New insights on health effects DHA/EPA

Ongoing research on the health effects could result in new insights on the health effects of DHA and EPA. This could be positive, but it is also thinkable that research reduces the positive expectations of PUFA in food and pharma. These insights could for example show that the health effects of pure DHA and EPA are less favourable than those of PUFA in fish or vegetables. It could turn out that EPA and DHA have negative side effects on health or that DHA and EPA do not have such a strong effect on health as is currently thought. As a result, the demand will decrease.

Sustainability questioned

Another cause of decreasing demand could be the public questioning of sustainability of PUFA from algae.

5 Indicators for LCC and socio-economic analyses

By: Marcel van der Voort & Jorieke Potters

P= Prorocentrum, T= Thalassiosira, C/R = Chloridella/Raphidonema and S= South, W = West, N = North
Het = PUFAs from heterotrophic microorganisms, F = PUFAs from fish cuttings, B= PUFAs from by-catch

		Least expected performance							Optimistic performance							Standard conditions		
		PUFAChain scenarios							PUFAChain scenarios							Alternatives to PUFAChain		
Indicator	Unit	P_S	T_S	C/R_S	P_W	T_W	C/R_W	C/R_N	P_S	T_S	C/R_S	P_W	T_W	C/R_W	C/R_N	Het	F	B
Production costs	€/kg PUFAs	848	1,359	1,156	1,196	2,058	2,344	N/D	704	468	932	997	753	1,915	3,903	900	900	850
Fixed capital investment	Million €	59	59	61	68	68	70	N/D	545	545	569	628	628	645	867	N/D	N/D	N/D
Local community																		
Labour conditions Health	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Labour conditions (Safety)	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-
Employment opportunity	-	++	++	++	+	+	+	+	++	++	++	+	+	+	+	+	0	0
Access to material resources (1)	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
Living Conditions (2)	-	+	+	+	0	0	0	0	+	+	+	0	0	0	0	0	0	0
General society																		
Consumers' health and safety (3)	-	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	+	+
Public commitment to sustainability issues (4)	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	- -	- -
Legal regulatory barriers (5)	-	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	++	+	+
Public perception (6)	-	++	++	++	++	++	++	++	++	++	++	++	++	++	++	+	-	-

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

1) Phototrophic can be produced on unproductive land, heterotrophic needs sugar. For differences between Nordic and southern locations see socio-economic analysis.
2) Production site may be observed as negative to landscape, this effect is less in less densely populated areas. Production could have a positive effect on the living conditions through economic development in remote areas in Portugal
3) Heterotrophic contributes as much as phototrophic to health, fish a bit less because of possible impurities and contamination
4) Fish oil production is linked to unsustainable fisheries
5) Heterotrophic algae are already authorised for different markets, fish oil is accepted though some discussion about its use in baby formula
6) Fish oil production is linked to unsustainable fisheries

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