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Macro-economics of algae products

Report WP2A7.02



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Macro-economics of algae products

1 Introduction

1.1 Aims of the EnAlgae project

The Energetic Algae (EnAlgae) project aims at contributing to a reduction of CO₂-emissions and wants to decrease the dependency on fossile energy sources in Northwest Europe. The project does so by accelerating the development of sustainable technologies for algal biomass production, bioenergy generation and greenhouse gas (GHG) mitigation from pilot phase to application, including the development of marketable algae products, processes and services. Amongst others, this goal is achieved by bundling know-how, finance and political support. The planned actions address the challenges and barriers related to algae energy technologies and bring forward innovative approaches to sustainable algae energy promotion and management.

1.2 Objective and method of this market report

This report is part of the EnAlgae Workpackage 2, Action 7, directed at the economics of algae production. The goal of this report is to highlight potential markets for algae. Per type of algae market the market size, product alternatives, constraints and prices are highlighted. Based on these market characteristics a conclusion is drawn on the market potential for algae products. Per market desk research is done and literature is consulted to create a reliable market outlook.

The value pyramid of algae products is applied to classify the potential markets (Figure 1). The report starts with the bottom of the pyramid with low value and high volume markets and works its way up to high value and low volume markets. Thus, the energy market is first described and discussed, followed by the chapters 'Chemicals & Materials', 'Food & Feed' and 'Personal care & Pharmaceuticals'.

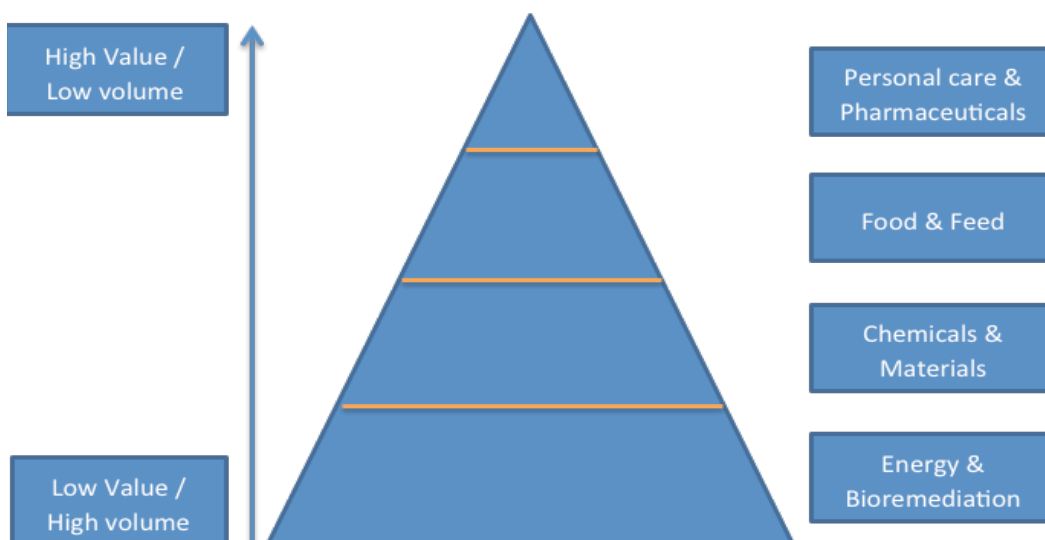


Figure 1: Value pyramid and markets.

In the chapter 'Chemicals and Materials' the potential for algae in the recycling of nutrients from digestates is assessed, as well as the potential of algae in the markets of biofertilizers, plant biostimulants, biopesticides and bioplastics. The chapter 'Bioremediation' closes this report. Although bioremediation does not lead to tangible products, it is a promising application of algae and substantial effort is dedicated to the development of this application in the EnAlgae-project.

2 Energy

This paragraph discusses the energy market in full. The energy market is very much a market with homogenous products which are easily substituted by each other. As the value pyramid shows, energy is a high volume market with low price levels. Per type of energy product, the potential market size and value and the opportunities and threats for algae in each of these markets are discussed. Since the renewable energy market is for an important part policy driven, the most relevant policies are discussed.

The two most powerful driving forces behind the demand for energy are population growth and economic growth (BP, 2011). For Europe a decline in population and slow economic growth are expected. The expected increase in world population and economic growth will to the larger extent take place outside of Europe. The demand for energy in Europe is expected to remain on the current level or slightly decline as a result of this demographic and economic development. On a global level, energy demand is expected to grow 30% to 40% by 2040 compared to 2010 (BP, 2011; ExxonMobil, 2012).

The world fossil fuel reserves are concentrated in a small number of countries. For example the EU had only 1.3% of the global natural gas reserves on its territories in 2009. More than half of the world's natural gas reserves are found in just three countries, i.e. Iran, Qatar and Russia. It is expected that the remaining European reserves of fossil fuels will be exhausted before 2030 (EEA, 2011). The European Union is already a net importer of energy products. Due to the depletion of its own energy resources, the European Union will become more dependent on energy imports from a limited number of countries. Especially the European demand for natural gas is expected to grow. The biggest increase in energy imports in the EU is therefore expected in natural gas, to a growth of about 40% by 2030 compared to 2005 (Capros *et al.*, 2010).

The current global economic downturn has led to a lower demand of fossil fuels worldwide, and as a result led to slightly lower oil prices. Nevertheless, due to increase in population and expected future economic growth, oil demand and oil price remain high, and are expected to stay high. IEA experts expect a crude oil price of USD 120 per barrel in 2035 (OECD/IEA, 2011). High energy prices influence consumer prices (Meyler, 2009). Any crude oil price development will therefore directly affect the price of energy products for European end users. In March 2014 the crude oil price was equal to EUR 57.8/barrel.

The European Union has promoted renewable energy through its policy. It is currently the largest market for renewable energy and is expected to remain so for a number of years. European renewable energy investments represent about 25% of the investments in renewable energy worldwide (Bloomberg, 2011). In the next years a policy review of the EU's energy policy is expected. One of the reasons for this expected review is for example the problem with subsidized renewable energy on the German energy market (Reuters, 2013). Also playing a significant role in the policy landscape is the review of the European Commission on the impact of the Renewable Energy Directive on indirect land-use change and effect on reduction of greenhouse gasses (EC, 2012). The review of the EU's energy policy is expected to slow down investments in renewable energy. The sovereign debt crisis will further influence the investments in renewable energy in European Union (Bloomberg, 2011). Despite the policy uncertainty and debt crisis, the investment growth rate in the European Union is nevertheless expected to be 8% per

year after 2015. This is mainly due to a number of EU member states that need to meet their renewable energy targets of 2020 (Bloomberg, 2011).

To recapitulate, the demand for energy products in the European Union is expected to remain on its current level. The energy prices are expected to remain high or increase even further. The investments in renewable energy are expected to slow down. The question is what the potential of algae products is in the European energy market taking into account the aforementioned drivers and developments.

2.1 Transport fuels

Transport fuels are responsible for the highest final energy consumption of all sectors in the EU-27, i.e. about 368 toe (tonnes oil equivalent) in 2009 or 33% of the total 2009 final energy consumption in the EU-27 (Eurostat, 2011). The transport sector is also the only sector showing an annual increase in energy consumption of 2% (Eurostat, 2011). Road transport accounts for about 82% of the final energy consumption in transport, followed by air transport for about 13.6% in EU-27 in 2009 (Eurostat, 2011). The dominant fuel types are diesel, petrol and kerosene, with a share of about 52%, 27% and 13.5% in total transport fuel consumption. The last 10 years diesel and kerosene use increased, with 30% and 17% in EU-27, while petrol decreased with 29% in EU-27 over the last 10 years (Eurostat, 2011).

Two trends, of which the effects are not certain at present, could slow down the growing demand for transport fuels. The first trend is the rapid penetration of electric vehicles and the second trend is the increasingly higher vehicle fuel efficiencies. This may affect the transport fuel demand in the long run. These developments are driven by high fuel prices and environmental policies (Bloomberg, 2011). An increasing price level of transport fuels could accelerate these developments. The second trend is what The Economist (2012) reports on, the falling car ownership as side effect of increasing urbanisation. Especially more and more young people in urban areas do not possess a car or even have a drivers licence. A drop in the number of cars has a direct influence on the demand for transport fuel. Furthermore, carsharing initiatives like e.g. Greenwheels, Snappcar.nl and MyWheels facilitate the younger generation in those cases when they need access to a car (NRC, 2013).

Algae biomass could serve as a resource for the production of renewable transport fuels, such as biodiesel and bio-ethanol. The European market for renewable transport fuels is predominantly determined by the EU directives. The market for biofuels in EU-27 was about 13.17 million toe (tonnes oil equivalent) in 2010. The biofuels used are mainly biodiesel (78%) and bio-ethanol (21%). The other biofuels on the market are bio-methane and vegetable oil, with both around 0.5% of the total biofuel market in the EU (EEA, 2011). The growth of biofuels consumption in EU-27 is decreasing. The growth between 2010 and 2011 was around 3%, which is significantly lower than the 10.7%, 24.6% and 41.7% growth in 2010-2009, 2009-2008 and 2008-2007, respectively (EurObserv'ER, 2012). The main reason for this decrease is the change of policy. Especially in Germany support was reduced in recent years due to the fact that subsidy costs rose too high. However, this decrease is not in line with European ambitions to achieve a 10% share of renewable energy in the transport sector by 2020 (EC, 2009). The 2020 target of the EU Renewable Energy Directive (RED) (2009/28/EC) is more stringent than the target of the previous 2003 Biofuel Directive. According to the 2009 RED directive, the expected biofuel consumption in 2015 is 18 million toe and 30 million toe in 2020 (EurObserv'ER, 2012).

The most significant concern is the food-fuel discussion. The competition between food and fuel markets for the same feedstock is regarded to be one of the drivers of the food price peaks of 2007/2008. Other sustainability concerns are land use change and loss of biodiversity, due to mono-cropping and increased demand for soybean and palm oil. The increased demand for soybean and palm oil (partly arising from the increased demand for biofuels) has led to deforestation in tropical countries. Due to this side effect, the potential to lower greenhouse gas (GHG) emissions through conventional biofuels is small or even

negative. In response the European Commission (EC) recently published a proposal to minimise the climate impacts of biofuel production (EC, 2012). The EC is proposing to amend the current legislation on biofuels, in particular the following:

- To increase the minimum greenhouse gas saving threshold for new biofuel installations to 60% in order to improve the efficiency of biofuel production processes as well as discourage further investments in installations with low greenhouse gas performance;
- To include indirect land use change (ILUC) factors in the reporting by fuel suppliers and Member States on greenhouse gas savings of biofuels and bioliquids;
- To limit the amount of food crop-based biofuels and bioliquids that count towards the EU's 10% target for renewable energy in the transport sector by 2020. The aim is to keep the food crop-based biofuels and bioliquids to the current consumption level, while keeping the overall renewable energy and carbon intensity reduction targets;
- To provide market incentives for biofuels with no or low indirect land use change emissions, and in particular the 2nd and 3rd generation biofuels produced from feedstocks that do not create an additional demand for land. These feedstocks include algae, straw, and various types of waste (EC, 2012).

The last bullet point refers to the potential of algae, as algae are regarded by the EC to be part of the 2nd and 3rd generation biofuels. This, combined with a growing demand for transport fuel in general, states a market opportunity for algae biofuels.

Lundquist *et al.* (2010) calculated the cost of large-scale algae production in raceway ponds. They conclude that oil production with microalgae will be expensive, even under favorable process assumptions. The cost of algae oil would be USD 405 per barrel, based on a 25% oil content, without a bonus for wastewater treatment. This is based on a scenario with biofuel production as main goal, wastewater providing water and nutrients, a pond/farm size of 100 ha and 10 operational months per year. If revenues of water treatment are taken into account, the cost of algae oil will be about USD 332 per barrel algae oil. If wastewater treatment is the main goal and the algae oil is a byproduct, then algae oil costs USD 28 per barrel (based on algae with 25% oil content and including a wastewater treatment bonus). In March 2014 the crude oil price was equal to EUR 57.8/barrel or EUR 0.483/L (energy.eu). To be competitive with fossil oil, the algae oil price should thus decrease with a factor 8 based on the estimations of Lundquist *et al.* (2010).

In Rösch *et al.* (2012) the production cost of algal biofuels is stated as being higher compared to the traditional biofuels. Rösch *et al.* (2012) indicate a theoretical price range of EUR 1.94 to 3.35 per liter of algae biodiesel if optimistic assumptions and technological progress are taken into account (based on Delrue *et al.* (2012; cited in Rösch *et al.*, 2012). Rösch *et al.* (2012) cites Norsker *et al.* (2012) who expect lowering of the costs of algae production in reactors from EUR 2.40-3.20 per kilogram dry biomass (possible today) to EUR 0.68 per kilogram dry biomass. The feasibility is greatly improved if algal biofuel is produced as byproduct of a high-value product. The bottleneck is to find a high-value market that relates to the significant quantities of transport fuels. It's unlikely that such a matching high-value market will be found.

2.1.1 Biodiesel

Biodiesel is a substitute for fossil diesel fuel. Biodiesel is primarily produced from vegetable oil and used cooking oil (Reuters, 2010). As mentioned above the biodiesel market in the EU is the largest biofuel market. Biodiesel consumption in the EU-27 was 10.34 million toe in 2010 (EurObserv'ER, 2012). The market outlook for biodiesel is positive, mainly due to the EU directives on renewable energy and fuels, especially for the 2nd and 3rd generation biodiesel production, such as algae based biofuels. As mentioned before, the discussion on sustainability criteria could lead to policy change in the EU Renewable Energy

Directive. The current production is primarily based on food crops. The European biodiesel market is expected to be 14 to 23 million toe by 2015 and 2020 (Hart Energy, 2012).

The current biodiesel industry was suffering from high feedstock prices and cheaper biodiesel imports. The change from 1st generation to 2nd and 3rd generation biofuels in the EU Renewable Energy Directive is, next to feedstock prices and cheap imports, also an issue for the biodiesel industry (Hart Energy, 2012). The rise in imports is primarily due to the shift from tax incentives to mandates. Due to the mandates, fuel suppliers are more likely to blend low cost biofuels into the total diesel fuel supply (Lamers, 2011). Until now the biofuel market in the EU was supported by the EU directives on the use of sustainable fuels. The EU imposed tariffs on biodiesel from the US and more recently on biodiesel from Argentina and Indonesia (Bloomberg, 2013). The algal biodiesel producer and policy makers could learn from the above, which is that changes in the markets, policies and trade influence the business of biodiesel production. The above-mentioned changes lead to an 8% drop in biodiesel production in the EU, while the consumption slightly increased (EurObserv'ER, 2012). The current European biodiesel producers have learned these hard lessons.

The price of fossil fuel co-determines the price for biofuels. The retail price of diesel is EUR 1.395 per litre, average of EU-27 (energy.eu, March 2014). The margins, taxes and duties on fossil fuels show a wide spread per EU member state (energy.eu). The price of crude oil is therefore expected to be the best guideline for price setting. In March 2014 the crude oil price for biodiesel was EUR 57.8/barrel or EUR 0.483/L.

2.1.2 Bio-ethanol

Bio-ethanol substitutes petroleum (gasoline) fuel. Bio-ethanol is produced primarily from sugar and starch crops, such as sugar beet and grain crops (Reuters, 2010). Bio-ethanol consumption in the EU was 2.68 million toe in 2010 (EurObserv'ER, 2012). Although different in nature, both biodiesel and bio-ethanol have similar market developments. The EU bio-ethanol market is also driven by the same policy developments and sustainability discussions. The production of bio-ethanol in the EU was 4.26 million litres in 2010 (EurObserv'ER, 2012). The primary feedstocks used for bio-ethanol production are, in order of importance, sugar beet, wheat, corn, rye and barley. A small volume is produced from the surplus of wine alcohol (USDA, 2011). The retail price of unleaded petroleum is EUR 1.466 per liter, average of EU-27 (energy.eu, March 2014). The margins, taxes and duties on fossil fuels show a wide range per EU member state (energy.eu). The price of crude oil is therefore expected to be the best guideline for price setting. The crude oil price for bio-ethanol is the same as for biodiesel, i.e. EUR 0.483 per liter (March, 2014).

2.1.3 Bio-methane (biogas) for transport

Biogas is produced by anaerobic digestion of organic matter. Bio-methane is obtained by separating biogas into methane and CO₂. Different studies mention the conversion of algal matter to biogas. Bio-methane for transport (bio-CNG or bio-LNG) plays a minor role in the EU-27, with a 0.5% market share in 2010. Bio-methane for transportation is primarily a Swedish phenomenon (EurObserv'ER, 2012). Biogas produced by farmers in other EU countries is mainly used in CHP installations to produce electricity and heat. The production of 'fuel-grade biogas' (i.e. of natural gas quality) requires additional infrastructure investments on-farm, but also distribution infrastructure investments and filling station conversion programmes. This mainly due to the fact that the current use of natural gas and/or LPG for transportation in European countries is limited. A solution could be found in captive vehicle fleet with own private filling stations (EurObserv'ER, 2010).

Bio-methane based on algal biomass is expected to encounter the same bottlenecks as the conventional bio-methane market. The market for bio-methane in transportation is expected to be a niche market. This

is mainly due to the distribution and filling station bottleneck. For reference, the crude LPG price was EUR 0.408 per litre LPG, excluding margins, excise duties and taxes (Energy.eu, March 2013).

2.1.4 Jet fuel

The IEA Bioenergy (task 40) reported on the role and potential of biofuels in commercial air transport. It is recognized that at this moment the most readily available feedstock and economic options are palm oil, soybean oil and rapeseed oil. Because of strong competition with the food market, non-edible feedstocks are sought for. IEA identified microalgae oil as a feedstock with considerable potential for biojetfuels. The IEA Bioenergy states that a number of reports concluded that there is currently limited potential for the production and economy of algae, but algae are seen as the best short or medium term option for alternatives. Compared to the other mentioned potential feedstocks, microalgae feedstocks offer additional benefits since algae can be grown on non-arable land (Rosillo-Calle *et al.*, 2012). The worldwide consumption of aviation fuels is about 211×10^6 tonnes in 2010 (53×10^6 tonnes in the EU in 2011 (Eurostat, 2013)). The consumption is expected to increase by approximately 1.5% to 3% per year, to between 375.10^6 tonnes and 575.10^6 tonnes by 2050 (Rosillo-Calle *et al.*, 2012). If a blend of 10% biojetfuel is used in 2050, then the market of biojetfuels would be of a size between 37.5×10^6 and 57.5×10^6 tonnes in 2050. Blends of aviation fuel (specified as type JP-8 /Jet-A) consisting of 50% of algae and 50% jatropha are already accepted as jet biofuel (Scotia Capital, 2010). The price indication of biojet fuel is about USD 2,- per gallon, which is about EUR 0.53 per litre (Scotia Capital, 2010).

2.1.5 Conclusions transport fuels

The expected stagnating economic and population growth in the EU will most likely not trigger a significant increase in energy consumption. The anticipated economic growth and population increase outside the EU will probably increase global energy consumption and therefore global energy prices, since there is limited potential on increasing the production of crude oil. The most likely factors to stimulate the growth of biofuel markets are the expected rising fossil energy prices and the EU directives to increase renewable energy use (among other in road transport). The market for renewable transport fuels is expected to grow in the future; this is in line with the expected growth of the total demand for transport fuels. The sustainability criteria for biomass (set out by the Renewable Energy Directive 2009/28/EC) present an opportunity for algae because algae are classified as a non-food biofuel feedstock, and therefore more in line with the sustainability criteria. The outlook for biofuels based on algae is promising. The biggest hurdle is to produce algae biofuels at a competitive price level. Another bottleneck is the required production capacity to produce huge volumes of biofuels, if algae biofuels want to be a meaningful substitute for oil. The annual market volume of diesel is about 70.7 million barrels of oil, which is about 11,240 million litres. With the EU requirement 10% share of biofuels this would mean 1,124 million litres of biodiesel are needed.

Table 1: The market of biofuels for transport and their substitutes.

Product	Substitutes	Market size EU (in toe)	Price of substitute (EUR per unit)	Outlook for algae
Biodiesel	diesel	10.34 million	0.483 litre	++
Bio-ethanol	gasoline	2.68 million	0.483 litre	++
Bio-methane	LPG	-	0.408 litre	-/+
Jet fuel	kerosine	-	0.53 litre	++

The outlook for bio-methane as transport fuel is limited due to the lack of distribution infrastructure and the required conversion of filling stations. The use of bio-methane as replacement for natural gas or for the production of electricity and heat has more potential.

The outlook for algal biofuel as jet fuels is promising. Tests indicate that algal biofuel is suitable as jet biofuel. The cost of algal biofuels is the main obstacle to commercialization.

2.2 Electricity and heat

In 2009 the EU-27 produced 587 TWh of renewable electricity, which is about 18% of the total electricity consumption (Eurostat, 2011). The price of electricity in EU-27 was EUR 17.1 per 100 kWh in 2010, but the variation in price levels per member states is significant (Eurostat, 2011). The same holds for industrial electricity prices levels. An algae (by-product) business case on electricity and heat could therefore differ quite significantly per EU member state.

2.2.1 Bio-methane (biogas) for heat and electricity

Algae biomass is expected to be used as feedstock in anaerobic digestion. In 2009, about 25.2 TWh of electricity was produced from biogas in the EU. The main sources of biogas are landfill gas, sewage sludge gas and other biogas sources, such as biogas produced in agricultural installations. The heat production based on electricity production from biogas in the EU was about 173.8 ktoe (2 GWh) in 2009 (EurObservER, 2010). Next to electricity and heat production, bio-methane can be used as a substitute for natural gas. Bio-methane injection into the natural gas grid is technically possible (FNR, 2006) and bio-methane should be accepted by EU member states and European grid operators as long as technical and safety standards are met (EU Directive 2009/73/EG).

The production of biogas falls into the scope of multiple EU directives. It corresponds to the main objective of the Renewable Energy Directive (2009/28/CE). The Renewable Energy Directive is aiming for a 20% renewable energy share in final energy consumption by 2020. The second relevant EU directive is on organic waste management (Directive 1999/31/CE on landfill of waste and Directive 2008/98/CE on waste) (EurObservER, 2010). Biogas produced from algae is only expected to fall within the scope of the Renewable Energy Directive.

The use of cogeneration technologies allows maximizing energy production by producing electricity and heat at the same time. A part of this heat is used to satisfy the internal heat requirement of the digestion process. The surplus heat can be used to heat local houses, buildings, greenhouses and other processes (EurObservER, 2010). As heat cannot be transported over a large distance, it is necessary that the demand for heat is located in close vicinity to the digester (or the other way round). The problem of large distances could be solved by placing the biogas plant next to the heat demanding building or process or by transporting the biogas to a cogeneration plant in the vicinity of the heat demand.

Contrary to wind and solar electricity, the benefit of producing electricity by biogas is that it is not restricted by certain weather conditions. One of the problems with renewable energy on e.g. the German energy market is the surplus of electricity in sunny and windy weather conditions (Reuters, 2013).

The price level for natural gas in Europe is, for the EU-27, around EUR 0.037 per kWh for industrial consumers and EUR 0.049 per kWh for household consumers (Energy.eu, Aug. 2013).

2.2.2 Conclusion electricity and heat

Relevant for all energy options are the low price levels of fossil alternatives. The price of energy products based on algae biomass is still too high to be competitive in the energy market, which is overall a bulk market with low price levels. The energy market could be interesting for byproducts of algae refinery.

Table 2: The market of biogas and its fossil substitutes.

Product	Substitutes	Market size EU ¹	Value substitutes ² (EUR/kWh)	Outlook algae
Electricity		3,210 TWh	0.10 – 0.17	++
Heat		2,413 PJ	-	-/+
Bio-methane	Natural gas	417 Mtoe	0.037 – 0.049	-/+

¹- Eurostat data of 2009, published 2011.

²- EUR/kWh for electricity and natural gas. The first number is the price for industrial consumers; the second is the household consumer price, Data of Energy.eu, August 2013.

The outlook for biogas installations in general also applies for biogas production with algae as feedstock. The electricity market is easy to access. The injection of bio-methane into the natural gas grid requires an additional processing step. The use of heat in close vicinity of the CHP installation is the biggest hurdle for heat.

3 Chemicals & Materials

3.1 Digestate nutrient recycling and slow-release fertilizer production

Energy production from microalgae calls for the simultaneous management of its nutrient-rich byproducts. Whether microalgae are used as a source of biodiesel by extracting their oil, or as a source of biogas through anaerobic digestion of their entire biomass, nutrient rich microalgae cell walls in the first case, or nutrient rich digestate after biogas production, are byproducts with their own intrinsic economic and strategic value as a fertilizer. Additionally microalgae can be implemented to convert nutrient rich streams from other feedstocks, e.g. manure digestion, aquaculture effluents and agricultural runoff to slow-release fertilizers that have less adverse effects on the environment than conventional fertilizers.

3.1.1 Nutrient surpluses in the environment

North-West Europe is a region marked by intensive livestock production. Since the 1950s animal production has increased spectacularly, relying on feeds that are imported. This has led to manure surpluses and excessive manure application on agricultural fields. The amount of unconsumed nutrients in the soil gradually increased, resulting in phosphorus-saturated soils, eutrophicated surface waters and groundwater too rich in nitrate (Figure 2) (Lesschen *et al.*, 2013).

Surplus of nutrients in waters triggers the growth of algae, which depletes oxygen supplies needed by fish and other forms of aquatic life, creating “dead zones”. Eutrophication is still one of the major environmental problems across Europe (EEA, 2005).

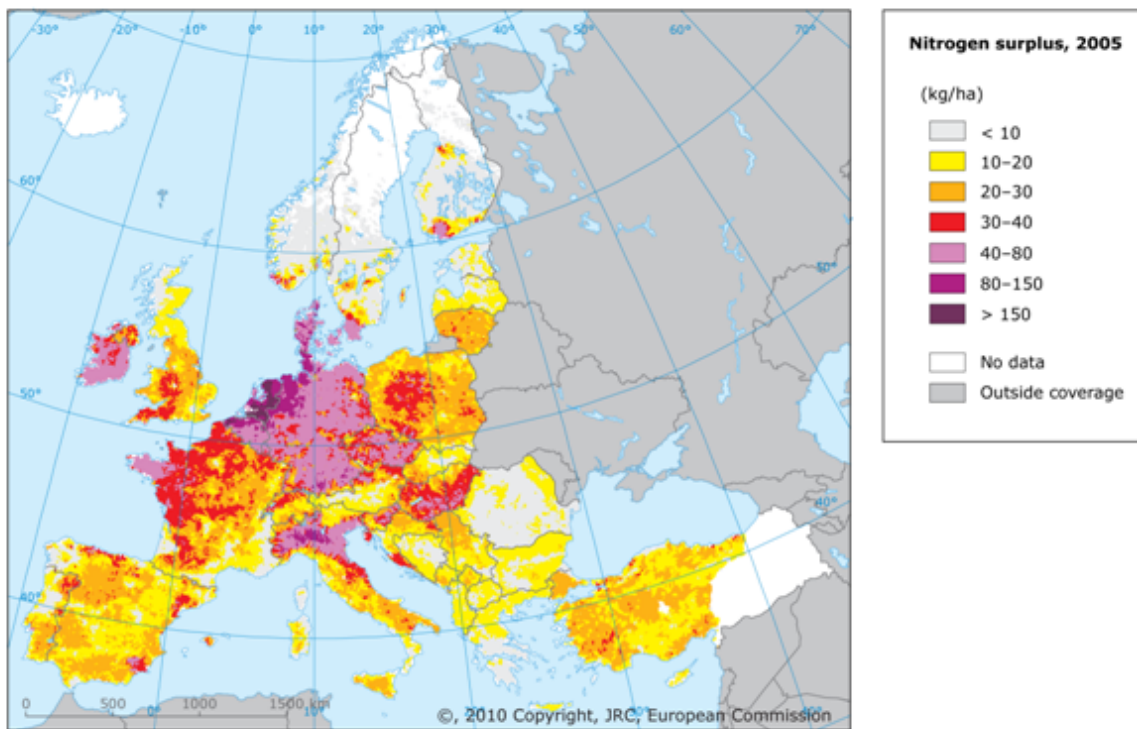


Figure 2: Estimated nitrogen surplus in Europe in 2005 (EEA, 2010).

The European Commission started tackling manure nutrient surpluses and the associated pressure of agricultural activities on water quality with the Nitrates Directive of 1991 (91/676/EEC). The Nitrates Directive aims to reduce nitrate pollution from agricultural sources in surface and groundwater by imposing measures such as limitation of manure application, requiring a minimum manure storage capacity and manure treatment in designated “nitrate vulnerable zones” (> 50 mg NO₃/L in groundwater). Outside “nitrate vulnerable zones” the voluntary adoption of codes of good practice is encouraged (Bloch, 2005; EC, 2010; EC, 2014).

3.1.2 Phosphorus supply gap

In contrast to nitrogen (N) whose supply is renewable and thus infinite, phosphorus (P) is considered a strategic resource. Since the 1960s the main source of phosphorus is mined as phosphate rock. The demand for phosphorus has since then been increasing rapidly. Phosphate rock is only found in a limited number of countries, all of which are outside of Europe (Malingreau *et al.*, 2012). Only Finland disposes of limited own mineral reserves, leaving Europe dependent on imports from just a few countries, such as Morocco (Malingreau *et al.*, 2012; Vaccari, 2009). Cordell *et al.* (2011) predict that phosphorus prices will go up due to dwindling phosphorus resources. Phosphorus production is assumed to reach a maximum or peak, like oil. Phosphate production will decline as accessible high quality phosphate rock reserves become depleted. A conservative analysis using industry data suggests that the peak in global phosphorus production could occur by 2033 (Cordell *et al.*, 2009). In the mean time changing economic and geopolitical conditions can lead to temporary shortfalls and very high prices, as has happened in 2008 (Malingreau *et al.*, 2012).

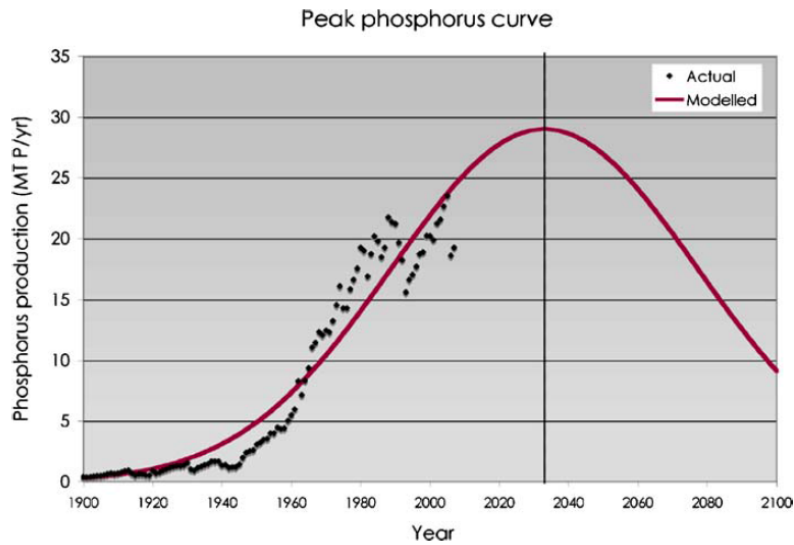


Figure 3: Indicative peak phosphorus curve, illustrating that in a similar way to oil, global phosphorus reserves are likely to peak after which production will be significantly reduced (Cordell *et al.*, 2009).

In 2008 fertilizer prices increased rapidly by 800% (Figure 4), as a result of an increase in energy prices, increased demand for fertilizers due to increased meat-based diets, increase in biofuel production, and panic buying by large consumers (Cordell *et al.*, 2011; Malingreau *et al.*, 2012). Since 2010 phosphate prices experience a gradual increase, and it is believed that they will continue to rise in the future (Cordell *et al.*, 2011).

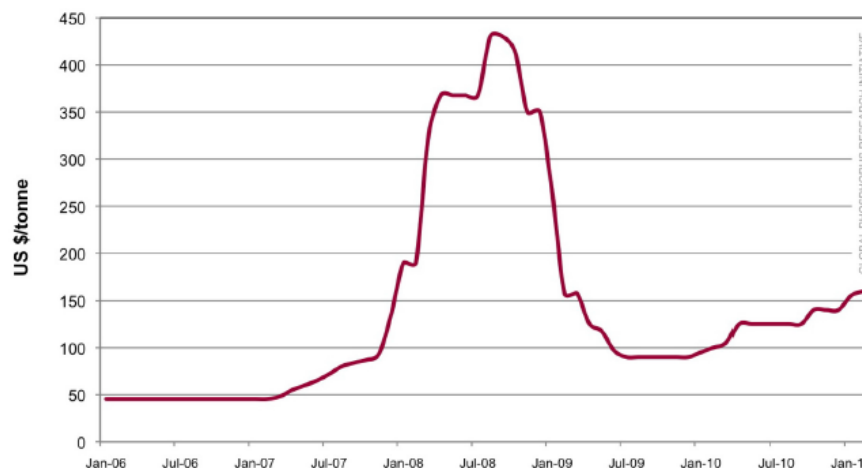


Figure 4: Phosphate rock price between 2006-2011, showing a price spike in 2008 and a gradual increase from 2010 onwards (Cordell *et al.*, 2011).

Although the situation is currently not critical with respect to the production and availability of plant nutrients, the European Union should remain vigilant. Europe's dependence on a vital non-renewable resource such as P that is not domestically available must be addressed in any long-term food security strategy (Malingreau *et al.*, 2012).

The European commission has identified minimizing losses from agro-ecosystems and recovering and re-use of NPK from all kinds of waste streams as a key area of research. On-going EU funded research is addressing the question of how to reduce the use of mineral fertilizers in agriculture and optimize the application of nutrients (Malingreau *et al.*, 2012).

3.1.3 EU policy on nutrient recycling

Efforts are undertaken on national and European level to establish a market for recycled phosphorus. In the Netherlands, the Phosphate Value Chain Agreement (“Ketenakkoord Fosfaatkringloop”), adopted in 2011 between private companies and public institutions, wants to establish a market for recycled phosphorus by 2013. Since then, similar initiatives in Flanders, Denmark and Germany have joined forces to develop cross-border business cases and eventually markets for phosphorus recovery (SNB, 2013; Vlakwa, 2013). Meanwhile at European level support for these national initiatives is given by the launch of the European Sustainable Phosphorus Platform in 2013, but a legal framework on EU-level has until now been missing (EU phosphorusplatform, 2013). The European Commission is finalizing a Green Paper on the sustainable use of phosphorus, which should end the over-application of phosphorus, reduce Europe’s dependence on foreign phosphorus and lessen the risk of price spikes (Speight, 2013).

In its resource efficiency policy, Sweden (as the only country) has put forward a target of 60% recovery by 2015 of phosphorus compounds present in wastewater for use on productive land. At least half of this amount should be returned to arable land (European Environmental Agency, 2011). Switzerland is in the process of making phosphate recovery from sewage sludge, animal meat and bone meal obligatory (ESPP, 2013).

Technologies to recover phosphorus still haven’t reached maturity to be deployed on a large-scale, but policies that build market confidence for recycled phosphorus encourage further research and development of these technologies and make them ready to be brought to the market (Eureau, 2013). The implementation of a nutrient credit-trading program would trigger the development of a market for recycled phosphorus (OECD, 2012).

3.1.4 Nutrient recycling from digestate with microalgae

Microalgae can be used to recover nutrients from various organic waste streams, like manure digestate, and can be used this way as a slow-release fertilizer. Manure digestate is an especially attractive feedstock to grow microalgae, as it is less contaminated than sewage sludge digestate.

As renewable energy policies support the production of biogas through anaerobic digestion of organic wastes like manure, the accompanying volumes of resulting digestate are also increasing. Today liquid digestate is mainly used as agricultural fertilizer (WRAP, 2011). Haraldsen *et al.* (2010) found that liquid digestate from anaerobic treatment of green household waste had the same fertilizer value as a (mineral) NPK fertilizer to barley.

Because of its liquid nature and its chemical composition, digestate application might worsen problems of nutrient leaching and runoff from agricultural lands, contributing to eutrophication problems of receiving water bodies.

Anaerobic digestion is a microbiological process that converts carbon compounds present in manure (or other organic feedstocks like sludge) into biogas (CH₄) and produces thereby a digestate, which contains non-digestible fiber, nutrients and water. The nutrient content of manure is unaffected, and the nutrient content of ingoing manure is the same as of the effluent (i.e. digestate). Research suggests that nutrients, however, are transformed during digestion into a form that is more readily available to plants. Organic nitrogen is partly converted into ammonium-nitrogen (SAC and ADAS, 2007) and organic phosphorus is

partly released from the organic fraction and becomes available as water-soluble P (SAC and ADAS, 2007; Tambone *et al.*, 2010). As a result of the digestion process, it might be anticipated that the proportion of readily available nutrients increases. Digestate nutrients become as such more vulnerable to environmental losses, e.g. nitrate leaching to surface and groundwaters and NH_3 losses to the atmosphere (SAC and ADAS, 2007; Sørensen *et al.*, 2011). However, research into the environmental effects of digestate is in its early phase, as digestate production is a rather recent phenomenon. More research is needed to improve current knowledge on the environmental effect of digestate and its fertilizer value under different soil and treatment conditions (SAC and ADAS, 2007; Sørensen *et al.*, 2011; Möller and Müller, 2012).

Although research results are preliminary, they do give an indication of the rather negative effect of digestate on the environment in comparison to untreated slurry. There is increased interest in creating improved fertiliser products from digestate, in order to increase its value, secure outlets and potentially generate an additional revenue stream for the biogas plant (WRAP, 2012). Microalgae could be used to recover nutrients from the liquid fraction of digestate and as microalgae incorporate these nutrients into their biomass, a fertilizer is created that is less prone to nutrient losses towards the environment (Wilkie and Mulbry, 2002; Mulbry *et al.*, 2006; WRAP, 2011). By reducing the volume of the liquid digestate, the nutrients become more manageable and some reclaimed water may be produced (WRAP, 2011).

A first study about the fertilizer value of microalgae grown on anaerobically digested dairy manure was conducted by Mulbry *et al.* (2005). Mulbry *et al.* (2005) showed that dried algal biomass produced from the treatment of anaerobically digested dairy manure could substitute for commercial fertilizers used for potting systems. Plants grown in potting mixes amended with algae¹ were equivalent in mass and nutrient content to plants grown with an equivalent amount (on an N-availability basis) of a commercially available fertilizer. According to Mulbry *et al.* (2005, cited in Adey *et al.*, 2011) dried algae are an excellent alternative to mineral fertilizers because they don't contain ammonia-N or nitrate-N that can leach into groundwater or runoff to surface waters at the time of application. Instead, when applied to the surface of or lightly incorporated into the soil, the dried algae break down as seedlings grow. About 25% to 33% of algal N becomes available to plants within 21 days after application, while only about 3% of the biomass N was available as mineral N at the time of application (Mulbry *et al.* 2005; cited in Adey *et al.*, 2011). Applying dried algal biomass to soils would not result in NH_3 volatilization as is the case with manures, and algal biomass may not have to be tilled into soil. This benefit may allow the algal biomass to be side-dressed into growing crops (Mulbry *et al.*, 2005). Kebede-Westhead *et al.* (2004) found that the concentration of heavy metals in microalgae grown on dairy manure were low enough not to reduce its value as soil or feed amendment.

Nutrient recovery from the liquid digestate fraction through microalgae biomass production stands next to other nutrient recovery technologies, like struvite precipitation and recovery of nitrogen as ammonium-sulfate. Nutrients are in this way recovered as minerals (Lesschen *et al.*, 2013), which are not slow-release fertilizers and thus more prone to nutrient leaching to the environment.

Currently there are various technologies available for digestate treatment and nutrient recovery, but high capital and operational costs are barriers to their implementation on a significant scale (Wrap, 2012). Struvite precipitation is starting to be implemented in demonstration pilots in the UK, Belgium, the Netherlands and Germany (EU phosphorus platform, 2014; Waste Management World, 2010).

¹Mulbry *et al.* (2005) assessed the fertilizer value of benthic microalgae, i.e. microalgae growing fixed to a surface. These microalgae

3.2 Biofertilizers, soil conditioner and plant biostimulants

Other than using microalgae as a slow-releasing fertilizer as their biomass decomposes (see chapter 3.1), living microalgae can be used as a nitrogen-fixator to bring atmospheric nitrogen into to the soil, and as soil conditioner.

Cyanobacteria are traditionally used as a source of organic nitrogen (N) in rice paddy fields, due to their ability to fix atmospheric N. Inherent fertility of tropical rice field soils was attributed to the activity of diazotrophic cyanobacteria. Agronomic trials on rice commonly show that N contributed by cyanobacteria is in the order of 20-30 kg N/ha (FAO, 1981; cited in Habib *et al.*, 2008; Goyal, 1993; cited in Chakdar *et al.*, 2012). Beneficial effects of cyanobacteria inoculation have also been reported in other crops (barley, oat, tomato, radish, cotton, sugarcane, maize, chilli and lettuce) (Chakdar *et al.*, 2012). Cyanobacteria could also find widespread application as soil conditioner. During their growth in soil they excrete certain organic compounds, which diffuse around soil particles and hold/glue them together as micro-aggregates. Organic amendments not only act by improving soil structure, but also strongly influence soil microflora (Chakdar *et al.*, 2012). Furthermore, cyanobacteria are able to solubilize and mobilize phosphorus and make it available to plants. As such, certain cyanobacteria can be exploited for efficient utilization of low-cost, low-grade rock phosphate fertilizers, while at the same time providing organic N through atmospheric N fixation (Chakdar *et al.*, 2012). Fertilizers that consist of microbial inoculants of bacteria, algae or fungi, which augment the bioavailability of nutrients to plants, are called biofertilizers. These biofertilizers enhance soil fertility by fixing atmospheric nitrogen and by mineralizing of phosphorus and potash (Markets and Markets, 2014). The market of biofertilizers was estimated at a value of \$440M in 2012 (AgroNews, 2014), whereas conventional fertilizers had a market size of \$2.44 billion in 2012 (Transparency Market Research, 2014).

In India, cyanobacteria (e.g. *Spirulina*) are sold on the market to be used as fertilizer by rice farmers. This natural nitrogen source is only one-third the cost of chemical fertilizer and it increases annual rice yield in India by an average of 22 percent. Where chemical fertilizers are not used, algae give the same benefit as 25 to 30 kg of chemical nitrogen fertilizer per acre. The use of *spirulina*-based fertilizers is impeded by readily available and preferred inorganic fertilizers (Habib *et al.*, 2008). Chemical nitrogen fertilizers are heavily subsidized in India (Anand, 2010), thus impeding the use of organic nutrients such as cyanobacterial nitrogen.

Next to some microalgae species that can provide an abundance of nutrients to plants, microalgae can also contribute to the vigour of plants, thus increasing the plants' resistance against biotic and abiotic stresses. Application of microalgae extracts on agricultural crops (e.g. wheat, barley, rice, tomatoes, broad beans, bananas, papaya and passion fruit) lead to better growth and yield performance (Abd el Moniem *et al.*, 2008; Garcia Senin, 2013; Dubey and Dubey, 2010). Increased antioxidant content, higher antioxidant activity, better root development, and higher number and weight of fruits and seeds are some of the effects that were observed during experiments. For example, *Nannochloris sp.* alleviates the negative effects of drought stress on plant development in tomatoes (Oancea *et al.*, 2013). Aqueous extracts of *Chlorella kessleri* increased the percentage of germination, seedling growth parameters, leaf area, pigments content and the fresh and dry weights of roots and shoots of *Vicia faba* (broad bean) compared to controls (El-Naggar *et al.*, 2005). *Chlorella* extracts allowed reducing the nutrient input and still obtain the same growth characteristics in soilless-grown squash (Dasgan *et al.*, 2010). Substances that improve the vigour of plants, without specifically targeting a certain plant disease and which do not provide significant quantities of nutrients are called biostimulants.

Biostimulants are organic materials that, when applied in small quantities, enhance plant growth and development such that the response cannot be attributed to the application of traditional plant nutrients. It acts on the physiology of the plant through different pathways to improve nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality. Biostimulants differ from crop protection products

because they act only on the plant's general vigour and do not have any direct actions against pests or disease (EBIC, 2011). In the case of cyanobacteria, a number of growth promoting substances, e.g. particular amino acids, bioactive polysaccharides, vitamins (B12, nicotinic acid, pantothenic acid, folic acid etc.) and growth hormones (IAA), have been documented (Chakdar *et al.*, 2012).

The work on microalgal biostimulants is a rather recent phenomenon in comparison to biostimulants made from seaweed. There are suppliers of macroalgal biostimulants in several countries of the EU and Asia and in the US. Biostimulants made from macroalgae have been on the market since the early 1980s and scientific research is now bit-by-bit unraveling the pathways through which these biostimulants work. Macroalgae (extracts) have since long been used as soil conditioner in coastal regions (Newton, 1951; Booth, 1969; cited in Sharma *et al.*, 2014). Research has shown that use of macroalgal biostimulants on crop plants leads to enhanced rooting, higher crop and fruit yields, freezing, drought and salt tolerance, enhanced photosynthetic activity and resistance to fungi, bacteria and viruses (Sharma *et al.*, 2014). The commercial use of biostimulants from microalgae is much smaller in comparison, but research into and commercialization of microalgal biostimulants is starting to take off.

There are no figures available on the size of the macroalgal biostimulants market, but the entire biostimulants market was estimated to be €500million in Europe in 2013 (EBIC, 2013). The market of biostimulants can be subdivided in (i) microbial inoculants, (ii) humic acids and fulvic acids (iii) aminoacid-based products and (iv) seaweed extracts (Calvo *et al.*, 2014). It is not known what the size of the seaweed extract biostimulants market is. Based on the number of products and suppliers to be found on Internet, it seems that the market size of microalgae biostimulants is much smaller than that of macroalgae biostimulants. Several producers of microalgae biostimulants have been identified, e.g. in Spain (Agroplasma S.A. and AlgaEnergy S.A.), Turkey (Mct Tarim), USA (AgroValley Inc.) and Soley Biotech (India). These extracts are based on the commonly produced microalgae, like *Spirulina*, *Chlorella*, *Nannochloropsis* and *Scenedesmus*. For example, Soley Biotechnology Institute commercializes organic microalgae soil fertilizers as mixtures of *Spirulina*, *Haematococcus*, *Chlorella sp.* and *Nannochloropsis sp.* (€9-23/kg) (Soley Biotechnology Institute, 2014). Agroplasma S.A. (Spain) sells its Ferticell microalgal biostimulants for €1300-1500/tonne. For these applications, microalgae are grown in freshwater, to avoid salt accumulation on agricultural fields and to avoid large variability in the microalgae composition. Since there is a distinct difference in composition between macroalgae (rich in polysaccharides) and microalgae (almost no polysaccharides, but rich in protein), their mechanisms of action will differ as well.

Biostimulants face competition from synthetic plant growth promoters. The global demand for plant growth regulators was valued at USD 3.4 billion in 2012 (Transparency Market Research, 2014). Biostimulants have a market share of 27% or approx. €900M in the global market of plant growth promoters (EBIC, 2013). The market outlook for biostimulants is good, as certain pesticides are (gradually) withdrawn from the market due to the effectuation of the EU Pesticide Authorisation Directive (EC 91/414). Furthermore, concerns about the development of resistance against commonly used pesticides; increasing costs of fertilizers and the anticipated effects of climate change in Europe (water and drought stress) (Sharma *et al.*, 2014) provide an impetus for the development and commercialization of microalgal biostimulants.

3.3 Biopesticides and antifouling agents

The use of microalgae in agriculture may go further than that of biostimulants. Microalgae, and especially *Spirulina*, produce a broad range of allelochemicals, which may be commercially exploited as biopesticides (Rastogi and Sinha, 2009; Hernandez-Carlos and Gamboa-Angulo, 2011). For example, majusculamide-C, a micro filament depolymerizing agent from *Lyngbya majuscula*, has shown potent fungicidal activity and may find application in the treatment of resistant fungal-induced diseases of plants and agricultural crops (Chakdar *et al.*, 2012). Other toxins were found to be active against parasites of malaria, Chagas disease and leishmaniasis (Linnington *et al.* 2008; cited in Chakdar *et al.*, 2012). *Chlorella vulgaris* has been found to have phytoprotective effects on grape seedlings infected with *Xiphinema* nematodes, though the mechanism through which *Chlorella v.* reduced the number of nematodes in the test plants was not determined (Bileva, 2013). Cyanobacterial metabolites that are toxic to other algae could also be used as algaecides to combat (toxic) algal blooms or in the development of environmentally friendly and tributyltin-free antifouling paints for ships (Bagchi *et al.*, 1990; Bhadury & Wright, 2004; cited in Volk, 2005). The ecological implications of using microalgal toxins for this purpose have not been evaluated yet (Rastogi and Sinha, 2009).

Today microalgae (extracts) are not yet on the market for use as biopesticide. Biopesticides are defined as mass-produced agents manufactured from a living microorganism or from a natural product and sold for the control of plant pests (Chandler *et al.*, 2011). Biopesticides are often used as a key component of integrated pest management (IPM) programs, mainly as a means to reduce the load of synthetic pesticides (Katti, 2010). IPM combines a range of complementary methods to reduce a pest population, while minimizing impacts on other components of the ecosystem. Synthetic pesticides with a single active agent are likely to induce the development of resistance in pests. Biopesticides on the other hand contain a complex array of compounds with multiple effects and are less likely to induce resistance development (Katti, 2010). Synthetic pesticides also give rise to environmental concerns, i.e. their toxicity towards a wide spectrum of organisms and the long residual action of these pesticides. Biopesticides are on the other hand selective, produce little or no toxic residue, and development costs are significantly lower than those of conventional synthetic chemical pesticides (Chandler *et al.*, 2011).

Nonetheless, the market for biopesticides is marked by difficulties. Because of their specificity, biopesticides are niche market products with low profit potential. The limited practical experience and evidence base of biopesticides aggravates the farmers' already high risk-aversion. Additionally, the large variance of products that can be used to compose the technology bundle of an IPM portfolio, and the interdependency between different products may make it difficult to substitute for new products or technologies as they come available (Chandler *et al.*, 2011). There are strong arguments for farmers to keep on relying heavily on synthetic pesticides. Synthetic pesticides are still cheaper than biopesticides (application costs of USD 5/acre vs USD 10-80/acre) (Cox and Radovich, 2010; Uri, 2006), they are readily available, easy to transport and store and have a longer shelf life.

Today's market of biopesticides is small in comparison to that of synthetic pesticides (USD 2,1 billion vs USD 35,4 billion), but it is expected to grow with 12% CAGR by 2017, whereas synthetic pesticides are only expected to grow with 7% by 2017 (BCC Research, 2012). The continuing assessment and (gradual) withdrawal of unsafe 'old chemistry' pesticides through the EU Pesticide Authorisation Directive (PAD) (EC 91/414) and the 2009 EU Framework Directive on the Sustainable Use of Pesticides (in which IPM takes a central place), provide a necessary stimulus to the development of safe and environmental friendly biopesticides (Chandler *et al.*, 2012; Hillocks, 2012).

3.4 Bioplastics

3.4.1 Status of the bioplastics market

Microalgae can be plasticized and incorporated into a wide range of bioplastics. The term bioplastics refers to a family of materials with varying properties and applications. According to European Bioplastics, a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties. The property of biodegradation does not depend on the resource basis of a material, but is rather linked to its chemical structure. Plastics that are 100 percent biobased plastics may be non-biodegradable, and 100 percent fossil based plastics can biodegrade (European Bioplastics, 2013) (Table 3).

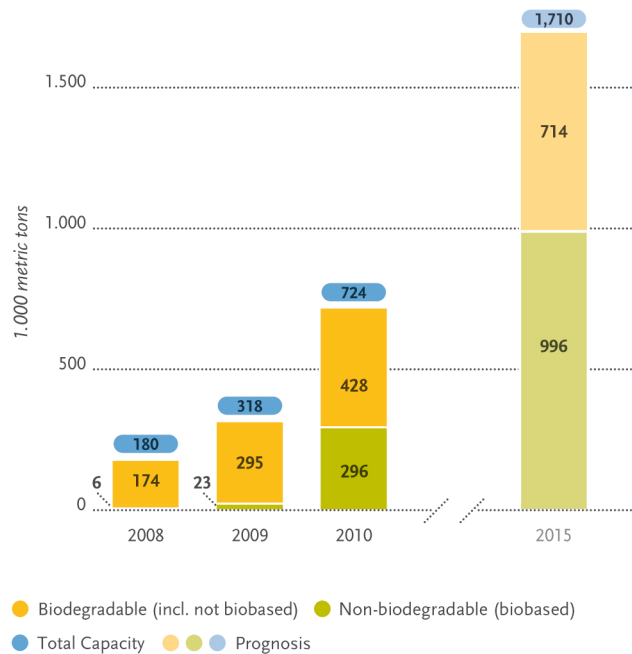
Table 3: Classification of bioplastics by material properties (European Bioplastics, 2013).

Renewable resources	(Partly) biobased bioplastics <i>'drop-in' bioplastics</i> Identical to their fossil versions e.g. PE, PP, PET,...	Biobased and biodegradable bioplastics e.g. PLA, PHA, starch blends
Fossil resources	Conventional plastics e.g. PE, PPT, PET, PVC	Biodegradable bioplastics e.g. PBAT, PCL
	Non-biodegradable	Biodegradable

Bioplastics have two large advantages. Biobased bioplastics provide a means to reduce the carbon footprint of some materials and products, by using biomass as a raw material that has sequestered carbon during its growth. Additionally, biodegradable bioplastics allow for the reduction of waste volumes that are sent to landfills because of their compostability (European Bioplastics, 2013).

Despite their surplus cost, bioplastics experience a growing market demand. Consumer demand for sustainable packaging, green branding, restrictions on landfilling and climate change policies, development of particular plastic properties and changing raw material prices are all driving the market of bioplastics (Harlin & Vikman, 2010). Between 2007 and 2010, the production capacity of the bioplastics industry has quadrupled (Bio-plastics.org, 2013). However, bioplastics have not been taken out of their specialty niche and brought to mass production (mainstream) markets yet. Today, they account for less than 1% of the world annual production of plastics (total global production of 270,000 kt/yr). However, prospects for bioplastics are favourable. European Bioplastics estimates that the annual global production of bioplastics will increase from 724 kt in 2010 to 1,710 kt by 2015. The increase is expected to be driven by demand for non-biodegradable bioplastics, the so-called 'drop-in' bioplastics that have the same properties as their fossil-based equivalents. Their consumption is estimated to go up from 6 kt in 2008 to 1000 kt in 2015, to be used in food-packaging, consumer goods and the automotive industry (Bio-plastics.org, 2013; Ceresana, 2014). Today, more and more applications for durable bioplastics are brought to the market, relying on innovation efforts by companies like BASF, DSM and Braskem, which have resulted in the development of high performance bioplastics (e.g. resistance to high/low temperatures, flexibility, transparency) (De Guzman, 2013b).

Global production capacity of bioplastics



Source: European Bioplastics | University of Applied Sciences and Arts Hanover (Status May 2011)

European Bioplastics | Fachhochschule Hannover University of Applied Sciences and Arts

Figure 5: Global production capacity of bioplastics (bio-plastics.org, 2013).

Companies are also expanding their business in the area of biodegradable plastics. For example BASF is stepping up its research biopolymers to be used in compostable waste bags and bio-based foam for electronics and food packaging (De Guzman, 2013c). Natureworks, currently the biggest global producer of PLA, is continuously expanding its production capacity. Their production capacity in 2013 has been estimated to be 300,000 tonnes/year (De Guzman, 2013a).

It is generally agreed that biodegradable plastics will succeed in the plastics market where their specific properties (e.g. biodegradability and gas permeability) bring added value (Smith, 2009). This market potential has already been proven for high value medical applications. However, their cost should drop to be able to serve low-value markets on a large scale. In 2007 bioplastics were sold at a price of \$2 to 5.5 per kg depending on the raw material, while the price of petroleum-based resins was \$1.55 to \$1.0 per kg (Smith, 2009; The Augusta Chronicle, 2007). Several other factors are also limiting the market penetration of bioplastics. Confusion amongst consumers about terminology and used claims, as well as conflicting definitions used within the industry have slowed down the adoption of bioplastics (SPI Bioplastics Council, 2012). Another restraining factor to the use of biodegradable plastics on a larger scale is the continuing lack of infrastructure for the disposal of compostable plastics (SPI Bioplastics Council, 2012). Additionally, the number of biopolymers available on a commercial scale is limited due to lack of R&D investments by the public and private sector in the development of bioplastics (SPI Bioplastics Council, 2012; Chen, 2009). However, the potential for innovation in this area of the plastics industry is large, and new developments are under way by the introduction of new biobased monomers such as succinic acid, butanediol, propanediol or fatty acid derivatives (European Bioplastics, 2013).

The biopolymer market was worth €3.67 billion globally in 2012, and is projected to grow to €13.7 billion (IfBB, 2013). At the moment the market is dominated by packaging applications, and it is estimated that bottles will represent 60% (or €7.5 billion) of the bioplastics market by 2016 (IfBB, 2013) (Figure 6 and Figure 7). The global plastics market has a value of more than \$400bn (Plaxica, 2010), of which \$180 billion is attributed to the packaging industry (Visiongain, 2010). Bioplastics are making inroads into a variety of markets, from agricultural applications (e.g. biodegradable pots and mulch film) to medical uses (e.g. drug delivery and lab ware) to consumer goods (e.g. packaging, electronics cables and housing, arm rests, seats, carpet backs) (SPI Bioplastics Council, 2012).

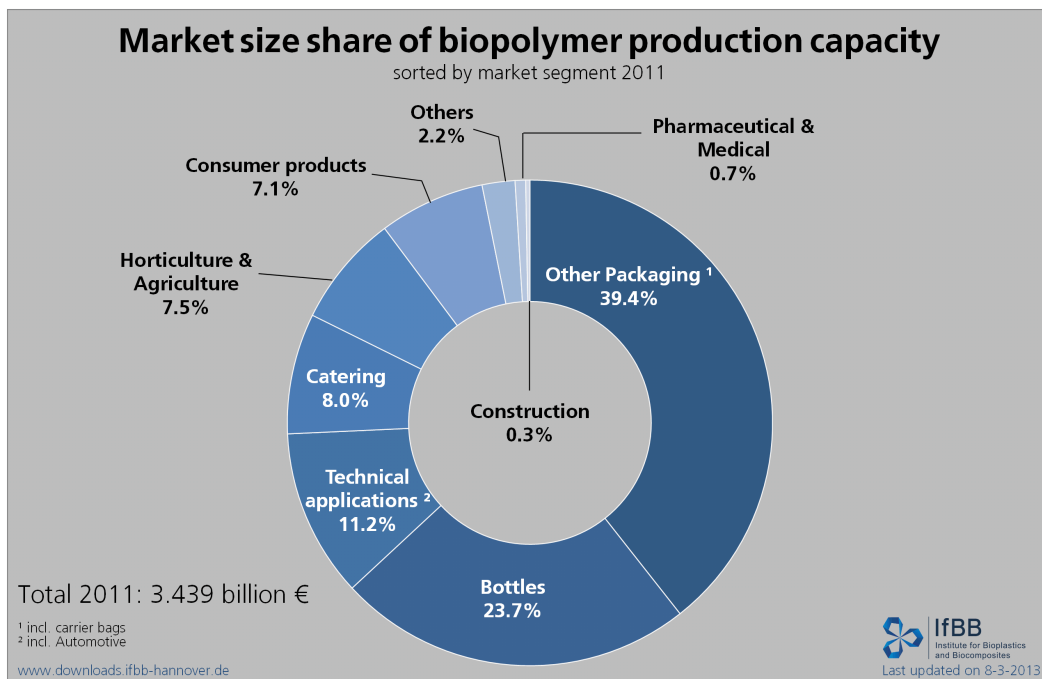


Figure 6: Market size share of biopolymer production capacity, sorted by market segment in 2011 (IfBB, 2013).

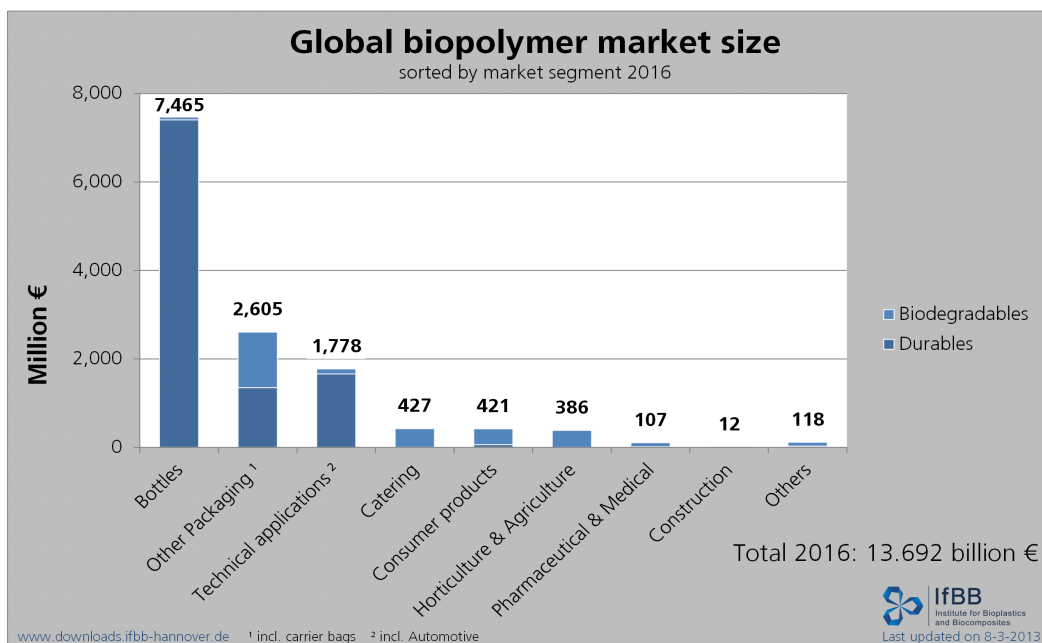


Figure 7: Global biopolymer market size, sorted by market segment in 2016 (IfBB, 2013).

3.4.2 Outlook for microalgae bioplastics

Microalgae can be used as a raw material for the production of bioplastics or as a catalyst for bioplastics production, depending on the production processes applied. Generally speaking biobased plastics can be produced according to three production processes (Figure 8). Firstly, biomass-sourced polymers can be considered as a relatively uniform hydrocarbon feedstock that can be plasticized by thermochemical processes, like extrusion. Extrusion is a shaping process in which polymer material is forced through a die by applying pressure, resulting in temperature increases that liquefy and shape the polymer material. When starch or protein biomass is used as raw material, processes of starch gelation and protein denaturation allow for the shaping of the material and determine its properties. This is how e.g. starch-based polymers are produced.

Secondly, biopolymers can be produced by chemical polymerization of monomers obtained from fermentation of agro-resources. The best-known example is polylactic acid (PLA) (Madhavan Nampoothiri *et al.*, 2010). Thirdly, bioplastics can be produced as intracellular inclusion in fermentative organisms. A wide range of bacteria is able to digest low molecular weight monomer feedstocks (e.g. sugar) and assimilate it into a bioplastic, like polyhydroxy-alkanoate (PHA) (Chen, 2009).

PHA and PLA closely match the characteristics of existing non-degradable plastics and are at the same time 100% biodegradable. However, these bioplastics are too expensive to be used in the common disposable applications such as packaging (Wolf *et al.*, 2005). Starch is a cheaper alternative natural polymer that is produced on a large scale. However, starch blends with an amount of starch higher than 25-30% typically have poor mechanical properties (due to thermodynamic immiscibility and non-wetting of starch with other polymers), therefore it is blended with other polymers. To allow for starch blends with more than 30% starch, starch and other polymers in the blend need to be modified by adding functional groups to make them more compatible (Kalambur & Rizvi, 2006).

About 80% of the biopolymer market is covered by thermoplastic starch (i.e. modified starch), blended with either biodegradable or non-biodegradable synthetic polymers. Bioplastics from starch are available at a price of €2.00 up to €4.50 per kg for specialty products (Bio-plastics.org, 2013). According to IfBB (2013) the five most important bioplastics on the market in 2012 were Bio-PET (29%), biodegradable polyesters (fossil-based) (19%), biodegradable starch blends (16%), PLA and PLA blends (12%) and bio-PE (10%).

BIOPLASTIC PRODUCTION TECHNOLOGIES	Thermochemical polymerization Natural, raw biomass polymers that are plasticized by means of heat Building blocks: - starch, sugars - protein e.g. soy, gluten - lignin	Chemical polymerization Monomers obtained through microbial fermentation (e.g. lactic acid) that are polymerized by means of chemical reactions Substrates for microbial monomer production: - starch, sugars - CO, CO ₂ - hydrolyzed lignocellulose	Intracellular accumulation Polymers produced within the cells of microorganisms Growth substrate for microorganisms: - sugars - CH ₄ , CO ₂ - fatty acids - hydrolyzed lignocellulose
RESULTING BIOPLASTICS	- Thermoplastic starch	- PLA (polylactate) - Bio-PET	- PHA (polyhydroxy-alkanoate) - Other e.g. bacterial cellulose
USE OF MICROALGAE IN PRODUCTION TECHNOLOGY	Protein-rich microalgae biomass as polymeric material (early commercialization)	Microalgae monomer exudates as building blocks for polymers (exploratory research)	Microalgae as PHA-producing cell factories (exploratory research)

Figure 8: Classification of biobased and biodegradable plastics according to production process (author's own scheme).

Microalgae could fit in the three production technologies for the production of plastics that are both bio-based and biodegradable (see Figure 8). Microalgae biomass can be thermochemically processed into bioplastics (Zeller *et al.*, 2013). Additionally, microalgae also have potential application as fermentative organism for either the production of monomer building blocks that are subsequently chemically polymerized into bioplastics (Sijtsma & Barbosa, 2013), or for the production of bioplastics by intracellular accumulation of polymers assimilated from simple feedstocks (Hempel *et al.*, 2011).

Microalgae bioplastics produced from thermochemically processed microalgae biomass have recently been brought to the market by American companies Algix LLC. and Algaeplast Inc. Although microalgae have low starch content, their protein content (30-60%, depending on species) can serve as a polymeric material (Slavin, 2012), analogous to soy protein and milk protein. The crude fiber portion of the algae biomass (containing e.g. cellulose and hemi-cellulose) has been shown to act like a reinforcing agent in plastics, increasing stiffness and tensile strength, but reduces elongation (Slavin, 2012).

Although protein is about 5 times more expensive than starch (approx. 1 €/kg versus 0.2 €/kg), protein is a polymer that is in demand to produce bioplastics. Proteins have unique functional properties (thermoplastic, elastomeric, adhesive), which are often very different from the properties of conventional fossil-based polymers or other hydrocolloids (e.g. starch or cellulose derivatives) (Guilbert *et al.*, 2006). Due to the variability of amino acid composition in proteins and the diversity in available formulations and material formation techniques, there is significant potential to modulate the properties of protein-based materials (Guilbert *et al.*, 2006). Protein waste fractions from industry, like wheat gluten, soy protein and casein, which are available at low cost have been processed into plastics, like bioplastic films and bio-based paints (Wool & Sun, 2005).

The potential to use microalgae as a producer of monomer building blocks for bioplastics is just beginning to be explored. First steps are taken by the European funded SPLASH-project (Sustainable Polymers from Algae Sugars and Hydrocarbons) (2013-2017), which aims to develop green alga *Botryococcus braunii* into a producer of building blocks for polymers. This alga excretes sugars (polyesters) and hydrocarbons (polyolefins), which will subsequently be converted into building blocks such as apidic acid from galactose, 2,5-furandicarboxylic acid from glucose, rhamnose and fucose. These building blocks will be converted through polymer condensation into polyethylene 2,5-furandioate (PEF) and (poly) 1,4-pentylene adipate-co-2,5-furandioate. In the project the optimal production circumstances for the desired sugars and hydrocarbons, in situ extraction and methods isolation are assessed. Researchers cooperate with the business community to develop plastics into food packaging and fibres for ropes and nets, as well as to develop new polymers and plastic products (Algaeobserver, 2013; Sijtsma & Barbosa, 2013).

3.5 Conclusion chemicals & materials

Nitrogen-fixing microalgae, like *Spirulina*, have a long history of use in rice paddy fields, where their benefit has been proven scientifically. The development of slow-releasing and environmentally friendly fertilizers based on microalgae holds significant promise (see also chapter 3 on nutrient recycling). Some microalgae species provide nutrients to plants, but an even larger number of species provides micronutrients or plant-stimulants. This improves the resistance of plants towards various stressors. Seaweeds are being commercialized for this purpose for over thirty years now, and developments in EU legislation concerning biostimulants provides good perspectives for microalgae-based biostimulants. The work on the potential of producing biopesticides from microalgae is still in the academic domain, but legislative developments concerning sustainable use of pesticides and establishment of integrated pest management (IPM) practices opens perspectives for the development of microalgae-based biopesticides. Bioplastics are an interesting new application for microalgae, and first commercial algae-bioplastics have been brought to the market recently. In these applications microalgae biomass is used as polymeric material to be processed thermochemically into bioplastics.

Table 4: Overview of synthetic counterparts of microalgae-based materials and chemicals, and outlook for microalgae in these markets.

Product	Substitutes	Market size (Global)	Value substitutes	Outlook algae
Biofertilizers	Synthetic fertilizers	USD 440M	EUR 0,2-0,5/kg	+
Biostimulants	Synthetic growth promoters	EUR 900M	EUR 30-250/kg (90% pure)	++
Bioesticides	Synthetic pesticides	USD 2,1 Bn	USD 5/acre	+
Bioplastics	Fossil-based plastics	1,710 kton	EUR 1.14/kg	+/-

4 Food and feed

Edwards (2008) reports that algae have been used as food product for over 4,000 years in Africa, Central and South America and Asia. The aforementioned expected growth of the world population, especially outside of the European Union, provides an opportunity for algae in the sector of foods and feeds. Algae could accommodate the expected increase in food and feed demand. In this chapter the food market and the potential opportunities and threats for algae are discussed.

4.1 Food

The consumption of algae is not a new phenomenon. In Asia, Central America and Central Africa microalgae like *Spirulina*, *Chlorella* and *Nostoc* were harvested from lakes and consumed for their nutritional value. In China the same microalgae were even used as medicine against diarrhea, hypertension and hepatitis (Chu, 2012). Edwards (2008) mentioned the consumption of over twenty algae varieties in Japan alone.

Algae are primarily made up out of lipids, carbohydrates and protein. The composition depends primarily on the algae species (Foley *et al.*, 2011). Microalgae are a source of high quality, essential proteins, bioactive polysaccharides and pigments with therapeutic potential (Dewapriya and Kim, 2014). The protein content of some microalgae species, including *Chlorella*, *Spirulina*, *Scenedesmus*, *Dunaliella*, *Micractinium*, *Oscillatoria*, *Chlamydomonas*, and *Euglena*, accounts for more than 50% of the dry weight. These proteins bear high biological value (Becker, 2007) and compare favourably with the recommended reference protein pattern of the WHO (Becker, 2004). In comparison to conventional plant-sourced nutrients, microalgae offer the advantage of fermentative production and comparative simplicity of extraction of these valuable components (Dewapriya and Kim, 2014).

The current use of algae in food is predominantly the use as capsules sold as health food. The capsules containing algal powder are sold as remedy to a wide variety of illnesses (Becker, 2007). The use of algae biomass in health capsules represents about 75% of the algae food market (Pulz *et al.*, 2004). Algae are also used as ingredient in pasta, drinks, snacks, candy and gum (Spolaore *et al.*, 2006). The use of algae as food product is overall still very limited. The species of micro-algae that are currently used as food or food ingredient are restricted. Only *Spirulina* (*Arthrospira*), *Chlorella* and *Dunaliella* are used. In some specific regions other species can be found, like *Nostoc* and *Aphanizomenon* (Pulz *et al.*, 2004).

Despite the positive nutritional composition, dried micro-algae have not gained significance as food or food ingredient. The reason for this minimal use in food is a number of obstacles. The first is related to the properties of dried algae biomass. The powder-like consistency, the green colour and the fishy smell of the algae biomass are the most significant obstacles. The high production cost is the final obstacle (Becker, 2007).

To facilitate the digestion of microalgae, the algae cell walls are disrupted. Several methods for algal cell disruption have been evaluated including ultrasonication, bead beating, microwave (at 100°C), osmotic shock (with NaCl) and autoclaving (at 121°C) with varied results. Sonication has the advantage of being able to disrupt the cells at relatively low temperatures when compared to microwave and autoclave. In addition, sonication does not require the addition of beads or chemicals, thus decreasing processing cost. Ultrasonication has been commonly used for cell lysis and homogenization, and could be an effective treatment for breaking up the rigid cell envelopes of microalgae (Jeon *et al.*, 2013).

4.2 Functional food and food additives

In a number of countries first steps are taken to explore microalgae as ingredient for food. Microalgae can already be found, as ingredient, in pasta, bread, yoghurt and soft drinks (Pulz *et al.*, 2004). A number of potential applications of algae as food ingredient will be highlighted in this chapter. Food products that are enriched with specific, bioactive compounds are called functional foods, e.g. foods to which algae ingredients are added for health promotion purposes.

Functional ingredients are mainly sourced from plants and microorganisms. There are well-established markets for omega-3 polyunsaturated acids, sterols, antioxidants, fibres, probiotics, vitamins, flavonoiden and minerals. The research done on numerous health effects and/of numerous algae is extensive. A list on microalgae species, functional components and health promoting effects is taken from Ibanez and Cifuentes (2013) (Table 5). Table 5 highlights the fact that a broad range of health effects have been observed, which are caused by a multitude of components produced by numerous microalgae species. This diversity indicates that potential food applications are plenty, resulting in a large potential market. The potential is based on the growing number of foodstuff on the market with additional ingredients, like PUFA's and vitamins. A few potential markets are briefly addressed.

As mentioned, the use of dried algae biomass in human health food supplements represents 75% of the total commercial value of microalgae. This market has a volume of 5,000 to 10,000 tonne dry matter/year (excl. processed products) and a turnover USD 1.25 billion a year (excl. processed products) (Pulz *et al.*, 2004; Spolaore *et al.*, 2006). It is estimated that in 2006 the nutritional market had a value of USD 228 billion, with an estimated share for functional foods of USD 50 billion to USD 85 billion.

Taken from Rosenberg (2008) the following price levels for products based on micro-algae are listed (Table 6). Estimations of the price and market size differ somewhat, resulting in price and market size ranges. The price levels, even if they may not be completely accurate, can be used to compare and assess food market segments with each other.

Table 5: Potential functional ingredients found in microalgae and their main health effects (Ibanez & Cifuentes, 2013).

Microalgae species	Functional compound	Health promoting effect
Dunaliella Salina	Carotenoids	Antioxidant, immunomodulation and cancer prevention
	Pheophorbide a-, b-like compounds	Inhibition of cytopathic effect of herpes simplex Virus 1
	PUFAs (n-3) fatty acids	Reduce risk of certain heart diseases
Haematococcus pluvialis	Carotenoids	Antioxidant, immunomodulation and cancer prevention
	PUFAs (n-3) fatty acids	Reduce risk of certain heart diseases
Chlorella spp.	carotenoids	Antioxidant, immunomodulation and cancer prevention
	PUFAs (n-3) fatty acids	Reduce risk of certain heart diseases
	Sulfated polysaccharides	Antiviral, antitumour, antihyperlipidaemia, and anticoagulant
	Sterols	Reduce total and LDL cholesterol, immunosuppressant effects
Arthrospira platensis (Spirulina)	PUFAs (n-3) fatty acids	Reduce risk of certain heart diseases
	Phycobiliproteins	Immunomodulation activity, anticancer activity, and hepatoprotective, anti-inflammatory and antioxidant properties
	Phenolic acids	Antioxidant activity
	Vitamin E	Antioxidant activity
Porphyridium spp.	Sulfated polysaccharides	Antiviral, antitumour, antihyperlipidaemia, and anticoagulant
	Vitamin E	Antioxidant activity
Cryptomonads	Allophycocyanin	Inhibition of cytopathic effect, delay in synthesis of viral RNA of enterovirus
Navicula directa Gymnodinium sp. Gyrodinium impudicum	Polysaccharides	Inhibition of hyaluronidase of herpes simplex and influenza A virus, antileukaemic activity
Peridinium bipes	Diadinochrome A, B, Diatoxanthin/cynthiixanthin	Cytotoxic effect in HeLa cells
Muriellopsis spp. Scenedesmus almeriensis Chlorococcum citrifforme Neosporangiococcus gelatinosum	Carotenoids	Antioxidant, immunomodulation and cancer prevention
Amphidinium spp.	Karatungols	Antifungal, antiprotozoan

Table 6: Food products, microalgae, price levels and producers per type of food product (Rosenberg et al., 2008).

Products synthesized by microalgae			
Product	Microalgae	Price (USD)	Producer
β-Carotene	<i>Dunaliella</i>	300–3000/kg	AquaCarotene (Washington, USA) Cognis Nutrition & Health (Australia) Cyanotech (Hawaii, USA) Nikken Sohonsa Corporation (Japan) Tianjin Lantai Biotechnology (China) Parry Pharmaceuticals (India)
Astaxanthin	<i>Haematococcus</i>	10,000/kg	AlgaTechnologies (Israel) Bioreal (Hawaii, USA) Cyanotech (Hawaii, USA) Mera Pharmaceuticals (Hawaii, USA) Parry Pharmaceuticals (India)
Whole-cell dietary supplements	<i>Spirulina</i> <i>Chlorella</i> <i>Chlamydomonas</i>	50/kg	BlueBiotech International GmbH (Germany) Cyanotech (Hawaii, USA) Earthrise Nutritionals (California, USA) Phycotransgenics (Ohio, USA)
Whole-cell aquaculture feed	<i>Tetraselmis</i> <i>Nannochloropsis</i> <i>Isochrysis</i> <i>Nitzschia</i>	70/L	Aquatic Eco-Systems (Florida, USA) BlueBiotech International GmbH (Germany) Coastal BioMarine (Connecticut, USA) Reed Mariculture (California, USA)
Polyunsaturated fatty acids	<i>Cryptocodinium</i> <i>Schizochytrium</i>	60/g	BlueBiotech International GmbH (Germany) Spectra Stable Isotopes (Maryland, USA) Martek Biosciences (Maryland, USA)
Heavy isotope labeled metabolites	N/A	1000–20,000/g	Spectra Stable Isotopes (Maryland, USA)
Phycocerythrin (fluorescent label)	Red Algae Cyanobacteria	15/mg	BlueBiotech International GmbH (Germany) Cyanotech (Hawaii, USA)
Anticancer drugs	N/A	N/A	PharmaMar (Spain)
Pharmaceutical proteins	<i>Chlamydomonas</i>	N/A	Rincon Pharmaceuticals (California, USA)
Biofuels	<i>Botryococcus</i> <i>Chlamydomonas</i> <i>Chlorella</i> <i>Dunaliella</i> <i>Neochloris</i>	N/A	Cellana (Hawaii, USA) GreenFuel Technologies (Massachusetts, USA) LiveFuels, Inc. (California, USA) PetroAlgae (Florida, USA) Sapphire Energy (California, USA) Solazyme, Inc. (California, USA) Solix Biofuels (Colorado, USA)

Over the years, algal biotechnology companies have brought a number of products to market, ranging from aquaculture feed to specialty chemicals. Currently, the development of pharmaceutical compounds and biofuels is a priority of the industry.

4.2.1 Omega-3 fatty acids and other valuable lipids

The market of omega-3 oils is primarily dominated by fish products. Nevertheless, the PUFA's of microalgae have advantages over fish oil. The PUFA's of micro-algae don't have unpleasant odours like fish oils do, and there is much less risk of chemical contamination. Heavy metal contamination is a reoccurring problem in fish oil. Extracting omega-3's from cultivated algae avoids this problem. The microalgae PUFA's are also easier to purify (Pulz et al., 2004). But more importantly, microalgae seem to be a solution to the dependence on forage fishing for the supply of omega-3 fatty acids (see chapter 5.3.1 on aquaculture). According to Frost and Sullivan (2011) the microalgae omega-3 market had a size of USD 82 million in 2012, and is expected to grow further, as opposed to the global omega-3 ingredients market with a size of USD 2.3 billion (123.8 kt) in 2013 (incl. fish oils, krill oils and algae oils) (Reportlinker.com, 2014).

4.2.2 Carotenoids

Microalgae have been used as a source of carotenoids for over 30 years. This is mainly beta-carotene from *Dunaliella*, which is used as a vitamin A precursor. Other commercially important carotenoids sourced from micro-algae are astaxanthin from *Haematococcus* to colour muscles in aquacultured fish and lutein, zeaxanthin and canthaxanthin used for chicken skin coloration and for pharmaceutical purposes (Pulz *et al.*, 2004).

The production of carotenoids is commercially one of the most important applications of microalgae. The worldwide demand for carotenoids was nearly \$1,2 billion in 2010 (BCC Research, 2011). A bottleneck for algae beta-carotene is that the price of algae beta-carotene can easily reach EUR 700,- per kilogram, while the market value of synthetic beta-carotene is only half of this (Guedes *et al.*, 2011). This indicates that the price of algae carotenoids is significantly higher than of their synthetic counterpart.

Table 7: Global market for carotenoids in 2004 and 2009 (US\$ Million) (Mortensen, 2009).

	β-carotene		Lycopene		Lutein		Cantaxanthin		Astaxanthin		Zeaxanthin	
	2004	2009	2004	2009	2004	2009	2004	2009	2004	2009	2004	2009
Supplements	125.0	128.0	50.5	68.7	54.0	85.0	3.0	3.0	3.5	4.8	22.0	35.0
Food	98.0	103.0	3.5	9.3	18.0	20.0	7.0	8.0	0	0	0	0
Cosmetics	6.0	7.0	0	3.0	0	0	0	0	0	0	0	0
Feed	13.0	15.0	0	0	67.0	82.0	138.0	145.0	230.5	252.2	0	0
Total	242.0	253.0	54.0	81.0	139.0	187.0	148.0	156.0	234.0	257.0	22.0	35.0

4.2.3 Food safety and taste, texture and odour

A number of studies show that food safety requirements are a bottleneck for the use of algae in food. A novel food item is only declared safe for human consumption, after a series of detailed toxicological tests (Becker, 2007). The introduction of novel foods and food ingredients on the European market requires detailed scientific information and a risk assessment report (EC regulation 258/97). The French company INNOVALG successfully applied for the *Odontella aurita* as a novel food against EC regulation 258/97 (Pulz *et al.*, 2004). This could be a first successful step towards an increasing use of algae in food and food ingredients. However, a successful introduction of the *Odontella aurita* would still mean that introduction of other novel food and food ingredients based on algae require separate application trajectories (EC regulation 258/97). This could be a hurdle for the introduction of further novel foods and food ingredients based on algae on to the European market.

Different studies mention the taste, texture and odour of algae as additional potential bottlenecks. Some studies indicate that the consistency, the colour and the smell of the algae biomass are the most significant obstacles (Becker, 2007); while other studies indicate that the algae are likely to take on the desired taste, texture and/or odour (Edwards, 2008). The taste, texture and odour are therefore relevant aspects to consider in the development of food products or food ingredients based on algae.

4.2.4 Conclusion food

The use of whole microalgae biomass as food supplement is commercially the most important application on the food market. Microalgae are also used as a source of food ingredients, most notably carotenoids and omega-3 fatty acids. The prospects for the most important microalgae ingredients, i.e. beta-carotene and omega-3 PUFA's are highlighted in Table 8. The natural beta-carotene ingredient market faces strong competition from synthetic beta-carotene. The PUFA ingredient market looks promising due to the benefits compared to fish PUFA. Although the food market is characterized by higher margins than the energy market, the economic viability of microalgae food (ingredients) still depends on the supply of

microalgae at competitive prices compared to more conventional foodstuffs to successfully enter the food market.

Table 8: Most important commercial applications of microalgae on the food market.

Product	Substitutes	Market size (microalgae products)	Value substitutes	Outlook algae
Whole microalgae biomass	-	USD 1,25 billion	USD 50/kg	+
Beta-carotene	Synthetic/natural	USD 98 million	EUR 220–2200/kg	+/-
PUFA	Fish-PUFA	USD 82 million	EUR 40/gram	++

4.3 Feed

The use of microalgae as aquaculture feed is a well-established application. It is estimated that about 30% of the current world algal production is sold for animal feed applications, primarily for aquaculture (Becker, 2007, Rosenberg *et al.*, 2008). The most promising animal feed markets are poultry and aquaculture. Research shows positive effects on animal health when small amounts of microalgae biomass are used in animal feed. The most important species of algae are *Chlorella*, *Scenedesmus* and *Spirulina*, which can positively affect animal health (Pulz *et al.*, 2004). This positive health effect is seen in (domestic) animals and in aquacultured fish.

A more high-end feed market application is the pet food market. The positive health effects can trigger consumers to buy pet food with algae biomass components. The positive health effects translate also to the external appearance of the pet (Pulz *et al.*, 2004).

4.3.1 Aquaculture

Currently the use of microalgae in aquaculture is one of the most important applications of algae. Microalgae are at the bottom of the aquatic foodchain. They are the primary producers of long-chain omega-3 fatty acids, and some aminoacids essential to animals and humans. In the aquatic foodchain, the constituents of the algae biomass ingested by lower trophic levels determines the composition of the biomass of higher trophic levels. Depending on feeder requirements (which often depend on life stages) microalgae are consumed either directly (e.g., by herbivorous fish, bivalve molluscs, larval shrimp and zooplankton), or indirectly through the 'algae-zooplankton' foodchain, which is the case for most fish (De Pauw *et al.*, 1984). The value of algae for aquaculture is found in the fact that microalgae are the primary and only producers of long chain omega-3 fatty acids and some essential amino acids. Microalgae are for example responsible for the omega-3 content of finfish and shellfish and their nutritive value to humans (Ronquillo *et al.*, 2012; Naylor *et al.*, 2009). It has been found that it is difficult to replace microalgae with substitutes to grow fish larvae and juveniles (Lavens & Sorgeloos, 1996).

The growth of aquaculture fish production should lead to better market opportunities for algae to replace aquaculture feeds. In the course of half a century or so, aquaculture has expanded from being almost negligible to being fully comparable with capture production in terms of feeding people in the world. In the last three decades (1980-2010), world food fish production of aquaculture has expanded almost 12 times, at an annual rate of 8.8% (FAO, 2012). Since the mid-1990s, aquaculture has been the engine driving growth in total fish production as global capture production has leveled off. Its contribution to world total fish production climbed steadily from 20.9% in 1995 to 40.3% in 2010 (Figure 9). The growth rate in farmed food fish production from 1980 to 2010 far outpaced the growth rate for the world population (1.5%), resulting in average annual per capita consumption of farmed fish rising by almost seven times,

from 1.1 kg in 1980 to 8.7 kg in 2010 (FAO, 2012). The European (EU-27) aquacultural fish production was 1.3 million tonnes in 2009 (Eurostat, 2013).

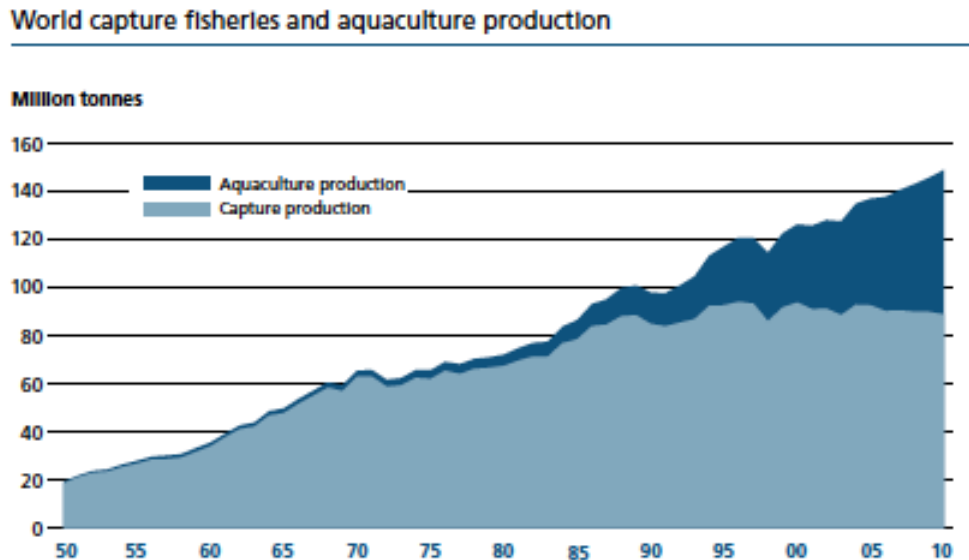


Figure 9: World capture fisheries and aquaculture production (FAO, 2012).

In aquaculture, microalgae are used as (mostly live) food for rearing larvae and juveniles of commercially important molluscs, crustaceans and fish (freshwater and marine). The microalgae are also indispensable for culturing several types of zooplankton (rotifers, cladocerans, copepods or brine shrimp), which are used as food in crustacean and finfish farming (De Pauw *et al.*, 1984). Once carnivorous fish and shrimp have reached adulthood, they are fed on pelleted compound feeds, which usually do not contain algae. The most commonly used species in aquaculture are *Chlorella*, *Nannochloropsis*, *Tetraselmis*, *Isochrysis*, *Pheodactylum*, *Thalassiosira*, *Pavlova*, *Chaetoceros* and *Skeletonema* (Spolaore *et al.*, 2006). Live feeds consist of a combination of several microalgae species to provide a well-balanced diet, which has demonstrated to deliver better growth and survival rates than feeds composed of only one algal species (Spolaore *et al.*, 2006; cited in Hemaiswarya *et al.*, 2011).

It is estimated that in 1999 the total production of microalgae for aquaculture was 1,000 tonnes (62% for molluscs, 21% for shrimps and 16% for fish) (Spolaore *et al.*, 2006).

The production of microalgae represents a significant cost to aquaculture farms. Algal culture cost is estimated to be on average between 30 to 40% of hatchery costs (Lavens & Sorgeloos, 1996; Helm *et al.*, 2004). A survey of Australian hatcheries even estimates the costs of microalgae production to be equal to 70% of hatchery costs. The surveys of Australian and overseas hatcheries showed costs ranging from about \$80 to greater than \$800 per kilogram dry weight (BEAM, 2013). A survey of Coutteau and Sorgeloos (1992) stated similar results but indicated that the hatcheries producing on a larger scale displayed lower production costs between USD 50,- and USD 100,- per kilogram dry weight (Coutteau & Sorgeloos, 1992).

The dependence of aquaculture on forage fisheries is significant once aquaculture fish reach the adult life stage. For the aquaculture sector as a whole, it took 1.04 kg wild fish to produce 1 kg of farmed fish in 1995. This ratio of wild fish input via industrial feeds to total farmed fish output (excluding filter feeders) has fallen more than one-third by 2007 to 0.63, a decline that underscores the expanding volume of omnivorous fish produced on farms and market pressures to reduce fishmeal and fish oil levels in aquafeeds. But some aquaculture species, like salmon and shrimp, still consume significantly more fish

than they produce, and the ratio for Atlantic salmon remains as high as 5,0 (Naylor *et al.*, 2009).

For the past few decades, the annual global production of fishmeal and fish oil has remained relatively steady at 5-7 million tonnes of fishmeal and 0.8-1.5 million tonnes of fish oil (FAO, 2008; cited in Naylor *et al.*, 2009). As most fisheries are fully exploited or are recovering from overexploitation, there is no prospect of expanding the supply of fishmeal and fish oil. Figure 10 and 11 show the price development of fish oil and fishmeal in comparison to soybean meal and soybean oil. The estimated total production of compound aquafeeds in 2002 was approximately 17.77 million tonnes (Tacon & Metian, 2008).

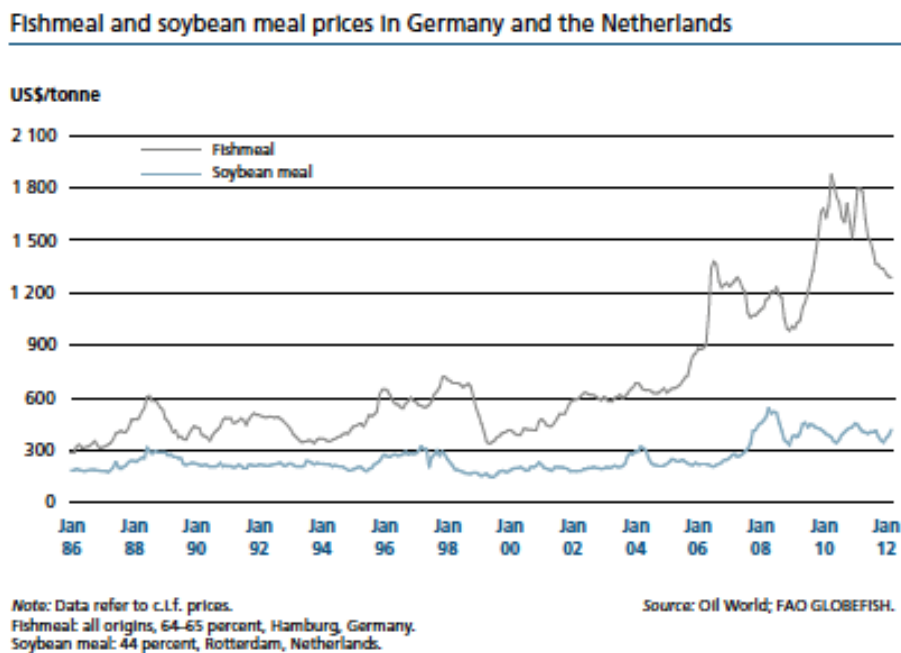


Figure 10: Fishmeal and soybean meal prices (FAO, 2012).

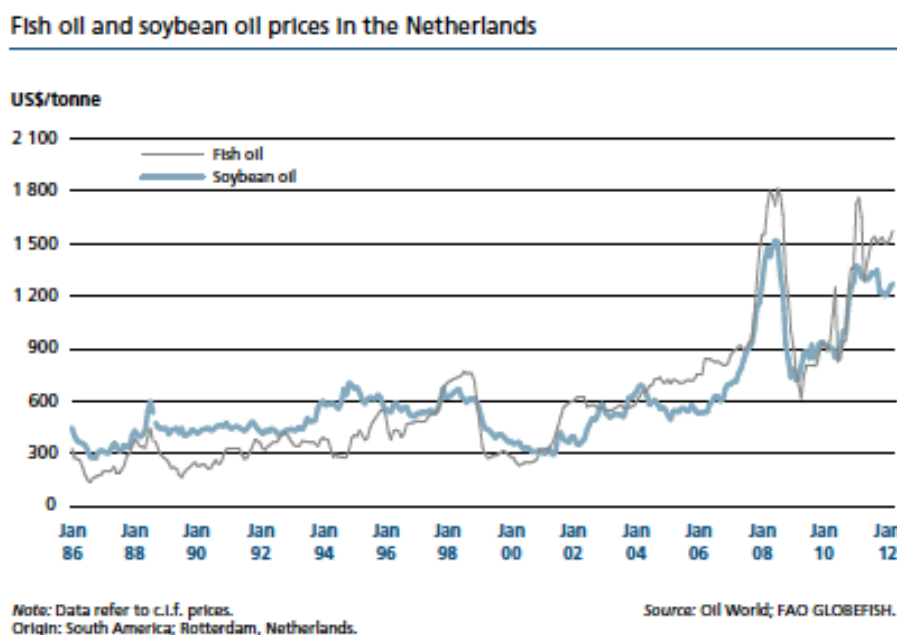


Figure 11: Fish oil and soybean oil prices (FAO, 2012).

The increasing demand for fishmeal and fish oil from increasing aquaculture and livestock production has pushed their price up. In 2009 the supply of fish from aquaculture surpassed the supply of fish from forage fisheries. Currently aquaculture consumes 68% and 88% of the global fishmeal and fish oil supply (Tacon & Metian, 2008).

4.3.2 Livestock feed

Algae biomass could be used in animal feed as substitute for protein sources, such as soybean meal, fish meal and rice bran (Becker, 2007). The compound feed market is then the main focus. The incorporation of algae into poultry rations offers the most promising prospect for the commercial use of algae in animal feed. The compound feed industry produced about 151 million tonnes of feed in EU-27 in 2010. The distribution per type of animal is that cattle, pigs and poultry represent 26%, 33% and 34% of the compound feed production (Fefac.eu, Oct. 2012). The share of soybean in animal feed differs per country and type of animal (Kamp *et al.*, 2008). If assumed that soybean meal accounts for about 15% of the total compound feed production, algae biomass could replace 22.65 million tonnes of soybean meal, in case of 100% replacement in compound feed production. This can only be the case when algae protein products would have high protein content with high lysine digestibility. Data so far indicate that algae aminoacid profiles could be adequate. Problems are high production cost and high water content of algae cultures. The price indication for soybean meal is USD 495 per tonne in December 2013 (Worldbank.org, 2014), as opposed to a spirulina price between USD 5,000 and 10,000 per tonne.

Poultry: Incorporation of algae into poultry rations offers the most promising prospect for their commercial use in animal feeding. Algae can be added safely up to a level of 5-10% of the compound feed as partial replacement of conventional proteins (Spolaore *et al.*, 2006). Lum *et al.* (2013) report on 10-20% algae in poultry diets. This was tested with *Chlorella* and *Scenedesmus sp.*

Pigs: Nearly all the pig-feeding studies indicate that microalgal biomass in general is a feed ingredient of acceptable nutritional quality and suited for rearing pigs. Algae can replace conventional proteins like soybean meal or fishmeal to a certain extent, the upper tolerable limit, however, has not been clearly demonstrated yet. Yap *et al.* (1982) studied the feasibility of replacing 33% of soy protein in a basal diet with proteins from *Spirulina maxima*, *Spirulina platensis*, and *Chlorella sp.* to pigs weaned on a dry diet at an age of four to eight days. The authors suggest that at least 50% of the protein supplied by soybean meal (33% of total) can be replaced by these algae without adverse effect. Pigs fed with the algal diet showed an improvement in weight gain as compared to the control groups. Evaluating the complete feeding period, pigs fed with 1 g algae per 1 kg diet tended to have the best feed efficiency, leaving room for the suggestion that lower levels of algae may have additional specific modes of action over being solely a protein replacement (Becker, 2004).

4.3.3 Feed additives

Many evaluations have shown the suitability of algal biomass as a feed additive (Becker 2004). Mainly the microalgae *Spirulina* and, to some extent, *Chlorella* are used in this domain for many types of animals: cats, dogs, aquarium fish, ornamental birds, horses, poultry, cows and breeding bulls (Spolaore *et al.*, 2006). The same animal spectrum is also mentioned as potential market for macroalgae like *Ulva spp.*, *Porphyra spp.*, *Palmaria palmata*, *Gracilaria spp.*, and *Alaria esculenta*. All of these algae enhance the nutritional quality of conventional feed products. Accordingly, the algae could positively affect the physiology of these animals.

The global animal feed additives industry was valued at \$31.4 billion in 2013. Asia-Pacific and North America are the top two consumers of feed additives in the world. Asia-Pacific is the largest market for feed additive consumption (accounting for a 41% share) and it holds a lot more potential due to the large untapped and unorganized livestock production sector, which still lacks awareness about the benefits of

feed additives. North America is the second largest consumer of feed additives with 25% share. The European market is one of the largest due increased health awareness of meat quality, and the shifting meat consumption trend towards poultry and pork, which require high feed additive inputs. (Research and Markets, 2014). The market is dominated by a small number of suppliers. It is estimated that 10 companies supply about 60% of the market, while in specific feed additive market segments the number of suppliers is even smaller (www.thepoultrysite.com).

4.3.4 Conclusion feed

The use of algae as feed is not new. Especially in aquaculture, algae have since long been used as feed. The market outlook for aquaculture products is good. The aquaculture is continuously growing since the mid-1970s. The use of algae proteins instead of fishmeal in the feed of adult fish would allow for a decoupling of aquaculture production from forage fisheries. Until now fishmeal and fish oil are still substantially cheaper than microalgae, which prevents microalgae to enter the aquafeed market. The lack of alternatives to microalgae for feeds for fish larvae and juveniles assures a market for microalgae in fish hatcheries.

The use of algae as feed ingredient in compound feed products looks promising, as microalgae have a favourable protein composition. They can be used in feeds at shares of about 10%, and have additionally a positive effect on the health of animals. The replacement of soybean meal in compound feed production is a potentially large market for algae. The price of microalgae will be determined by the level of the soybean meal price.

The outlook for microalgae to be used as feed additives is positive, due to the various positive effects on animal health that were described. Furthermore, the aim in certain countries to reduce the use of antibiotics is a driver to the use of other health improving feed additives.

Table 9: Overview of feed markets and substitutes for algae products used as feed.

Product	Substitutes	Market size EU	Value substitutes	Outlook algae
Aquaculture	Fishmeal/ fish oil	1.9 million tonne	EUR 55-500/kg dm	++
Livestock feed	Soybean	22.65 million tonne	USD 300/tonne	-/+
Feed additives	Botanicals, antibiotics etc	\$5.2 billion		++

5 Pharmaceuticals and personal care

5.1 Personal care

Microalgae are a promising source of bioactive ingredients for the personal care market. Several microalgae-based skincare ingredients already made it to the market, and the origin of the ingredients is in some cases used as a unique selling proposition. The skincare market is a relatively easy market to access for microalgae-based ingredients and given its large size, represents significant commercial opportunities.

Companies that have engaged in the microalgae personal care market are from all over the world, e.g. Solazyme (US), Frutarom (Israel) and Innovalg (France). They create a new, specific brand for their algae-containing product or productline. For example, Solazyme's skincare line Algenist™, distributed by beauty-retailer Sephora, is based on alginuronic acid. According to Solazyme, alginuronic acid (i.e. a mixture of polysaccharides) encourages cell regeneration and elastin synthesis, decreases melanin formation and provides protection from cellular and DNA damage following UVB exposure (U.S. Patent No. 8,277,849) (Solazyme, 2012). Frutarom's Alguard™ skincare line contains a naturally sulfated polysaccharide that hydrates the skin and protects it from oxidative stress and inflammation (<http://www.frutarom.com>).



Figure 12: Solazyme's Algenist™ skincare line, based on alginuronic acid.

The cosmetics and skin care markets are driven by consumers' desire to look young and healthy. Skin care has been the cornerstone of beauty and personal care market for the past 15 years. It even grew during the global recession, adding a further USD 15 billion between 2007 and 2011 to reach a value of USD 96.5 billion, according to Euromonitor International (Tyrimou, 2012). Skin care products make up for 20% of the total global beauty and personal care market (Tyrimou, 2013). Consumers are increasingly aware of the science behind skin care products, and the development of new ingredients provides unique selling propositions in a market that is increasingly more saturated. Personalized and targeted products appeal to consumers that look for a solution to specific problems like hyperpigmentation, redness or dark circles under the eyes. A growing trend, also currently present in many other beauty and personal care categories, is the use of natural ingredients. Although this used to be a niche for companies it is now becoming more mainstream, with brands such as Garnier and L'Oréal increasingly turning to natural and

nature-inspired ingredients (Tyrimou, 2012). As consumer demand for natural products increases, product developers are challenged to find new ingredients and formulations that are natural while providing the same results consumers expect from synthetic products (Mittennes, 2013).

According to market research firm Kline (2013 and 2014) the size of the global market for specialty active ingredients used in personal care products was estimated to be \$980 million in 2013, with a share of \$400M for the EU. However, these numbers should be treated with caution, as most of these ingredients are not only traded to the cosmetic industry, but also find their way to the food and pharmaceutical industries. Partly due to this reason, data regarding the use of specialty ingredients for personal care are scattered and difficult to obtain (CBI, 2008).

We could estimate what the microalgae production and production area should be to obtain this market value through microalgae. The market of bioactive ingredients is largely made up by bio-actives that are cheaper than those of microalgae, sourced from commonly produced crops like citrus fruits, berries, vegetables, and flowers. On the trading website of MakingCosmetics.com most botanical extracts are valued at a price between €50 and 70/kg (www.makingcosmetics.com). Knowing that fluidextracts represent a 1:1 ratio of herb to extract solvent (Dentali, 2010), the price of semi-pure bioactives comes down to between €100 and 140/kg. The market volume of functional ingredients for cosmetics would thus approximately be the size of 8,166,667kg (€980M: €120/kg). If this market would consist entirely of microalgal beta-carotene produced by *Dunaliella salina* (containing on average 100 mg beta-carotene/g algal biomass (Ben-Amotz (2004); cited in Del Campo *et al*, 2007), and growing at 2g/m².d in Nature Beta Technologies' raceway ponds in Israel (Ben-Amotz, 2011)), then the required raceway surface area would be 20,940 ha². For the EU market of \$400M, the required surface area would be 8,547 ha. According to the producers of DunaliellaGoldTM, 100 g of their *Dunaliella salina* contains 2.1g beta-carotene, 0.1024 g alpha-carotene, 0.0976 lutein&zeaxanthin, 0.0465 g crypoxanthin. Beta-carotene is for *Dunaliella* growers clearly the main bioactive compound that is produced, dwarfing potential revenues from the other bio-active compounds. If we repeat the calculation for a global ingredients market made up of only astaxanthin (with 3%wt astaxanthin in microalgae biomass, produced in photobioreactors at 2.2 mg astaxanthin/L.d according to Olaizola (2000; cited in Del Campo, 2007)) then a photobioreactor volume of 19,036,520 m³ is needed.

5.2 Pharmaceuticals

Extracts from microalgae have been found to contain compounds with antiviral, antibacterial, anticancer and anti-inflammatory characteristics, which could be developed into therapeutic agents. Marine organisms in general have been found to synthesize toxins (or bioactives), which are more potent than toxins produced by terrestrial organisms. For this reason, and because of the immense biological diversity in the sea as a whole, it is increasingly recognized that a huge number of natural products and novel chemical entities exist in the oceans (Haefner, 2003). Gerwick and Moore (2012) found that the current success rate of discovery of bioactive compounds from marine organisms is 1.7 to 3.3 times higher than the pharmaceutical industry average.

The early days of marine natural products discovery efforts focused on those organisms most conspicuous and easily collected, like sponges and soft corals, which were early on shown to produce a multitude of quite unique molecular species such as highly halogenated terpenes and acetogenins from Rhodophytes (Suzuki and Vairappan, 2005; cited in Gerwick and Moore, 2012). With continued exploration, unfamiliar and obscure groups of organisms were studied (Piel, 2009; cited in Gerwick and Moore, 2012). It has been confirmed or still strongly suspected that microalgae, cyanobacteria and

² harvest efficiency of 65% and 300 production days per year

heterotrophic bacteria living in association with invertebrates (e.g. sponges, tunicates and soft corals) are the true source of many bioactive and useful constituents (Gerwick and Moore, 2012).

Many components of microalgae have potential medical applications, e.g. carotenoids, proteins, omega-3 fatty acids and sterols, toxins and sulfated polysaccharides. De Jesus Raposo *et al.* (2013) highlighted the broad range of microalgal components that have shown anti-oxidant, anti-inflammatory, immunomodulatory, hypolipidemic, hypoglycemic, anti-coagulant, anti-thrombic, anti-cancer, anti-viral, anti-fungal and anti-bacterial properties. Whole microalgae biomass of species like *Spirulina*, *Porphyridium*, *Dunaliella salina*, *Chlorella* has exhibited anti-allergic activities, providing a remedy for allergic diseases like allergic rhinitis (Vo *et al.*, 2012). Nostocales genera cyanobacteria show potential as a skin anti-infectant against antibiotic-resistant *Staphylococcus aureus* (Lukowski *et al.*, 2008). The WHO has stressed the importance and urgency of the development of new antibiotics, as drug-resistant pneumonia, tuberculosis and other common infections are spreading around the world (Boseley, 2014).

Although the market share of marine natural products (MNPs) is growing, MNPs still represent only a niche in the total global pharmaceutical industry, which had a value of USD 955 billion in 2011 (LEK, 2013). The market of active ingredients for pharmaceuticals had a size of USD 101 billion in 2010, with an expected growth of 8% between 2011 and 2016 (MarketsandMarkets, 2011). There are no aggregate numbers available of the value of all marine-derived pharmaceuticals on the market. However, the annual sales value of cancer fighting agents from marine sources was estimated to be USD 1 billion in 2005, some herpes treatments had a combined value of USD 387 million (e.g. Zovirax) and the AIDS drug retrovir had a value of USD 23 million in 2005 (Leary *et al.*, 2009). The market share of marine natural products in the pharmaceuticals market is thus far smaller compared to the omnipresent terrestrial-derived bioproducts. This is not due to a lack of potential for discovery, but is attributed to the fact that marine bioprospecting is still in its infancy (Gerwick and Moore, 2012). Until today no microalgal-derived pharmaceuticals have entered the market yet. Taking into account the discovery rate of effective bioactives and the fact that microalgae are easier to cultivate than other marine (micro-)organisms (Singh *et al.*, 2011), the prospects for microalgal pharmaceuticals are promising.

5.3 Conclusions personal care and pharmaceuticals

In the last few years, the potential of microalgae as source for interesting pharmaceutical and personal care ingredients is explored, and first steps towards exploitation and commercialization have been taken. The markets of personal care products and pharmaceuticals are high-value, low-volume markets. For these high value applications refined algae compounds are used, and not whole algae biomass, to improve the bioavailability of the algae compounds. The market of functional ingredients for personal care and pharma were worth together almost USD 2 billion in 2013. The significant size of these markets combined with a consumer demand for natural products signals a strong potential for algae. Today no microalgae pharmaceuticals have been commercialized yet, but the skin care market already counts numerous microalgae-based products by international companies. The personal care market is relatively easy to access for microalgae-based products. The success rate of new active ingredient discovery from marine organisms is higher than from terrestrial organisms or from conventional combinatorial chemistry techniques used in the pharmaceutical industry.

6 Bioremediation

As microalgae assimilate nitrogen and phosphorus as nutrients, they can be used to purify eutrophicated wastewater. This seemingly simple application poses however many technical questions (Lundquist, 2012). Microalgae are today already indirectly used in waste stabilisation pond systems to treat wastewaters in an extensive manner in small communities around the world (Park *et al.*, 2011). Current interest lies in the use of microalgae in high rate algae ponds (HRAPs). HRAPs are shallow, open raceway ponds with dense algae cultures that are kept in suspension by the mixing of paddle wheels (Lim

et al., 2010). They are conceived as a potential substitute for the commonly used activated sludge systems, which are efficient and compact, but are at the same time energy-intensive and require complex infrastructure built of huge amounts of steel and concrete (Lundquist, 2012). The resulting production of microalgae biomass in HRAPs could be used to make biofuels from (Lundquist *et al.*, 2012; Osundeko *et al.*, 2013). The concept of biofuel production together with wastewater treatment was first proposed in the 1960s. HRAPs are until now still subject of exploratory research, as fundamental questions on microalgae biology need to be resolved and applied engineering Research and Development on HRAPs is still in its infancy (Park *et al.*, 2011). Experiments have been done on various kinds of wastewaters, like landfill leachate, domestic wastewaters and piggery waste (Van Den Hende *et al.*, 2011; Mustafa *et al.*, 2012).



Figure 13: High Rate Algal Ponds (HRAPs) (ECN, 2014).

Some preliminary cost analyses of HRAP's for wastewater treatment have been performed. Craggs *et al.* (2012) estimates that capital and operating cost of an HRAP for nutrient removal are only 25% or 30% of those of electromechanical systems that remove nutrients. According to Craggs *et al.* (2012) these capital and operating costs can be fully covered by revenues from the wastewater treatment function.

Lundquist *et al.* (2010) estimated the profitability of a hypothetical microalgae wastewater treatment plant that produces in Case 1 bio-oil of the harvested microalgae and in Case 2 produces biogas. Their hypothetical HRAP of 100 ha (individual ponds of 4 ha)³ receives the wastewater of a population centre of 165,000 to 235,000 persons (22,740 ML/yr). In both Case 1 and Case 2 the farms receive wastewater treatment credits of \$1.23/kg BOD removed. The average microalgae biomass production in the HRAPs is 22 g/m² day or 80 mt/ha.yr, with a 25% triacylglyceride content. The harvested algae biomass either undergoes oil extraction with the residual biomass being anaerobically digested (resulting in 12,770 bbl/yr oil) (Case 1), or alternatively the entire biomass is digested with only biogas produced (resulting in 3x10⁶ m³/yr) (Case 2). The oil production cost in Case 1 is \$28/bbl, and in Case 2 the plant makes a profit of \$0.17 per kWh produced. In Case 1 the extraction of bio-oil adds considerable expense compared to production of biogas only (Case 2). Compared to Case 2, Case 1 results in capital costs that are 30-40% higher, and operational costs increase with 100%. This study indicates that wastewater treatment with HRAPs could be profitable when all biomass is converted to biogas (Case 2) and when the other

³ Debt financed at 5% over 30 years and 3% depreciation

conditions of this study are fulfilled. These results are very sensitive to changes in costs or revenues, because total costs nearly equal total revenue for Cases 1 and 2 (Lundquist *et al.*, 2010).

Next to removal of nutrients from the water, microalgae are also capable of removing heavy metals from water by actively incorporating them into their biomass or by (passively) absorbing them onto their cell wall. Furthermore, certain organic (toxic) chemicals, like textile dyes or pesticides, can be absorbed or converted into harmless metabolites by microalgae (Enot, 2010; Lim *et al.*, 2010). In Japan, exploratory research is done on bioremediation of radio-polluted soils and waters of the Fukushima nuclear disaster. Certain microalgae are able to accumulate high amounts of radionuclides from polluted water. Further research is required to identify efficient biomass production and harvesting technologies as well as optimal remediation species (Fukuda *et al.*, 2014).

Because of their ability to biodegrade organic pollutants, microalgae have been proposed to remediate soils polluted with toxic organic chemicals like pesticides (Shimoda *et al.*, 2011; Subashchandrabose *et al.*, 2013). The research on microalgae for soil remediation is still in its early days. For the moment microalgae do not play a significant role in the soil bioremediation sector.

7 Literature

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EnAlgae is a four-year Strategic Initiative of the INTERREG IVB North West Europe programme. It brings together 19 partners and 14 observers across 7 EU Member States with the aim of developing sustainable technologies for algal biomass production.

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