Microalgae: the green gold of the future?

Large-scale sustainable cultivation of microalgae for the production of bulk commodities

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Preface

The cultivation of microalgae can play an important role in environmental-friendly production of raw materials for biodiesel. In addition, algae offer several other useful materials for the food and chemical industry.

This booklet describes the possibilities for economically viable large scale algae cultivation for the production of valuable products, including raw material for biodiesel.

Chapter 1 illustrates the potential role of microalgae in developing a more sustainable society.

Chapter 2 describes some important groups of algae and the opportunities they offer as producers of useful substances.

Chapter 3 deals with the main algae cultivation systems and the current state-of-the-art of algae cultivation in the Netherlands.

Chapter 4 discusses the benefits of algae cultivation in relation to other agricultural crops.

Chapter 5 analyses the possibilities of cost-effective, large-scale microalgal production and the significant role that the new algae centre in Wageningen, AlgaePARC, will play in the research on optimization of algae cultivation.

Chapter 6 is a summary of the conclusions and recommendations for cost-effective microalgae cultivation.

Contents

1. Introduction

Emerging economies and the growing world population rely heavily on the natural resources of the earth. In 2050, the world population is estimated to be around nine billion people; this is 1.5 times the current population. The demand for commodities will rise explosively. Never before the necessity and challenge for a sustainable society was larger than in this century.
Sustainable production methods for food and energy are necessary if we do not want to convert all available nature into agricultural land. In addition, there is a need for alternatives for the finite oil reserves. The society focuses increasingly on sustainability and therefore on the recycling of waste streams, sustainable production and efficient use of energy.

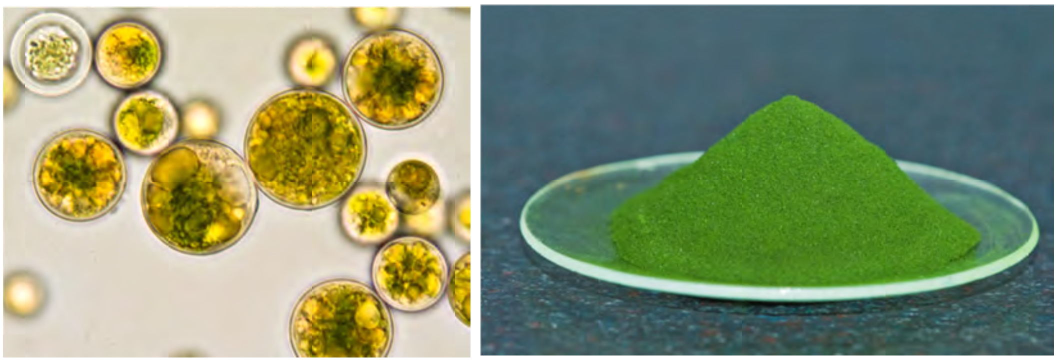

Photo 1: Green algae cells with oil droplets inside and algae powder (source Wild Frontiers/Hans Wolkers)

The cultivation of microalgae can make an important contribution to the transition to a more sustainable society or biobased economy. Algae are not only suitable for environmentally friendly production of many commodities, but also for the use of waste streams. They grow excellent on e.g. carbon dioxide from flue gases, residual water of agro-industrial companies and even diluted digestate from manure. In return they produce valuable raw materials. Algae recycle nutrients that thus remain available in the nutrient cycle, instead of being wasted and pollute the water.

Algae are not only promising as waste converters and recyclers. The algal cell contains many useful substances and microalgae are cultivated increasingly for the production of valuable raw materials. For example, it is possible to produce oil, proteins, starch and pigments (e.g., beta-carotene). Applications of these materials are numerous, ranging from biodiesel and bioplastics to colorants and hamburgers.

2. Microalgae

Species

Microalgae, also called phytoplankton by biologists, are very small plant-like organisms between 1-50 micrometres in diameter without roots or leaves. Together with the seaweeds (macroalgae or large aquatic plants), microalgae are part of the so-called aquatic biomass.

Microalgae are very common (hundreds of thousands species exist) and occur both in freshwater and seawater where they form the basis for most food chains. Most species contain chlorophyll, use sunlight as an energy source and convert carbon dioxide (CO_2) into biomass. In this process of photosynthesis the algae produce oxygen (O_2). On a global scale microalgae produce more than 75% of the oxygen required for animals and humans.

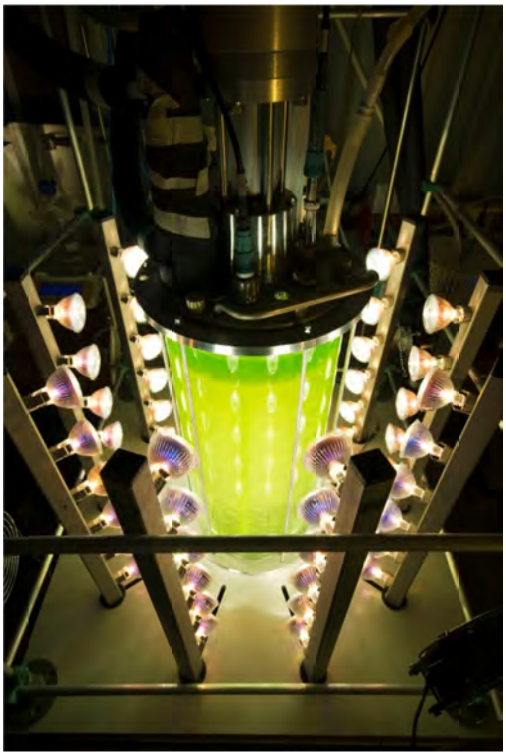

Photo 2: Experimental algae reactor (source Wageningen University)

Normally microalgae are not visible by the naked eye, but if the water is eutrophic, massive algal blooms occur, changing the water in a green, brown, blue, or orange liquid mass. Only a few tens of thousands, out of a total of 200,000 to 800,000 different species, have been described in literature. With so many unknown algae species an almost inexhaustible source of possibilities exists.

The genetic analysis and ranking of all types of microalgae is still in progress and there is not yet a complete and consistent classification. At the moment taxonomists have distinguished the following main groups:

- Green algae. With 7500 species they form one of the largest groups of algae. These algae contain chlorophyll (like in plants) and a large amount of proteins. In addition, under stress conditions they produce starch and oil that are stored inside the cell. Green algae exist as unicellular or multicellular species. *Chlorella* is a well-known single-celled species, which also is grown commercially.
- Red algae are a group of 5000 mostly multicellular marine species, living in the tidal zone of the sea.
- Diatoms. With more than 100.000 species, this group of unicellular algae produces most of the biomass on earth. They are an indispensable food source for the zoöplankton in freshwater and seawater. These algae have a particularly attractive skeleton of silica that fits together like two halves of a sphere. Diatoms produce mainly oil that is stored in the cell. By varying the amount of oil they can regulate their buoyancy.

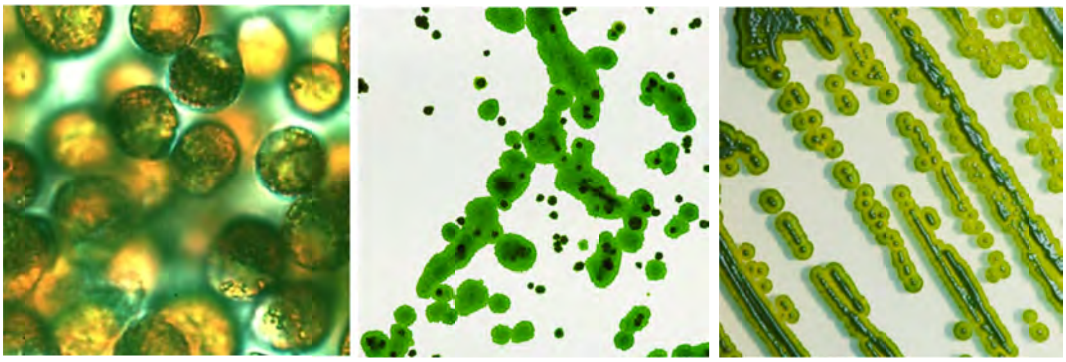

Photo 3: Algal cells accumulating carotenoids (left photo, source Wageningen University) and cultures of two green algae (middle and right photo, source Wild Frontiers/Hans Wolkers)

- Brown algae. Virtually all 1500 to 2000 species are multicellular algae existing almost exclusively in the sea. Brown algae like kelp are often found on the beach, and are therefore regarded by many people as the traditional seaweed.
- Gold algae. This group of 1000 species of beautifully coloured unicellular algae exists mainly in fresh water, but also a number of marine species are known. They possess flagella that are used for displacement.

- Yellow-green algae. They are close relatives of the brown algae, but most of the approximately 600 species are unicellular and live in fresh water. *Nannochloropsis* is an exception as this fast-growing species is found in the sea. These algae produce large amounts of oil as a food reserve and are therefore highly suitable for the production of raw material for biodiesel.
- Blue algae or cyanobacteria. Notorious algae that can produce toxins and, in situations of high concentrations, can seriously affect the water quality. Blue algae store food reserves in the form of starch, while the cell can consist for more than half out of protein. The species *Spirulina* is cultivated worldwide and used as a dietary supplement.

Raw materials from algae

Many algae contain a considerable amount of high-quality oils, partly consisting out of omega-3 and omega-6 fatty acids, which are used as raw material for food supplements. Omega-3 fatty acids in fish originate from microalgae.

At the moment numerous agricultural crops are grown for the production of oil or starch-like substances, which can be used for the production of fuel. Algae contain, in addition to raw materials for energy, also a wide variety of other useful components. In recent years more than 15,000 new chemical compounds were discovered in algae. In addition to fatty acids algal cells also contain carotenes (yellow to red pigments) and other colorants, antioxidants, proteins and starch. These components can be used by the chemical- and food industry as raw material for numerous products, and the list of products made from algae is expanding steadily.

Besides high-added value products for niche markets, such as algae powder for the dietary supplement industry and algae extracts to control moulds in golf fields, there is also increasing interest in bulk products such as raw materials for bioplastics, biofuels but also algae protein for food applications.

Production of valuable substances by algae can be manipulated by the design of cultivation conditions. Especially under suboptimal conditions the algae experience stress and, as a result, produce substances like pigments, starch and oil. For example, excess of light stimulates the production of carotenes in the cell. At the same time these pigments are antioxidants and protect the cell from harmful free radicals generated by the overdose of light. However, growth is then reduced and the colour changes from green to orange.

If the supply of the nutrient nitrogen is limited, algae start to especially accumulate oil. Algae producers use this by putting the algae on an obligatory diet, with insufficient nutrients in the culture medium. This inhibits growth, reduces the production of proteins, and increases the production of oil that is stored in the cell as small globules.

3. Algae cultivation

Cultivation Systems

Microalgae have been grown for decades at small scale, especially in Asia and North America, mainly for application in food and feed. However, this concerns only a small number of species; *Spirulina* and *Chlorella* are well-known examples. Growers produce these species especially for the dietary supplement industry. At this moment approximately 5000 tonnes of dried algae are produced per year worldwide.

Four different cultivation systems are currently in use by algae growers:

1. Open ponds or raceways

Open ponds or raceways are shallow, annular channels where mixing takes place using paddle wheels. These are the most common cultivation systems worldwide. An important advantage of this basic design is the relatively low cost. On the other hand, a large open pond is difficult to monitor compared to a closed cultivation system. Water evaporation takes place and the system is susceptible to infections, limiting the choice of algae to resistant, fast-growing species.

Photo 4: Raceway pond at Ingrepro (source Wild Frontiers/Hans Wolkers)

Algae ponds are not the most effective cultivation system. Theoretically up to 10% of the energy from solar light can be converted in chemical energy in biomass via photosynthesis, while the remaining part is lost as heat. In practice however, this photosynthetic efficiency is much lower. For example, for an algae pond this is about 1.5%. This is caused by the limited penetration of sunlight into the turbid algae pond. As a result only the algae cells near the surface receive a lot of light which they cannot efficiently convert into biomass.

Algae cultivation in sunnier regions is potentially much more productive, provided that the utilization of solar energy is more efficient. By reduction of the antenna size of algae by genetic modification it is possible to decrease the amount of light absorbed by the algae. Reduced absorption of light at the surface will result in more light penetration into the algae pond, thus providing more algae with sunlight for photosynthesis. A possible drawback of this method is that the genetically altered algae might be outcompeted by wild type algae.

Photo 5: Algae cultivation in horizontal tube reactor at the Hogeschool Zeeland in cooperation with Wageningen University for the Zeeuwse Tong project (source Wild Frontiers/Hans Wolkers)

2. Single-layer or horizontal tube reactors

This is a closed culture system, composed of a single layer of horizontal tubes. In such a tube reactor it is easier to control the process and the productivity per square meter is higher than in a pond. In addition, this system is easy to scale by simply extending the tube length.

A major drawback of this design is the high light intensity on the tube surface. This is detrimental to the algae, growth is reduced and as a result the productivity is lower. Another disadvantage of tube reactors is the high energy cost of circulating the liquid suspension. Also the gas exchange in these systems is not optimal; O_2 accumulates and this is toxic to algae at high concentrations. In addition, the construction costs might be higher compared to open cultivation systems.

3. Three-dimensional tube reactors

Photo 6: Three-dimensional tube reactor at AlgaePARC (source Wild Frontiers/Hans Wolkers)

This system is composed of multiple layers of tubes that are placed vertically on top of each other and in this manner form a construction of vertical panels of tubes. This type of reactor has partly the same advantages and disadvantages as the single-layer tube reactor, but the three-dimensional tube reactor does not suffer from a high light intensity because the vertically placed tubes are placed in each other's shade. The productivity is higher compared to a single-layer tube reactor because more tubes fit on the same horizontal surface, thereby increasing the yield per square meter.

4. Flat plate reactors

These are closed reactors constructed from series of flat, parallel plates. These systems are in theory the most productive. There is no accumulation of the toxic O_2 and also the light intensity at the surface is not too high. Disadvantage of this system is the relatively high amount of energy required for mixing of nutrients and keeping the algae in suspension. Besides this high energy consumption, adding extra CO_2 is more difficult and scale-up is complex.

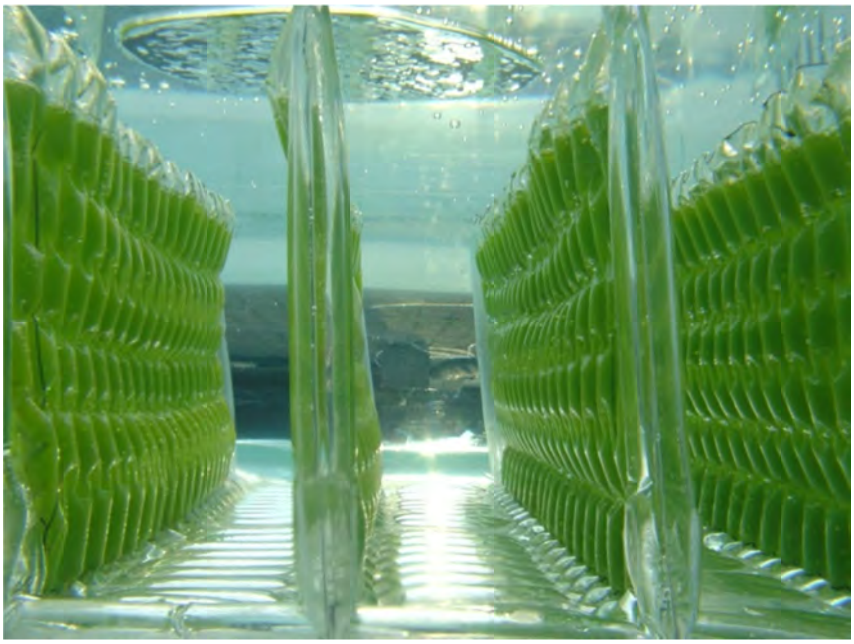

Photo 7: Variation on flat plate reactor at Proviron (source Proviron)

Algae cultivation in the Netherlands

Algae cultivation is a relatively new activity in the Netherlands. Many projects started to investigate cultivation of microalgae. For example, the Foundation Zeeuwse Tong studies the possibilities of land fish farming in a closed loop system: waste water from sole breeding serves as a food source for cultivation of siliceous algae, also known as diatoms. The cultured diatoms are in turn food for shellfish. The first results are promising. The diatom cell is vulnerable, but the siliceous algae can be cultivated in the newly designed reactor of transparent perspex tubes.

Some Dutch companies such as AF&F, Algaelink, Aquaphyto, Lgem, Ingrepro, Maris and Phycom grow algae on a small scale for a number of years, focusing on niche markets. Ingrepro, located in Borculo (Gelderland), produces algae in two open ponds of approximately 4000 m^2 in total. Large paddle wheels keep the algae suspended and the daily harvest is done fully automatically. After harvesting, the algal suspension is thickened and dried to paper-thin sheets. The dried algae, whether or not compressed to small pellets, form the basic raw material for a range of algae products that the company produces for a wide range of customers.

Photo 8: Highly concentrated algal soup, dried paper-thin sheets and the final product, small pellets, at Ingrepro (source Wild Frontiers/Hans Wolkers)

LGem also serves a niche market. This company produces *Nannochloropsis* in three closed cultivation systems of flexible tubes of 300 m^2 per system. When the density is high enough the algal suspension is harvested. A powerful centrifuge separates the algae from the water and transforms the algal soup in a sticky, green paste. LGem produces on average about 30 kilos of algae paste per day, corresponding to approximately 3 kilo of dry algae. After freeze drying and grounding into a deep green algae powder, the final product is

Costs of open and closed cultivation systems

The costs of algae biomass production in open systems would in theory always be lower than in closed systems. However, this is only true for the existing systems, because so far closed photobioreactors have only been used for the production of algae with very high market values (niche markets). The design was never adapted for large-scale production of bulk products. An extensive calculation of the costs of production in open ponds and closed photobioreactors showed that production costs in both systems did not differ much from each other. Yet, the costs of closed systems can be reduced to a larger extent compared to open systems by improving the design. There are still many uncertain factors and challenges that need to be addressed. It is still too early to state that some systems are better than others. Innovations are necessary to reduce costs and improve sustainability of the technology to make commercial production of algal biomass for bulk products possible.

ready for sale. LGem delivers algae products especially to the dietary supplement industry, but also to fish farmers that cultivate fish larvae by using algae. The production costs for the paste on this relatively small scale are more than € 40 per kilo of dry matter, not taking into account the costs for freeze drying and packaging. On the other hand, the market prices of freeze-dried algae powder vary around € 400 to 500 per kilo.

4. Algae in the Biobased Economy

Cost Reduction

Cost reduction is not a top priority for companies that make algae products for niche markets because of the high market price for these products.

Large-scale production makes less sense because the small markets would become oversaturated. In the much larger market for bulk products of lower quality, such as raw material for biodiesel, reduction of production costs is vital as these products must compete with already existing raw materials. The price of algal oil should approach the price level of commodity oils like petroleum and palm oil before algae can be used for commercial production of biodiesel at large scale.

Value of the algal biomass

Currently the value of palm oil is approximately 0.50 €/kg. We think we will be able to reduce the production costs of one kilogram of algal biomass to 0.50 €/kg. If that biomass consists of 40% of oil it is clear that it is necessary to exploit all other valuable components present in the algae as well. By fractionating the algal biomass into different components, each with a certain value, a calculation is made of the total value of 1 kg algae.

For example, consider algae biomass is composed of 40% oil, 50% protein and 10% sugars (see Figure 1). Part of the oil will be used for the production of biofuels and the other part serves as raw material for the chemical industry.

Photo 9: Algal oil (source: Wild Frontiers/Hans Wolkers)

Water soluble proteins can be used in food instead of soy protein, and partly in cattle feed. Also the sugars have numerous applications. In addition, the O_2 produced by algae and the removal of nutrients from residual streams generate income.

In total, the algal biomass is worth 1.65 €/kg at a production cost of 0.50 €/kg. That means that in theory it is worthwhile to produce algae for a combination of products including biofuel. In this calculation biorefinery costs are not included.

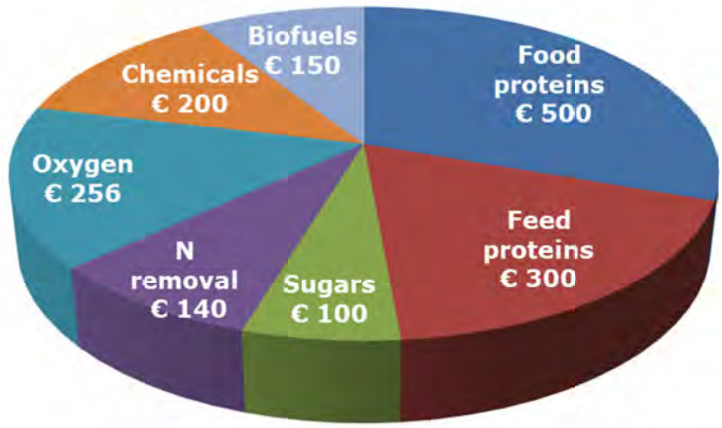

Figure 1: Value of ingredients in algal biomass

Food, fuel and biodiversity

There is debate about the sustainability, the negative impact on biodiversity and competition with food crops of biofuels produced from e.g. palm oil and rapeseed oil. Currently a large part of the oil needed for biodiesel is originating from oil palm and rapeseed. Palm oil plantations, however, exist at the expense of large parts of tropical rainforest. Also the rapeseed cultivation has drawbacks as agricultural land is occupied that could also be used for growing food crops.

The current biofuel production competes in many cases with rain forest and food production. Algae have fewer disadvantages in the field of competition for food and biodiversity, making this form of agriculture an attractive option. Microalgae can be cultivated intensively in closed systems on places where no other agriculture is possible and where nature is not harmed. Some desert areas in Africa or Australia, oceans, roadside verges, flat roofs or contaminated soil are suitable locations for the production of algae.

With the introduction of a new species also risks are involved. Products intended for the food chain must be safe for consumer and environment. Large-scale cultivation should not result in overgrowth and displacement of natural populations. Most algae do not contain toxic components and are cultivated under special conditions (high salt concentrations, high pH) and have no competitive advantage over the natural populations. Potential risks should be assessed and limited and these assessments should become an integral part of the research and development programs.

Water and nutrient needs

Algae are also attractive as a sustainable alternative because they are economical with water and can grow on CO_2 and excess nutrients in waste streams. Approximately 5000 litres of freshwater is required for the production of 1 litre of biofuel using oil crops. Algae production in salt water requires potentially only 1.5 litres of freshwater per litre of oil produced.

If fuel based on algal oil would replace all transport fuels in Europe (400 billion litres of oil/year) and assuming a yield of approximately 40.000 litres of oil/ha/year, an area of about 10 million hectares is needed. This is about the size of a country like Portugal. That is certainly a large surface, but it fits well within Europe, and Europe would then be self-sufficient for transportation fuels. As a by-product 0.3 billion tonnes of protein are produced, corresponding to 40 times the amount of soy protein currently imported. In summary, algae can produce both food and fuel.

In addition to sufficient fuel for European transport, large-scale algae cultivation has positive effects on both the CO_2 balance and the surplus of nutrients in waste water and manure. For the growth of this amount of algae a quantity of 1.3 billion tonnes of CO_2 (Europe produces yearly 3.9 billion tonnes of CO_2) and 25 million tonnes of nitrogen (Europe produces yearly 8 million tonnes of nitrogen in waste water and manure) is necessary.

These calculations show that the cultivation of algae does not need to be done at the expense of biodiversity and food production and can substantially contribute to a sustainable economy.

Stand-alone systems: the future

Large-scale algae cultivation systems are required for the production of sufficient biodiesel for the replacement of fossil fuels. Ideally this would be met by growing algae in areas with lots of sunshine and surface that are not used for agriculture, *i.e.* deserts. The availability and supply of water, fertilisers such as phosphate and nitrogen, and delivery of CO_2 for these kind of remote areas will be problematic in case of large-scale production. The ultimate aim is therefore to design a cultivation system that is independent on the supply of those substances and that produces algae only with salt water, CO_2 from the air and without any input of nitrogen and phosphate: a *stand-alone* system.

In deserts freshwater is scarce but usually salt groundwater is available, offering the possibility to grow algae without the use of fresh water. Also the supply of CO_2 is possibly no longer necessary in the future. Currently CO_2-rich gas is used for algae cultivation. Research on the improvement of the CO_2 transfer in cultivation systems may lead in the future to an efficient cultivation on CO_2 from the air, which is omnipresent. Finally, a great challenge of this *stand-alone* system will be the production of algae without the use of nitrogen and phosphate. This is in principle possible because algae contain nitrogen and phosphate, but the oil harvested from the algae does not. If a method is developed to isolate oil from the cells while they stay alive, algae are then 'milked', production of algal oil on only sunlight, CO_2 and salt water is possible. Currently, a *stand-alone* system is not yet possible but research is focused on the development of such a system.

5. AlgaePARC

Background

Wageningen UR has more than ten years research experience in the field of microalgae cultivation. Research topics focus in particular on the efficiency of light energy conversion into algal biomass in photo bioreactors. These are closed systems in which algae can be cultivated with (sun) light as the energy source at a high degree of control and optimization.

The interest of the industry in microalgae was limited since the last oil crisis in the 1970s. In 2005 a VICI grant was awarded to René Wijffels, Professor of Bioprocess Engineering by STW Technology Foundation. With this grant the project 'Photosynthetic Cell Factories' was initiated. In this project Wijffels and his team examined the optimal efficiency of alga biomass production. In addition, research focused on methods to manipulate culture conditions in such a manner that the algae started to produce commercial products such as pigments in excess. Researchers also looked at biorefinery methods to isolate these commercial products without quality loss.

Since a few years biodiesel is gaining interest and the industry showed an increasing attention in microalgae production. The fact that the cultivation of microalgae not only offers great opportunities for the sustainable production of biofuels, but also for a whole range of other useful commodities, is very important.

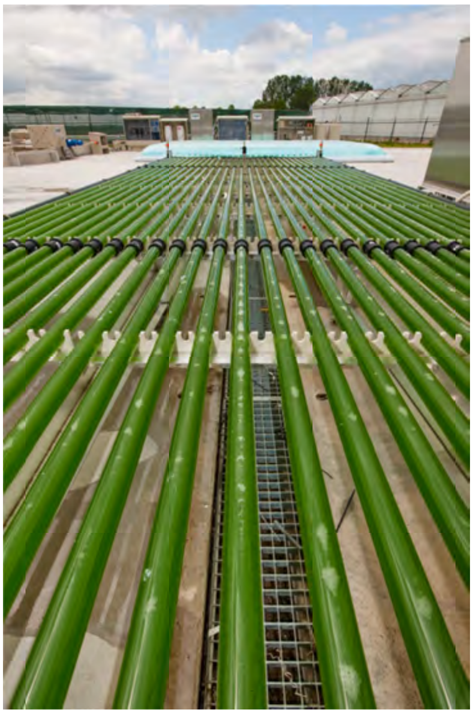

Photo 10: Horizontal tube reactor in operation in AlgaePARC (source Wild Frontiers/Hans Wolkers)

The cultivation capacity of microalgae is currently relatively small and inefficient and there is little experience with large-scale, cost-effective production. Therefore, Wageningen UR, together with the industry will investigate the optimization of algae production in outdoor systems. For that reason, a new test facility is built in Wageningen, *i.e.* the Algae Production And Research Centre, commonly known as AlgaePARC.

This facility has been financed by the Ministry of Economic Affairs, Agriculture and Innovation, the province of Gelderland and Wageningen UR. The research done at AlgaePARC during the first 5 years is part of the research programme BioSolar Cells. AlgaePARC, in which 18 companies participate, is one of the utilization projects in the Biosolar Cells program. Teams of scientists will study various aspects of the algae cultivation. To make the production of algae competitive at the bulk product market a strong economic and technological boost is needed.

Research in AlgaePARC

The production costs of algae cultivation must be decreased drastically, to one-tenth of the current level. Increasing the photosynthetic efficiency is one of the most important stipulations. This can be achieved by applying improved reactor designs and use more efficient algae. In addition, a substantial saving on nutrients becomes possible by making use of waste and residual flows and recycling of these nutrients. Furthermore, a considerable reduction of energy consumption can be reached by means of mixing the algae soup less and the use of energy-efficient pumps. Also better harvest and downstream processing methods (biorefining) can significantly contribute to reduce costs, but also to improve the final product.

For example, conventional methods to isolate oil from algae cells are quite harsh, *i.e.* high pressure and temperature disrupt the cell wall causing the oil to be released. However, because of the harsh conditions the proteins will denature resulting in a lower value of the biomass. Therefore, mild biorefinery techniques to isolate the algae products are necessary. Finally, shifting the cultivation to sunnier locations might contribute to a higher efficiency and substantial cost reduction.

AlgaePARC must be a bridge between small-scale laboratory research and large-scale production. The research team will verify the results of the small-scale experiments on larger scale in AlgaePARC. In addition, the team will compare the four major algae cultivation systems regarding costs, growth efficiency and sustainability.

Photo 11: Overview of AlgaePARC with a horizontal tube reactor filled with algae (source Wild Frontiers/Hans Wolkers)

An open pond will serve as reference as it is the most common cultivation system worldwide. The researchers will compare the performance of closed systems, for example, horizontal layers, vertically transparent tubes, flat plates and a raceway pond, throughout the year. Each cultivation system has specific advantages and disadvantages, but the ultimate goal is maximum production of high quality algae at the lowest possible price throughout the year.

Besides the type of cultivation system, it is also important to design the cultivation conditions in such a way that an optimal production of the desired algae product, *e.g.* oil, is obtained. Traditionally the algae are grown until a certain density. Subsequently they are starved from nutrients; the algae stop growing and start to produce more oil. Usually these two processes are run in sequence: first the amount of biomass is increased rapidly, and then the oil starts to accumulate slowly. In AlgaePARC the goal is to design a process aimed at the optimal production of certain metabolites (such as oil or starch) and not of biomass. Because production conditions will continuously change, production strategies that are aimed at a constant quality of the final product will be designed, by means of measuring and controlling.

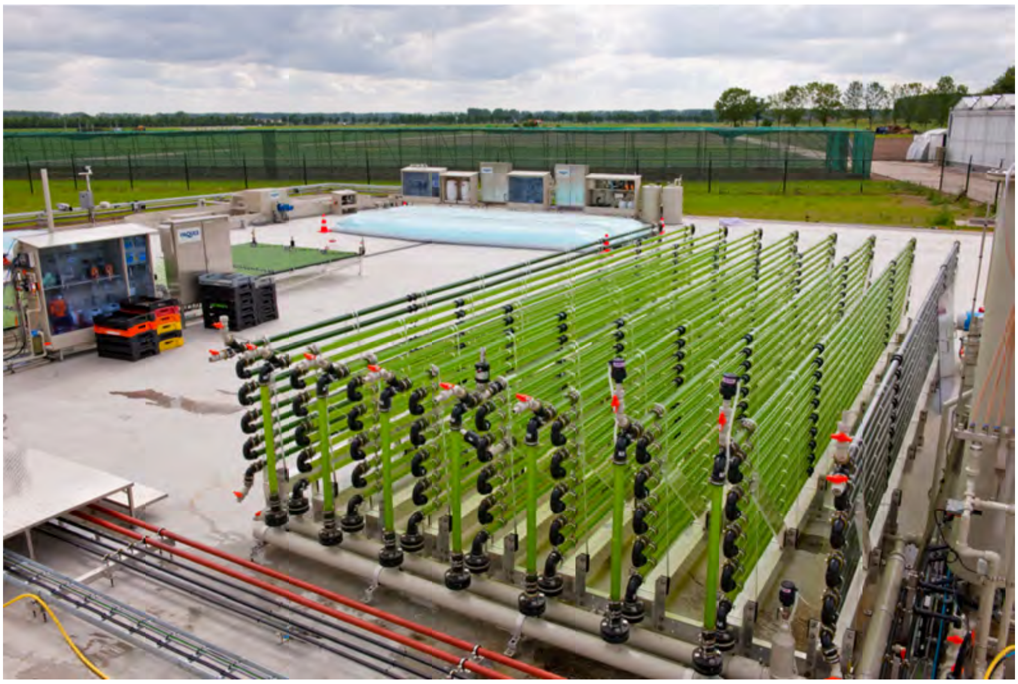

Photo 12: Three-dimensional tube reactor in AlgaePARC (source Wild Frontiers/Hans Wolkers)

The test facility is just a start of what should become the leading algae testing centre of Europe. Particularly research and development of methods aimed at making specific end products will be further expanded in the coming years. Not only reactor design will get attention, but also the search for new algae species and improvement of existing algae strains by genetic modification.

In addition, there will be a lot of attention for improved biorefinery methods and sustainability of the entire production chain. Wageningen UR wants to do innovative research on algae cultivation technologies in collaboration with other knowledge institutes and industry within the Netherlands and abroad. This can be both fundamental and applied research. It is also important that the research on algae is an inspiring learning environment for students.

Photo 13: Cultures of various algae species (source Wild Frontiers/Hans Wolkers)

AlgaePARC will be a success if after 5 years we:

- Are able to make a good comparison of different production systems based on the following parameters: photosynthetic efficiency, volumetric productivity, energy use, use of nutrients and water availability, robustness and scalability
- Have achieved and maintained throughout the year, a photosynthetic efficiency on sunlight outdoors of 5%
- Have developed an improved reactor concept and/or process strategy in which the production costs and energy needs are lower compared to traditional systems
- Have obtained sufficient basic information for the design of a large-scale production facility

Worldwide research on algae is emerging. Companies and governments invest a lot in algae research programmes. In the United States there are large projects in the field of genetic modification of microalgae, China does a lot in bioinformatics of algae and in Europe scientists will realise the first demonstration facilities within some years.

 

Photo 14: Demonstration plant of Wageningen University and Neste Oil at the University of Huelva in Matalascañas (source Wageningen University)

Wageningen UR distinguishes itself from these activities by working in an integrated, multidisciplinary manner on the improvement of the technology. This means working at the same time on the improvement of species, on development of efficient production methods and on biorefinery- and sustainability aspects.

6. Conclusions

Algae can play an important role in the biobased economy. Algae are efficiently cultivated in places that are unsuitable for agriculture and where nature is not harmed. Sustainable production of biodiesel, but also many other products such as proteins, colorants and raw material for bioplastics is achievable.

To achieve profitable cultivation of algae, the production efficiency must be increased three times and costs must be reduced ten times. In addition, besides oil for biofuel, other useful substances such as proteins must also be extracted from the algae.

AlgaePARC will play a key role in the optimization of algae cultivation. The research team will test various cultivation systems and compare them. Based on these results and data obtained from the laboratory, the team will develop a new reactor design for application on commercial scale.

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Colophon

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