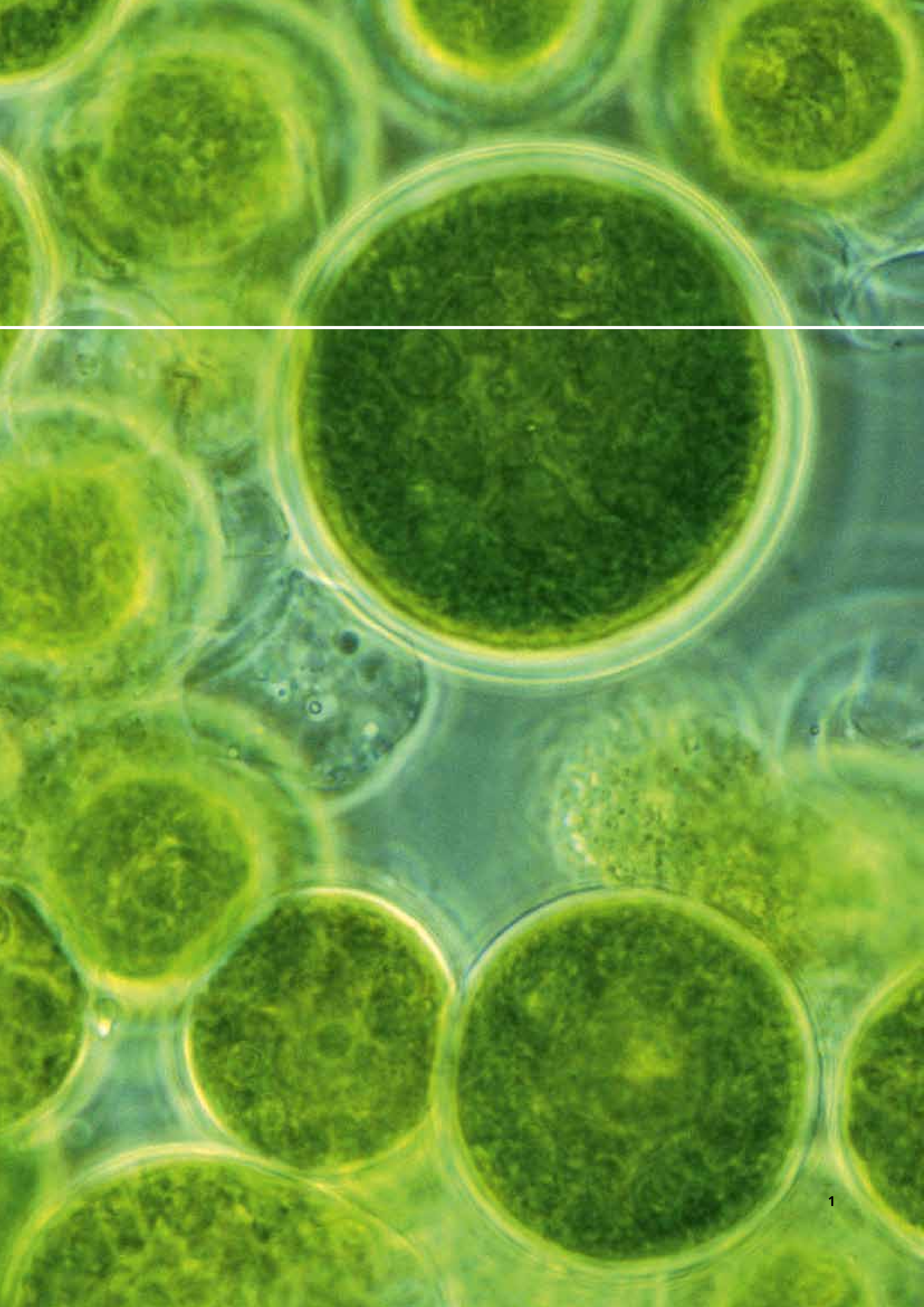
Fraunhofer IGB

FRAUNHOFER INSTITUTE FOR INTERFACIAL ENGINEERING AND BIOTECHNOLOGY IGB

MICROALGAE
A SUSTAINABLE RESOURCE FOR VALUABLE COMPOUNDS AND ENERGY



PRODUCTION OF VALUABLE COMPOUNDS WITH MICROALGAE

Photosynthesis is the only process using sunlight as the energy source and CO_2 as the carbon source for the production of biomass. Especially the potential of microalgae photosynthesis for the production of valuable compounds or for energetic use is widely recognized due to its more efficient utilization of sunlight energy compared with higher plants. Microalgae can be used to produce a wide range of metabolites, such as proteins, lipids, carbohydrates, carotenoids or vitamins for health, food and feed additives, cosmetics and for energy production.

Why microalgae?

- Their growth rate is 5 to 10 times higher than the rate of higher plants.
- Essential for growth are sunlight, CO_2, and mineral nutrients like nitrogen and phosphorous.
- Carbon dioxide emitted from combustion processes can be used as a source of carbon for algal growth (1 kg of dry algal biomass requiring about 1.85 kg of CO_2).
- Microalgal can be cultivated in seawater or brackish water on nonarable land, and do not compete for resources with conventional agriculture.
- Microalgae biomass can be harvested during all seasons.
- The biomass is homogenous and free of lignocellulose.
- The biochemical composition of the algal biomass can be modulated by varying growth conditions resulting in secondary metabolites such as carotenoids or lipid or starch accumulation.
- Microalgae grow in an aquatic medium, but need less water than terrestrial crops.
- Net energy production is possible.

However, so far microalgae are only used as natural feedstock for high-value products. Because these advantages are offset by the fact that algae production plants have high investment costs and, depending on the type of photobioreactor used, high operating costs, too.

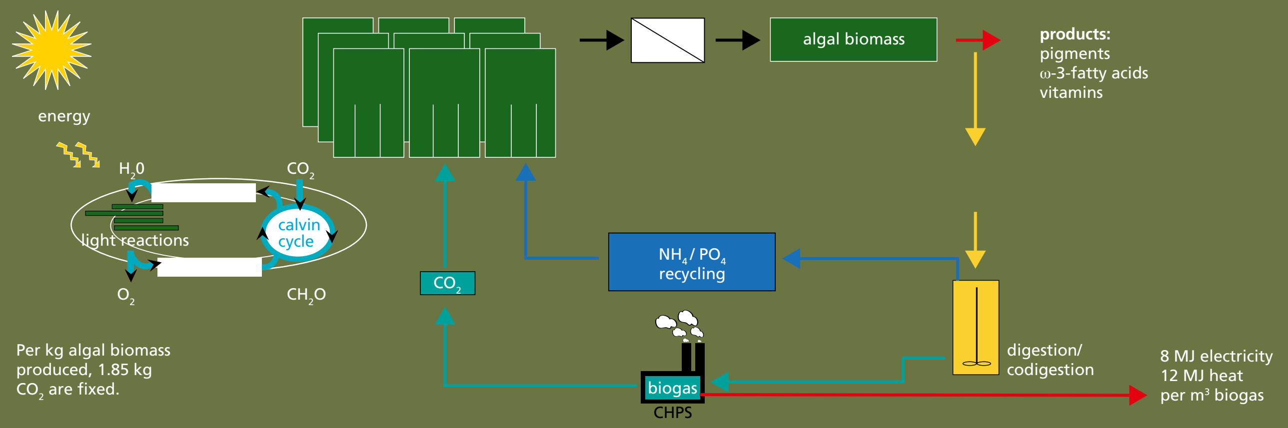
Valuable compounds from microalgae

The Fraunhofer IGB develops processes for the production of miscellaneous algal products. These processes include triacylglycerides for biodiesel or as feedstock for biobased chemical compounds, starch as substitution of agricultural sourced feedstocks for conversion of carbohydrates to bioethanol or algae with repellent and antifungal effects useful in organic farming.

The Fraunhofer IGB is concentrating its activities on two markets in the food supplement sector: natural pigments and highly unsaturated fatty acids (omega-3 fatty acids), which play an important role in human cardiovascular and inflammatory diseases like rheumatoid arthritis and multiple sclerosis. For example in the microalgae *Phaeodactylum tricornutum* as much as 40 percent of total fatty acids is eicosapentaenoic acid (EPA).

At the Fraunhofer IGB processes for the production of astaxanthin and EPA were developed under outdoor conditions. Process parameters such as light intensity, CO_2 and nutrient concentrations, as well as the cultivation method, were optimized.

1 *Haematococcus pluvialis.*



ENERGETIC USE OF MICROALGAL BIOMASS

Microalgae offer a high protein, carbohydrate or lipid content, depending on growth conditions. Fast growing microalgae have a high protein content with a favorable distribution of essential amino acids. Many microalgae have the ability to produce substantial amounts (e.g. 20 – 70 percent dry cell weight) of triacylglycerols (TAGs) or starch as a storage product when under stress and growing slowly, and simultaneously high light intensities are available.

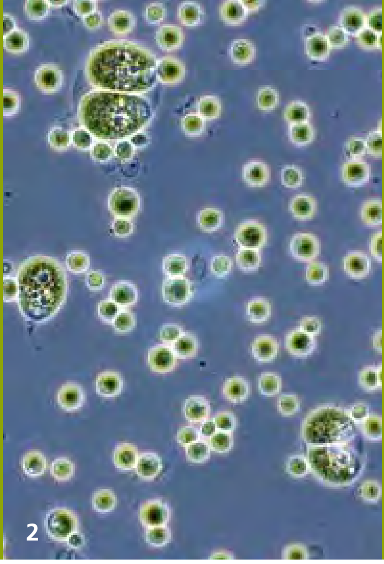
In screening tests at the Fraunhofer IGB various algae were tested for their ability to produce storage lipids under the conditions of a flat panel airlift (FPA) reactor. Lipid content increased up to 70 percent of dry cell weight and starch contents up to 60 percent are achievable. Under these conditions mainly monounsaturated fatty acids with 16 and 18 carbons were synthesized. Lipid productivity was not specific for a certain strain but depended largely on the light intensity per cell.

Starch can be used as sugar feedstock for miscellaneous biotechnological processes for biofuels or biobased chemicals. The Fraunhofer IGB has developed a two-stage process for production of starch-rich microalgae, which has been established under outdoor conditions as well as scaled up to pilot scale in the range of 100 kg dry biomass.

Sustainability by recycling of nutrients

The Fraunhofer IGB is developing sustainable, resource-efficient and ecologically friendly production processes for the production of valuable products and the energetic use of microalgae combining the use of flue gas from combustion processes or offgas from biotechnological fermentations like bioethanol as the carbon source (combined heat and power stations with biogas or natural gas). Our intention first is to recover valuable products from microalgae followed by digestion of the residual biomass to biogas. Carbon dioxide is recycled to the algal cultivation process. For a positive net energy balance the use of waste gas as the carbon source is a basic requirement for photoautotrophic microalgal biomass production. Additionally, recycling of nitrogen and phosphorous from anaerobic digestion effluents is possible.

1 *Closing cycles of CO_2 and nutrients between algae production and anaerobic digestion.*
2 *Mixed culture adapted to digestate.*
3 *Chlamydomonas reinhardtii with accumulated starch.*
4 *Pilot plant with 180 liter reactors (© Thomas Ernsting).*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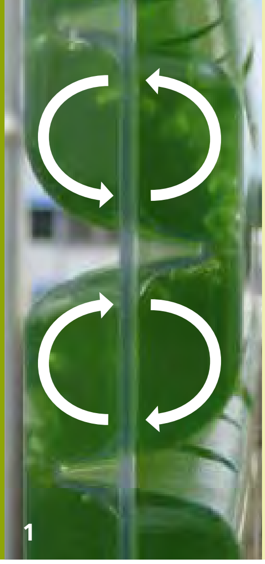
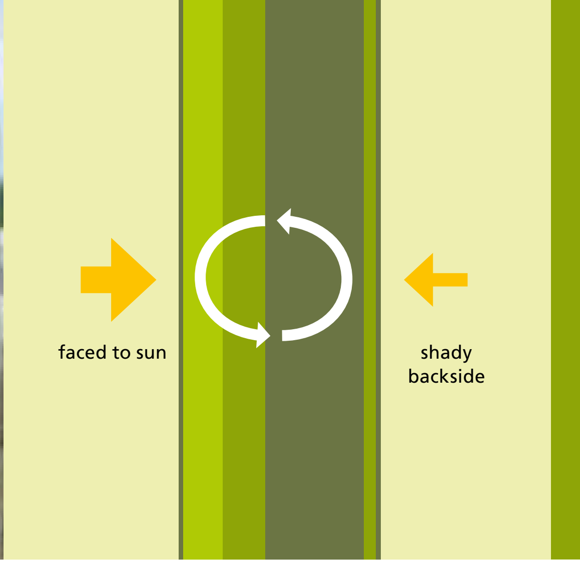




FLAT PANEL AIRLIFT PHOTOBIOREACTOR

The most important process parameter in the mass cultivation of microalgae in photobioreactors is the light intensity, which has an impact on every algal cell in the photobioreactor volume. This determines the biomass productivity and thus the growth rate and cell concentration of the algae in the reactor. To achieve high cell concentrations, the light availability for every individual cell in the photobioreactor has to be increased.

The photobioreactor system developed and patented (Patent number WO 00926833.5; EP 1326959) at the Fraunhofer IGB and scaled-up by the Fraunhofer spin-off Subitec GmbH takes these parameters into account. Airlift-driven intermixing combined with static mixers offers efficient distribution of light with a low energy input for intermixing and low shear forces taking effect on the algal cells. Due to the static mixers, uprising gas bubbles induce definite vortices in the interconnected reactor compartments. In these definite vortices algal cells are transported at short intervals to the reactor surface to intercept high light intensities and then transported back to the dark. Sufficient CO_2 and O_2 mass transfer for unlimited growth is ensured by the combination of the airlift-driven principle and static mixers. The flat panel airlift (FPA) reactor is well-suited for small-scale and large-scale production of microalgae. The reactor itself is inexpensively made from two deep-drawn plastic sheets including static mixers, manufactured by twin-sheet technology.

In a scale-up process the volume of the FPA reactor was increased from 6 liters lab scale to 28 liters and finally to 180 liters by Subitec GmbH. The scale-up step to a pilot plant consists of linking several reactor modules (each 180 liters).

Automation of photobioreactors

To design an outdoor process which is independent of light and temperature, the Fraunhofer IGB developed an automation concept with an easily accessible measuring technique. The automation concept was achieved – in line with the current industry standard – with the aid of a programmable logic controller (SIMATIC S7-1200, Siemens).

Both reactor temperature and pH are controlled. Control of pH is achieved by control of CO_2 concentration in the supply air: the higher the CO_2 concentration in the supply air, the more becomes dissolved as carbon dioxide in the culture medium. This lowers the pH value. This is counteracted by the ammonium dissolved in the medium: the higher the ammonium concentration, the higher the pH value in the culture medium. If in such a system the pH value is constantly regulated by means of the carbon dioxide concentration in the supply air, this allows conclusions to be drawn about the ammonium concentration in the reactor. This correlation was used to determine the consumption of nutrients in the reactor. On the basis of these calculations, we were able to successfully control feeding cycles and exclude nutrient and carbon dioxide limitation.

When setting up the control software, it was ensured that it was very user and operator-friendly. The overall process is visualized on a display screen and all online data continuously recorded. The control software is constructed in a modular way and can therefore be implemented easily in new production facilities.

Advantages of automation system

- Continuous process monitoring
- Automated feeding and harvesting cycles possible

By estimating the amount of ammonium in the culture via CO_2 concentration in the supplied air:

- Allows constant nutrient supply
- Allows consistent nutrient concentration in the culture due to low feeding amounts
- Feeding of nutrients depends on nutrient consumption and is independent of weather conditions and therefore suitable for outdoor production
- Growth limitations by culture medium components are detectable (via decreasing ammonium consumption rates)
- Monitoring of growth is possible if correlation factor of nutrient demand per gram biomass is known

The algae plant at the Fraunhofer CBP

At the Fraunhofer Center for Chemical-Biotechnological Processes CBP a new reactor facility was constructed by Subitec GmbH, a Fraunhofer IGB spin-off. The total capacity of the facility is 11.7 cubic meters within 110 reactors each with volumes totaling 6, 28 or 180 liters. For outdoor production a capacity of 7.2 cubic meters in four lines each with ten 180-liter reactors outdoors is available. This modular construction also facilitates the use of the system to carry out a wide range of experiments. The control and automation system described above is employed, too.

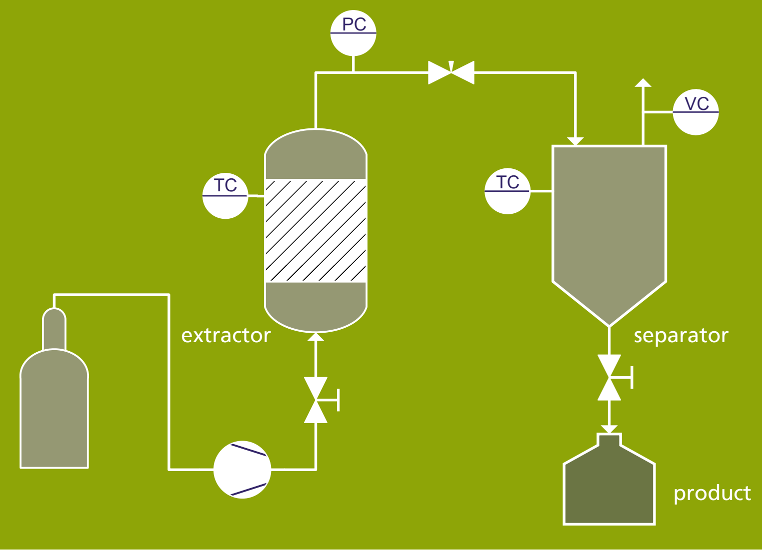
The Fraunhofer CBP now has an algae production facility available both for CBP research projects and to produce algal biomasses of specific composition on behalf of clients.

1 *Ascending gas bubbles generating a defined intermixing in FPA reactors.*

2 *Process visualization on the display screen of the SIMATIC S7-1200 controller.*

3 *Reactor module of the outdoor facility.*

4 *Outdoor facility at the Fraunhofer CBP.*


PC
VC
TC
TC
extractor
separator
product

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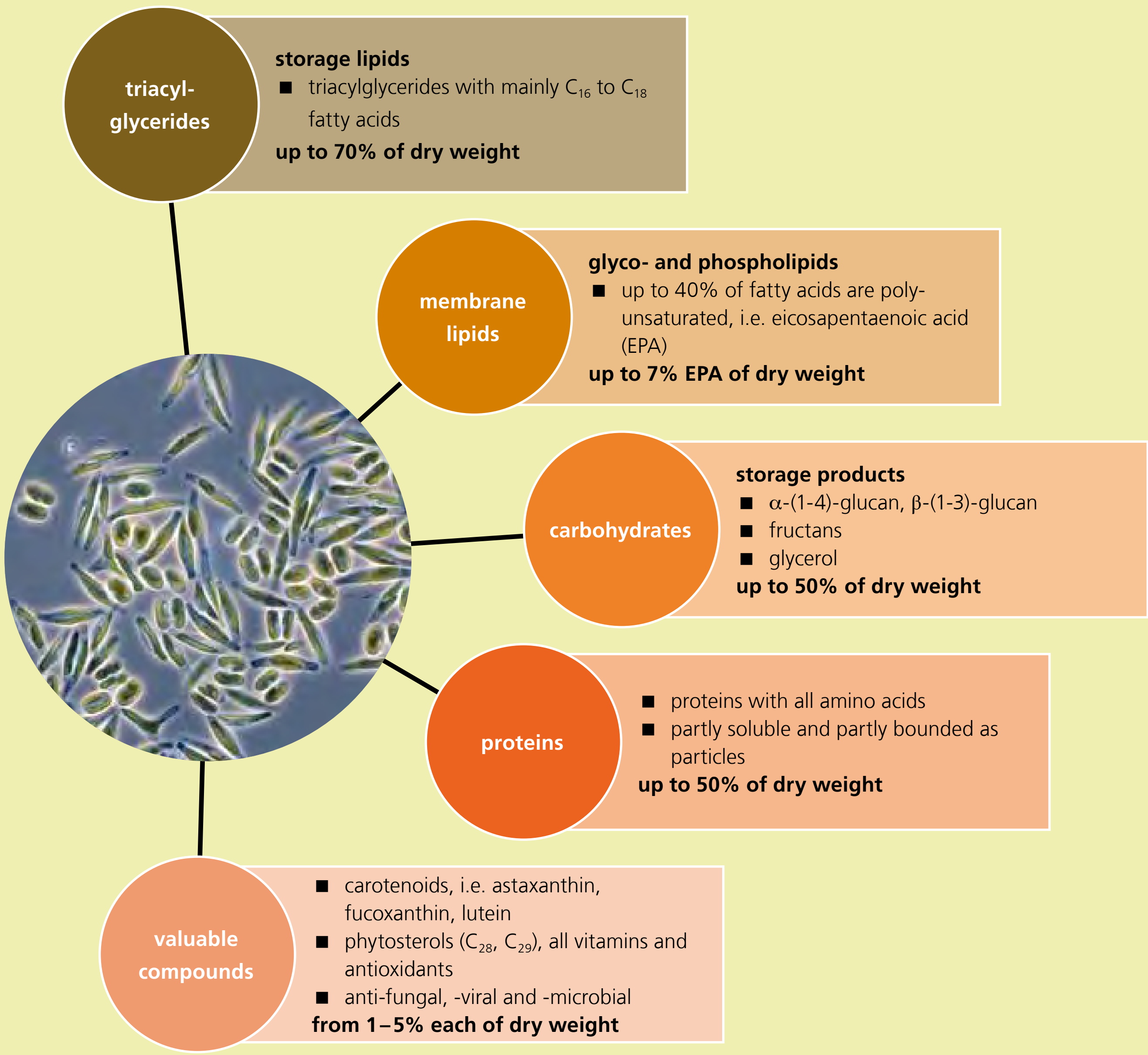
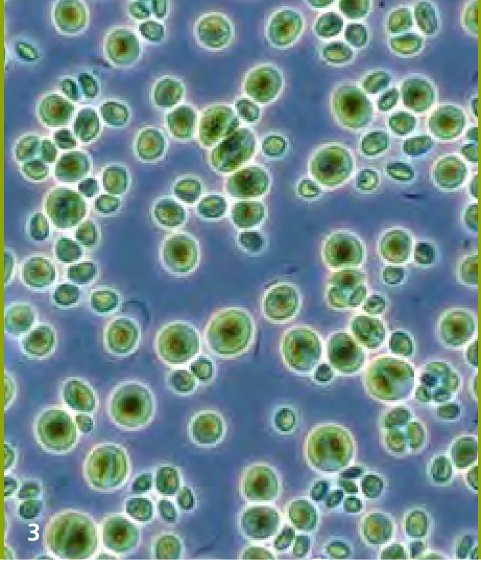

triacyl-
glycerides
storage lipids
■ triacylglycerides with mainly C_{16} to C_{18} fatty acids
up to 70% of dry weight
membrane
lipids
glyco- and phospholipids
■ up to 40% of fatty acids are poly-unsaturated, i.e. eicosapentaenoic acid (EPA)
up to 7% EPA of dry weight
carbohydrates
storage products
■ α-(1-4)-glucan, β-(1-3)-glucan
■ fructans
■ glycerol
up to 50% of dry weight
proteins
■ proteins with all amino acids
■ partly soluble and partly bounded as particles
up to 50% of dry weight
valuable
compounds
■ carotenoids, i.e. astaxanthin, fucoxanthin, lutein
■ phytosterols (C_{28}, C_{29}), all vitamins and antioxidants
■ anti-fungal, -viral and -microbial
from 1–5% each of dry weight

2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BIOREFINERY CONCEPTS

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce multiple products and thereby can take advantage of the differences in biomass components and intermediates, and maximize the value derived from the biomass feedstock. As energetic use alone of algal biomass is not economically substantial in the near future, integrated processes which use the complete biomass, for example proteins, will increase valorization of algal biomass.

With the aim of maximizing the value derived from different microalgal components, the innovative microalgal biorefinery concept includes both high-value products like pigments and major components like proteins, storage lipids or starch as they constitute up to 50 percent of the algal biomass. The Fraunhofer IGB develops processes together with partners regarding the influence of biomass composition due to differences in species and cultivation on applicable disintegration and separation methods. The overall aim is to obtain several fractions consisting of proteins, polar membrane lipids comprising omega-3 fatty acids and pigments, and to use them in food applications.

1 *Flowchart of the plant for the extraction with supercritical fluids.*

2 *Utilizable components of algal biomass.*

3 *Nannochloropsis limnetica.*

4 *Harvested biomass of Chlorella sorokiniana.*

Recovery of algal products

To obtain valuable products from microalgal biomass and further use of residual biomass, notably employing a cascade, there are some clearly defined requirements. Principally the extraction and separation methods are determined by the chemical character and the market specification such as the required purity of the product.

Additional requirements are:

- Use of wet biomass avoiding energy intensive drying
- Localization of the desired component in the cell and application of specific disruption methods, thereby preserving the functionality of the desired product (i.e. avoiding harmful high temperatures)
- Mild extraction which allows separation of additional components

Supercritical fluid extraction, a "natural and green" way of achieving product extraction, has received increasing attention as an important alternative to conventional separation methods because it is simpler, faster, more efficient and avoids the consumption of large amounts of organic solvents, which are often expensive and potentially harmful. The separated product can be converted directly and supplied to the market as a nutraceutical or food ingredient. Residual biomass from such processes can be fractionated into additional products like proteins or carbohydrates from microalgal cell walls. To increase polarity of supercritical fluids like $scCO_2$ ethanol is added, enabling selective extraction of polar glyco- and phospholipids which contain omega-3 fatty acids like EPA. This difference in extraction properties with and without ethanol can even be used for consecutive extraction of unpolar triacylglycerides or carotenoids and polar lipids like omega-3s.

RANGE OF SERVICES

- Screening for microalgae and cyanobacteria with different properties and ingredients
- Development of photoautotrophic processes for microalgae and cyanobacteria in flat panel airlift reactors from laboratory to technical plant scale
- Process optimization for improving productivity and biomass yield using flue gas and digestate as carbon and nutrient source
- Development and adaptation of software for outdoor control and feedback control systems
- Development of processes for the isolation, separation and purification of algal products
- Commissioned production of algal biomass with defined composition up to 100 kg

1 *Lab-scale flat panel airlift reactors with LED lighting and control system for automated feeding and harvesting cycles.*

2 *28 liter flat-panel airlift reactor with high biomass concentration (Chlorella sorokiniana).*

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Fraunhofer IGB

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