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USE OF MICROALGAE AS RENEWABLE RESOURCES

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Summary

The commercial production of microalgae started in the early 1950's. Especially in the last two decades, these amounts have tremendously increased. In view of growing world population and limited fossil fuels, microalgae are seen as one promising alternative source for biofuels and high value products (like proteins and ω-3 fatty acids) in different industry branches (e.g. food, feed, cosmetic and pharmaceutic products or waste water treatment). Currently, they are mainly used for food and food supplements. The potential of the small photosynthetic microorganisms for other applications were proven in lab scale experiments. There are obstacles as high processing costs, low production yields and production stability which continue to prevent the commercial use. Furthermore, without artificial lighting and heating, the production in Europe is limited from March to October. As a result, the market prices are often the bottle neck in order to sell products. There is a need for the optimisation of the processes and reactors (e.g. important growth factors, selection of microalgae species and design) to tap the full potential of the green cell factories.

Keywords: microalgae, biomass, sustainable, biofuel
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Introduction

Microalgae are described as unicellular or multicellular, photosynthetic organisms with a less complex morphology that occur in sizes from 3 to 80 µm (fig. 1). Around 40,000 species have been identified but approximately 15 species are used industrially (BERG-NIELSEN 2006). Each year, more than 10,000 tonnes dry matter of microalgae biomass is produced worldwide (SCHULZ 2006). Of this, China accounts for approximately 50%. Further producing countries are Japan, Taiwan, USA, Israel and Australia.

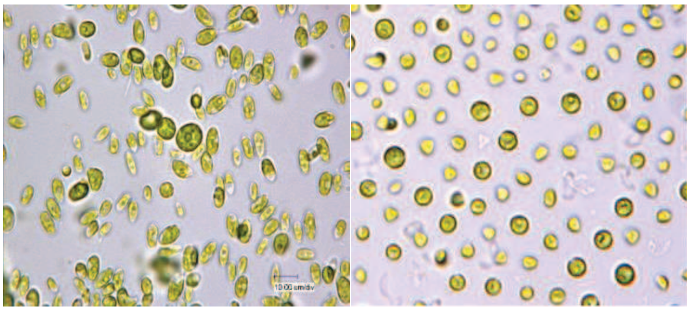

Figure 1: microalgae species *Scenedesmus obliquus* (left) and *Chlorella vulgaris* (right) with 2000x magnification (own illustration)

Microalgae have been classified according to the following main criteria: kinds of pigments, the chemical nature of the storage products and of cell wall constituents (TOMASELLI 2007). Additional criteria are cytological and morphological features.

Eukaryotic microalgae were typically classified in Rhodophyta (red algae), Chlorophyta (green algae), Dinophyta, Chrysophyta (golden brown algae), Prymnesiophyta, Bacillariophyta (diatoms), Xanthophyta (yellow-green algae), Eustigmatophyta, Rhaphidophyta, Phaephyta (brown algae) (TOMASELLI 2007).

Microalgae have significant advantages, particularly when compared to higher forms of terrestrial plant species as rice or soybeans. These includes no competition for land area with present food crops, a 5 to10 fold higher growth rate (30 - 550 t ha^{-1} a^{-1} compared to soybean 6 - 7 t ha^{-1} a^{-1}) and high oil yields (SOEDER 1971, PULZ 2009, SCHARFF et al., 2013). Beyond that, the cultivation is not tied to typical growing seasons. Because of their chemical composition microalgae can serve to improve the nutritional value of common food preparations and feed (SPOLARE et al. 2006).

Currently, the commercial use is limited by inefficient yields, which are caused by the high level of complexity of the extraction process of sensitive compounds and the high processing costs itself. High expenses are caused by customized nutrition, energy-intensive cultivation (e.g. temperature and light exposure) and preparation of the microalgae like drying and cracking prior to processing.

Cultivation parameters

The growth of algae is determined by many factors, including nutrient composition, pH-value, salt content, carbon availability, temperature and light. With some exceptions the optimum temperature ranges from 20 to 27 °C degrees. Carbon, nitrogen (constituent in proteins and chlorophyll) and phosphor (for transfer of energy and biosynthesis of nucleic acids) are the most important nutrients for microalgae growth. Further composition influencing factors are the salinity and the amount of each macro elements as S, K, Na, Fe, Mg, Ca and of trace elements like Cu, Mn, Zn, Mo, Co, V and Se (GROBBELAAR 2007).

Light is one of the key factors during the microalgae production (GRIS et al., 2014). Light quantity and quality and the distribution in the cultivation system can alter the microalgae physiology (e.g. metabolism, cell division and growth rate) as well as the biochemical profile of these organisms (BOUTERFAS et al., 2006). Artificial lighting with fluorescent lamps or LED lights enables the possibility for year-round production when conditions regarding the target of microalgae biomass as well as special metabolites are clearly defined. However, cultivation under suboptimal conditions or stress such as nutrient deficiency, light stress or high salinity can increase the production of certain metabolites like lipids and carotenoids

(WOLKERS et al., 2011). Depending on their individual demands, microalgae can be cultivated phototrophic, (photo-) heterotrophic and mixotrophic.

Microalgae can be produced in open and closed systems (tab. 2). Open systems can be natural waters (i.e. lakes, lagoons and ponds) or artificial plants like raceway ponds. The typically depth of raceway pounds is about 0.3 m for a good light penetration. The mixing of the culture circulation is commonly performed by a paddlewheel. Advantages of open systems are their inexpensive and simple establishment. Disadvantages are that they are less controllable due changing growth parameters like light, temperature and pH, the fluctuating conditions and dependency on environmental parameters like sun exposure, clouds, precipitation, evaporation and the high contamination risk with other microorganisms. (PULZ 2001, MATA et al., 2010). In addition, biomass yields are much lower, when compared to closed systems (in open systems: 1 g * L^{-1} resp. 10-25 g * m^{-2} * d^{-1}; closed: 3-15 g * L^{-1} resp. 25-50 g * m^{-2}*d^{-1}). The biomass yield of higher oily plants like rape is with 0.8-1.6 g * m^{-2} * d^{-1} much lower as the productivity in open systems. (ROESCH and POSTEN 2012) Nevertheless of the party inefficient operation, 98% of the generated algae biomass is currently produced in open systems (FAO 2012).

Closed systems have various advantages compared to open systems (tab. 3). Closed systems allow a controlled process performance by lower contamination risk and higher biomass yields of 35 - 40 g m^{-2} d^{-1} for Chlorella (PULZ 2009). To optimize important growth factors such as light permeability and nutrient absorption, different reactor designs have been developed. These are either tubular, foil bags or flat panel reactors (tab 2.).
High-value products like carotenoids and fatty acids can be prepared with certain purity for industrial applications. Closed systems can be operated with natural sunlight or with artificial light which then directly implies a high energy input (BRENNAN and OWENDE 2010). A higher energy input is also required for the processing of the algae in order to create the desired products.

Table 2: Open and closed systems for microalgae production

Open system	Closed systems		
raceway	**tubular**	**flat-panel**	**foil-bags**
 KYNDT 2010	 SCHROEDER 2011	 FRAUNHOFER INSTUTUT 2012	 NOVAGREEN 2010
simple construction	optional assembly	thin plastic modules for low light ways	simple, mobile, no cleaning costs

Table 3: Comparison of open and closed systems

Parameter	Open system	Closed system
Area requirement	**high**	**low**
Water requirement	**high**	**low**
Energy demand	**low**	**high**
Temperature control	**no**	**required**
Cleaning	**no**	**required**
Contamination risk	**high**	**low**
Product quality	**fluctuating**	**reproducible**
Biomass productivity	**low**	**high**
Operating costs	**low**	**high**

(after ROESCH and POSTEN 2012)

Application of microalgae

Microalgae biomass and its high-value compounds can be used for energetic and material use. It is necessary to ensure the selection of the algae species with regard to the targeted end product, because the different species have distinct characteristic product ranges of metabolites. With a view to limited fossil fuels, microalgae have become a promising feedstock as an alternative source of bioenergy. The total lipid content of microalgae ranges between 1 and 75%, with average lipid levels between 20–50% of the cell weight with greater accumulations during stationary phase and under certain conditions (up to 85% of cell dry weight) (METTING 1996, BECKER 2007, CHISTI 2007, MATA 2010). The green microalgae species *Botryococcus braunii* is intensive studied as rich natural source for lipids. Stored lipids can be used for the production of biodiesel. The biomass can also be used for the production of biogas. In addition, intensive efforts have been made to produce hydrogen with microalgae (e.g. with *Chlamydomonas reinhardtii*). Particularly in form of using the microalga hydrogenase for the efficient hydrogen production in other cell systems. (MELIS et al., 2007, SCHARFF et al., 2013) However, high market prices limit the commercial use of microalgae biofuels. Concerning this aspect, research is just as necessary as for the above mentioned fields.

At present, microalgae are mainly used as food supplements (about 70%) and are added in drinks, in candies, bread, pasta etc. (BECKER 2007) Currently, the second focus is the use as animal feed for fish, pets and farm animals (ROSELLO-SASTRE et al. 2010, BECKER 2007). They are also considered to be as highly promising organisms as production organisms for high value bioactive products as proteins, carotenoids, fatty acids and carbohydrates. This can be used in various industrial applications ranging from food, pharmaceutical, and cosmetic to the chemical industry (tab. 4) (SFORZA et al., 2012, SIMIONATO et al., 2013, GRIS et al., 2014). In this view, that there is a competition between the cheaper synthetic produced pigments and the natural microalgal based ones. The advantage of microalgal pigments is the provision of natural isomers with better physiological properties compared to synthetic products.

Microalgae can also be used as CO_2 storage or to remove pollutants like heavy metals or for the reduction of nitrogen and phosphate from industrial, agricultural and municipal waste waters (HUNT et al., 2009). In addition, microalgae can be used as fertilizers and plant protection compounds, as well as for the production of recombinant proteins. Further concepts for non-terrestrial applications in aerospace are under investigation (PULZ et al., 2004, ROSELLO SASTRE et al., 2010, KIT 2012). As a result of this, microalgae have attracted the attention of various branches of the economy.

Table 4: Examples for the application of high value compounds

Cell contents	Samples	Application
Fatty acids	polyunsaturated fatty acids like ω-3-fatty acids (docosahexaen acid, eicosapentaen acid)	- food supplements (e.g. in breast-milk substitutes) - pharmaceuticals and cosmetics - feed (e.g layer, aquaculture)
Carotenoids	astaxanthin, lutein, ß-carotene, lycopene	- food supplements - food (e.g. margarine , cheese, sausage) - pharmaceuticals and cosmetics - feed
Pigments	chlorophyll, carotenoids	- food - pharmaceuticals - feed (e.g. colouring of salmon)
Polysaccharides	β-1,3-glucan, starch	- food - cosmetics and pharmaceuticals (e.g. substrate of drugs) - production of bioplastics
And other	iodine, polyphenols, amino acids, proteins, enzymes, antioxidants, toxins, vitamins (A, E, B1, B2, B6, B12, C, K)	- food and food supplements - pharmaceuticals and cosmetics (e.g. skin tightening) - feed

(adjusted from PULZ et al., 2004, BEACHAM 2010, FRAUNHOFER INSTUTUT FUER GRENZFLAECHEN- UND BIOVERFAHRENSTECHNIK 2010, ROSELLO SASTRE et al., 2010)

Economic state

High processing costs, low production yields and production stability, low space-time yields and high efforts for the preparation of the products are currently major problems for an economic production and the commercialization of the algal technology (SCHARFF et al., 2013). The average market price of microalgae is 36 € per kg dry matter (*Chlorella*) (BRENNAN and OWENDE 2010) and high-value compounds such as astaxanthin (carotenoids) can reach prices of 2000 € per kg and higher (SPOLARE et al. 2006). These high-value compounds make up only a small portion of less than 10% of the total biomass. (HEJAZI and WIJFFELS, 2004, ROSELLO SASTRE and POSTEN 2010).

Different strategies have been worked out to improve the economic use of microalgal products. This means three main segments: product oriented selection or (genetic) modification of microalgae species (g. higher product yield, increasing photosynthetic efficiency), optimized design (e.g. flat panels, tubes or foil bags) and operating conditions of photobioreactors (e.g. light (wavelength composition, light-dark cycles), nutrition composition, pH, temperature, mixing and pumping strategies of the microalgae broth, air feed etc.) and the development of efficient methods for the preparation of the partly sensitive products.

The development of biorefinery processes will further expand the microalgae usage possibilities along the value chain. This offers the option for an efficient use of every component of the microalgae biomass (fig 2). It can be produced simultaneously high-value products, biofuels, animal feed and electrical power. The concepts include the recycling of residues as substrates for the algae culture and the efficient use of exhaust gases and different sources waste waters.

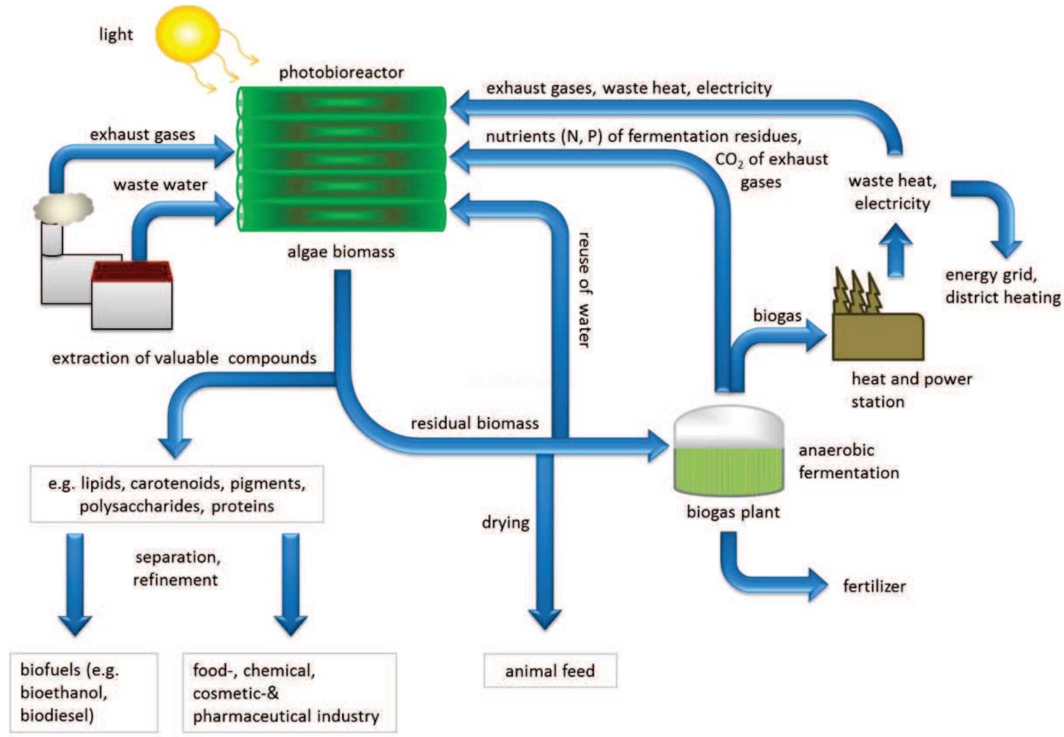

Figure 2: Microalgae use in biorefinery concept (own illustration)

Outlook

It could be demonstrated that microalgae can be used for versatile applications like the production of bioenergy, high-value compounds, food and food supplements, feeds, in agriculture or pharmaceutical and chemical industry. In view to growing world population, shortage of fertile land, rising demand of food crops and additional limited resources for fuels it will become clear, that alternative and sustainable sources are needed to provide these goods in future for next generations. To exploit the potential of microalgae, further intensive research effort is needed in the direction of optimized growth parameters and operating conditions in order to make microalgae production and processing a competitive renewable resource in the long-term.

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