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Advances in Biochemical Engineering/Biotechnology

Aims and Scope

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Microalgae Biotechnology

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Status, Challenges, Goals

One of the biggest global challenges of the twentieth century is to sustainably supply a growing world population with food, raw materials, and energy in times of climate change. In doing so, biomass plays an important role, as the plants, with the help of sunlight and carbon dioxide from the atmosphere, can produce all these components sustainably and without consuming fossil energy sources. This photosynthesis-based capacity of plants, hence, is the cornerstone of the current bioeconomy concept. However, there are clear limits: The available and even decreasing agricultural area and the yield per unit area that can hardly be increased any further.

Microalgae are a promising—some people say the only—way out of this limitation. Even residual biomass—the so called biomass of the second generation—is available only in limited amounts compared to the huge needs in energy supply. So microalgae have been classified as the biomass of the third generation. The potential for a novel type of biomass production for bioeconomy is enormous. The two major advantages on this strategical level can be identified:

- Per unit area, microalgae can form up to five times more biomass than classical energy plants. Values of 100 t biomass per hectare and year are considered to be realistic.
- No valuable agricultural area is required. It is possible to use practically any areas not claimed for other purposes. This includes dry areas, industrial wasteland, brackish water zones or open seas.

But where are the large-scale production facilities for economically efficient supply of basic foodstuffs, bulk chemicals or chemical energy carriers? Even if the potential of microalgae for biomass supply is quite obvious, there is still a great need for research to develop relevant applications and to find out, how microalgal biomass can be produced in reliable and profitable manner in large scale. This editorial will give a look over current trends, identify existing obstacles, and specify biological and technical research needs necessary for an economically efficient microalgae-based bioeconomy.

Microalgae: Solar Cell Factory for Bio-based Resources of the Third Generation

Microalgae are microscopically small plants naturally occurring in water bodies, such as lakes, rivers or seas. For some time now, microalgae have also been cultivated and used by man. For this purpose, open ponds or closed reactors are applied. There, microalgae grow suspended in an aqueous medium. Apart from the microalgae, this medium contains mineral nutrients only. Some high-quality food or feedstuff supplements and cosmetic products have long been introduced on the market. Examples are the red dye astaxanthin for fish cultivation and polyunsaturated fatty acids (PUFA) for healthy human nutrition. However, the quantity produced worldwide totals some thousand tons only. Several demonstration plants for the production of bioenergy carriers have been built.

Besides the already mentioned advantages the potential of microalgae on the biological level can be summarized:

- Many species grow in saltwater even at high salt concentrations, reducing problems with water supply.
- For many species carbon flux can be partitioned to lipids or carbohydrates without loss of photosynthetic efficiency. Intracellular concentrations are far above those of classical land plants showing high concentrations for example only in seeds.
- Accumulation of pigments namely antioxidants or other strongly reducing compounds is possible thanks the specific cell structure. Similar concentrations cannot be reached in genetically modified heterotrophic microorganisms.
- Microalgae do not have any roots or wooden parts in the sprouts and leaves. Hence, the complete microalga or all its components can be used without any problems.
- The different microalgae species contain multiple different compounds for commercialization, making the biorefinery profitable.

Diversity of Microalgae: The Unexplored Potential

Microalgae do not represent any consistent biological group, but can be divided into several, partly extremely different strains from several phyla. The term microalgae, hence, is understood to comprise forms of microscopically small plants that predominantly live in aquatic habitats. In that sense also the procaryotic cyanobacteria are often included in this term. Of the several hundred thousands of alga species estimated, some ten thousand have been classified so far. Only a fraction of them, i.e. about 20 microalgae, are used for economic purposes.

Comprehensive screening programmes in all parts of the world constantly deliver new strains for strain collections. These strains are then applied in a variety of high-concentration products. In spite of the application of latest methods, e.g. growth tests in highly parallel microtitre plates, however, the products can be customised to a certain extent and for a few defined environmental conditions only. Often, attention is paid to a certain substance class exclusively. In the second stage, a process-oriented strain selection has to be made. Important criteria are robustness in the bioreactor, temperature stability, or the possibility of specifically excreting valuable substances.

For thousands of years, human beings have been growing higher plants for the production of food, construction materials or fabrics. In the last decades, this process was further analysed and advanced thanks to better insight into life processes. On the one hand, initial diversity converged towards a manageable quantity of useful plants with high yields, such as corn or cotton. On the other hand, a large plant variety developed and was optimised for regional climate conditions or special applications. This step that is referred to as domestication still remains to be accomplished for microalgae screening and strain development within the shortest possible time.

Strain Development: Biological and Technical Optimization

Microalgae-based molecular biological methods are still behind the development in the area of classical microorganisms like bacteria and yeasts. Recently, however, its importance increased strongly. Research concentrates on production of recombinant proteins, a technology that is expected to have major biological and technical advantages when using microalgae. Known products also are in the focus of genetic engineering. Even if photosynthesis as such cannot be improved significantly, it is succeeded in increasing the partly low concentrations of highly valuable substances or in adapting e.g. the fatty acid profiles of the oils produced to the needs of foods, lubricants, or biodiesel.

In addition, process-oriented properties are studied and produced specifically. Algae cells that flocculate "on command" largely facilitate harvest. Another idea is that algae with reduced pigment concentrations utilize light more efficiently during cultivation. Process technology is also influenced by the specific excretion of products from the alga cell. Work in this area does not necessarily lead to the use of the genetically modified strains in practice, but is considered to serve as a model to test the molecular effect and practical use. In view of the high diversity, the findings can then be used in the screening for natural strains.

This development process, known as domestication, is still in an early stage. Strains with interesting products are not yet adapted to the intensive conditions in bioreactors. Comparing the improvement by breeding of terrestrial crops over centuries or the increase of productivity for heterotrophic microorganisms, the high development potential still to be realized becomes obvious.

Products: From High Value Compounds to Bulk Chemicals

Microalgae have been known as food supplements for a long time already. Examples are proteins of high biological quality, vitamins in particular of the B group, polyunsaturated fatty acids, antioxidant pigments, such as carotenoids, minerals, and other substances. The cyanobacterium *spirulina* (biologically correct term *arthrospira*) and the green alga chlorella vulgaris are cultivated for this purpose and marketed in the form of disrupted cells or extracts. *Astaxanthin* from *haematococcus pluvialis* plays an important role as a pigment in the cultivation of salmon. Research additionally covers pharmaceuticals, such as immuno-stimulating polysaccharides or medicine for Alzheimer's disease.

What applies to food supplements also applies to basic foodstuffs. Plant-based biomass cannot be supplied, unless additional agricultural areas are made available. This is where microalgae-based technology comes in. Several international companies in the food production sector deal with microalgae. Work is aimed at offering e.g. colourless, odourless, and tasteless protein components. Polysaccharides, such as alginate or carrageenans, are produced from macroalgae and processed in foodstuff already. They are suitable basic substances for food. They are not to be considered supps only, but can contribute decisively to world food supplies.

Another important application field is animal feed. Facing the overfishing of oceans consensus is given that sustainable aquaculture has to be further expanded. Fish is at the end of food chain, microalgae at the beginning. A healthy fish being healthy for humans as well needs many of the compounds of microalgae. Currently fish a fed with fish meal, what has already run short. Consequently, aquaculture has become a major driver for microalgal biotechnology. Ongoing research is directed to finding and cultivation suitable algae strains especially for this purpose.

Algae-based biotechnology wants to achieve a market share not only in the sector of high-quality products, but also in the area of mass products of medium and low price levels. Discussion focuses on resources for chemical industry, such as monomers for bioplastics and other fine and platform chemicals. Examples are certain fatty acids and isoprene. More than 5 % of the crude oil imported by Germany are used for plastics. This is a market that may be made more energy-neutral by using microalgae.

Renewable energy sources will have the biggest share in the energy mix of the future. An important element will be the use of biomass. Apart from increasingly criticised biofuels of the first generation and the use of residual biomass, microalgae represent another source of sustainable biomass for energy production, which is independent of agricultural production. In analogy to residual biomass, microalgae may be fermented to methane in biogas facilities. Even more interesting is the use of the large oil fraction. It can be processed to biodiesel after extraction and further conversion. Hence, this option yields a liquid fuel urgently required in aviation. Again, biology can directly support process technology. Research focuses on algae that directly produce and excrete hydrocarbons. As a result, extraction and transesterification may no longer be necessary. Another option is the direct production of hydrogen and bioethanol.

Many algae that have not been studied so far have an enormous potential for use in food, pharmaceutical, cosmetic, and chemical industries. Potential target products, however, have not yet been detected or searched for in the screening process. Genetically modified strains are under investigation for production of recombinant proteins. For *Chlamydomonas* this technology is already quite well developed, for the chloroplast and for the nuclear genome. Problems persist for most of the other strains. In addition genetic modification might be decisive to extend the product portfolio for the energy and chemical substances sectors and help adapt product quality to high standards.

Dialogue between industry with its concrete needs and biology focusing on diversity has to be intensified and broadened to identify the potential in detail. Screening programmes and application of genetic engineering methods developed for model algae to other species will open up further substance classes. Apart from material aspects, strain development also has to focus on technical implementation, robustness, and the capability of excreting valuable substances.

Photobioprocesses: Technologies Along the Value Added Chain

The potential of microalgae has finally to be realized in production plants by process engineering means. Major advantages in terms of production conditions are:

- Microalgae are produced largely automatically by process technologies in open or closed reactors.
- Microalgae do not have any pronounced seasonal growth periods like classical land plants, they can be grown throughout the year depending on the availability of light.
- Growth in closed reactors minimises the use of water. In addition, a reduction of fertilisers and crop protection agents seems to be if possible.
- For recombinant extracellular proteins specific advantages like clear medium for easy separation and strongly reduced virus problems apply.

Of course, the biomass factory of the future will require large areas, as solar energy has to be collected and radiation is quite diluted per se. But this is the only similarity to agriculture. Microalgae production units will appear more like a technical oriented facility. An interesting option is however the coupling between agriculture and algae production.

Photobioreactors: Technical Hub of the Production Process

The photobioreactor is the location, where the microalgae meet with light, CO_2, water, and nutrients and where growth and product formation processes take place.

Open ponds, e.g. raceway ponds, still are the workhorses of commercial microalgae production. They allow for the production of algae biomass at moderate costs and with a moderate energy consumption. Yet, production concentrations and productivities are also low and hardly exceed those of classical agricultural areas. The large surface area exposed to the surroundings is a gateway for contamination, water is lost by evaporation. More ambitious objectives cannot be reached, as the technological development potential is lacking.

These drawbacks might be overcome with the help of closed reactors. The alga suspension is contained in a transparent box through which light may enter. The incident (sun-) light is to be distributed as homogeneously as possible in the suspension. Contrary to a chemical substrate, this cannot be done by mixing. Mutual shadowing effects of the algae produce strong gradients. For this reason, several design criteria have to be observed. For example, the transparent surface area has to be large compared to the medium volume that is to have the form of thin layers. Moreover, microalgae are not capable of processing high light intensities occurring at noontime, for instance. This means that the light has to be "diluted" over a reactor surface that is larger than the footprint area. Two basic reactor designs have been developed, plate reactors and tubular reactors. Several attempts are currently undertaken to make reactor design lower to reduce hydrostatic pressure and to apply light guiding structures to reduce the light gradient inside the medium. Horizontal designs can be regarded as endpoint of this development line.

The capacity of the cells to build complex molecules plays the most important role in the production of moderate amounts of high-quality substances. Energy aspects are less relevant. Artificial illumination may be used. This includes application of colours different from colours. A high "red" fraction e.g. is suitable for photosynthesis and minimizes the energetic effort of the cultivation. Rapid development in the area of LEDs has pushed this technology. Larger foil reactors or smaller glass reactors with external illumination may be purchased on the market. It is also possible to backfit classical reactors with internal illumination systems. In this case, all requirements relating to process control are met. GMP qualification of such a reactor for e.g. the pharmaceutical sector appears to be much easier than for reactors depending on daylight and having large exposed surface areas.

Still, it is a problem to produce algae biomass at low costs and in an energy-neutral manner. One of the reasons are the costs of the reactors per unit area in relation to the gain from collecting sun energy. Research projects relating to inexpensive reactors with a reduced material consumption are to solve this problem in the near future. Like all reactors, photobioreactors for microalgae have to be equipped with mixing and gasification systems. The use of CO_2 with solar energy may be considered a political advantage, but represents a big technical challenge. This particularly applies to low-energy mass transfer into the algae suspension.

Again, this challenge was accepted by industry and academia. The first significantly improved pilot reactors are passing practical tests in demonstration scale at the moment.

Another important aspect is heating up of the reactors by incident sunlight. One way to solve this problem is to select seasonally adapted algae strains. Marine reactors already benefit from cooling by the ocean water. For a more sophisticated technological answer to the problem biologists, bioprocess engineers, and thermodynamics experts cooperate to find ways to store the excessive heat of the day and use it during the night. Patents to filter out the infrared fraction of light are published. That can even be done using transparent photovoltaics and fitting the demand of auxiliary energy by the electricity gained. The complete energy autarkic photobioreactor is a high-level objective but nevertheless it is thinkable. It would be a break through with respect to production costs.

The biomass factory of the future will use large fallow areas for “harvesting sunlight”. There, closed reactors will not be protected by greenhouses for reasons of costs. Hence, contamination cannot be prevented completely in the long term. Employing extremophiles is common in open ponds, co-cultivation of different algae are under investigation. Environmentally compatible procedures will have to be established for future production without any herbicides and other polluting measures.

Depending on the specific value added and the location conditions, various designs of photobioreactors will prevail. To ensure economic efficiency, however, few standard models will be envisaged. They will be offered to potential users by special companies. A parameterisation has to be made according to biological/engineering standards. Clear geometrical design criteria are still lacking. Further input from material sciences is needed with respect to UV-resistance, workability or anti-fouling properties. For the usual materials like PMMA or polycarbonate already many different coatings are on the market for different purposes, so progress is likely to happen soon. Measurement, control and the development of process strategies is another fast developing field. Here algorithms from other technical fields like adapted control can be applied to the specific needs of photobioreactors as excellent properties of the medium and the cells for optical measurements on the one hand and fast changing environmental conditions like sun-light, being the “disturbance” in control engineering view.

Downstream Processing: The Difficult Path Towards the End Product

Cell harvesting is the next step in the chain of values added. This technical task of solid-liquid separation may be achieved in principle by flotation, filtration, or centrifugation and yields a pasty product, called slurry, for further processing. Special devices for the separation of microorganisms have been developed and commercialised for decades. In the case of microalgae, however, a specific problem is encountered. The solid matter content is far below of the values reached by classical fermentation technology. Hence, several times the amounts of water is needed to be processed per harvested microalgal biomass. Moreover, production of chemical energy carriers from microalgae has to be energy-neutral, a requirement that is not encountered elsewhere in biotechnology. Industry has responded to this requirement by developing e.g. novel centrifuges and cross flow devices. To reach the anticipated amounts of biomass, however, further process technology research is required.

Similar to the processing of plant materials, algae processing is followed by necessary or optional steps, such as drying, mechanical dissolution, extraction or chemical conversion. In principle, processes have already been developed for the use of sustainable resources, but they remain to be adapted to algae at least. The pasty structure of the slurry, for instance, cannot be subjected to simple mechanical pressing like rape seed is. In addition, the relatively high water content of the cells makes it difficult to use solvent extraction or hydrolysis processes for biofuel production. Hydrothermal liquefaction or gasification are actively under research and development. On the other hand, algae are much better accessible for many chemical processes, such as energy production in biogas facilities and fractionation, than straw or wood wastes. In this area, research teams are active worldwide.

Biorefinery: Pathways for the Holistic Use of Microalgae-Based Biomass

In an oil refinery complex crude oil is fractionated into different compounds which are fully processed leaving nearly no residual fractions. In analogy, the different compounds of biomass should be isolated and refined in order to gain a complete energetic and material use of biomass. For example, the polyunsaturated fatty acids can be used for human food, while saturated fatty acids can be used for technical purposes. Proteins can in a next step be separated for animal feed, while the residual biomass is finally used energetically in biogas plants.

This concept has to be profiled for different cases. First of all, one of the advantages of microalgae is that they can be used as a whole cell e.g. for human food or animal feed. A small fraction in the daily diet has been shown to deliver minerals and vitamins especially in underdeveloped countries, where only carbohydrate sources are affordable. A basic problem of the biorefinery lies in the different orders of magnitude for the amounts of the produced compounds and the market volume. High value products are usually present only in small fractions of the biomass and are needed only in small amounts. The value of the residual biomass is negligible. The full potential of the biorefinery may be obtained for medium sized plants. In case of bulk chemicals or especially fuel production processes the residual biomass accrues in gigantic amounts which cannot be absorbed by any market. This holds for the processes currently know delivering a fraction of e.g. 50 % oil in the biomass.

A basic scientific problem is in finding cultivation conditions shifting intracellular stoichiometry to the main product or to by-product ratios best for a given market without losing productivity. High concentrations for carotenoids e.g. are purchased by high light intensities but long cultivation times. Limits for shifting stoichiometry to calculable costs are in most cases not quantitatively known. Innovation lies here in developing strains producing extracellular compounds. This has been shown for polysaccharides and hydrocarbons produced by wild type algae or ethanol formation with genetically engineered strains. Glykolate and isoprene are other candidates. Final target is to partitioning most of the fixed carbon into the product leaving the cells themselves with growth rates close to zero. A side benefit is given by employing biofilms reactors with low mixing rates and saving of cell separation. This concept has been declared as "New Green Chemistry".

Algal biomass can turn out to be an important alternative to fossil fuels. Integrated production and commercialization concepts have to be developed, which are sensible in sustainable and economical aspects. Flexible adaptation to market conditions is one pre-requisite. Doing so, the microalgal based biorefinery has the chance to become the key for an internationally competitive economy. Algae demonstration plants have to be set up by combining the different products and production steps to deliver quantitative numbers for predicting commercial exploitation costs.

Process Integration: Microalgae Production in the Ecological, Economic, and Social Setting

Microalgal production processes have to be carefully be integrated into the environment for sustainability. Some of the advantages of microalgae in terms of process integration are:

- Production processes with microalgae can be integrated comparatively easily into existing energy and material cycles (wastewater, salt water, waste heat, exhaust gases). Cycles can be closed by smart feedbacks.
- Production on land for which no other claims exists will minimize conflicts with other industries or local population.
- Food from microalgae will be more and more accepted starting from taste-, smell-, and color-less preparations. Polysaccharides from macroalgae can be found already in many consumer products.
- Sunny areas with salt water available can be found all over the planet. Microalgae plants will reduce the dependency from oil producing countries and bring working places to structurally weak regions.

It is easy to say that CO_2 for the microalgae comes from industrial plants like gas power stations or lime stone processing. Indeed, it turned out to be a logistic problem as algae cultivation plants will be remote from industrial areas. A promising concepts among others is to couple heterotrophic production like bioethanol processes with microalgal plants to get benefit from CO_2-recycle. Residual biomass from the microalgal biorefinery could be a good carbon source for the heterotrophic stage in the sense of cross-feeding.

Delivery of mineral salts for nitrogen or phosphor supply is a cost factor for production as along as no sensible recycling on the production plants is foreseen. In case of oil production nearly all minerals are basically recyclable from the residual biomass eventually indirectly from the biogas effluent. In the case of protein production nitrogen leaves the plant and has to be replaced. For phosphate a world-wide shortage has been anticipated and needs special attention when whole cells are sold and distributed. This in mind, municipal waste waters are often addressed as feasible sources of N and P. Coupling of microalgal cultivation with aquaculture is often mentioned, because feeding the fish with the algae and recycling the fish waste water including N,P back to the cultivation seems to be sensible. To these scenarios many research project shave been published. However, some technological problems seems to be unsolved like unsuitable stoichiometry of the nutrients or low concentrations making cell retention necessary. Some algae show good abilities for mixotrophic growth to use up organics from wastewater. Another positive issue is the constant temperature of waste water making cooling superfluous. In the same sense cooling water from industry has been proposed for temperature control what means cooling during warm days and warming up in when it is cold to keep growth at its optimum. These aspects have to be studied carefully in life cycle analysis (LCA) to quantitatively assess costs versus benefits taking into account material and energy flows as well as their respective couplings from the intracellular level, over the reactor to the production site and even more to the production environment.

Location Issues: Where to Go Between Light and Shadow, Desert and Sea

The choice of a suitable site is essential for the success of any algal production plant. However, the different way of using microalgae lead to different demands for the production site. Some studies about possible regions show the potential of the microalgae biorefinery but do not reveal a clear preference for certain countries or regions. Solar irradiation is not really a decisive factor. Availability of water, CO_2, nutrients and auxiliary energy are additional points to be considered. In the Sahara about 2.5 times more sun energy per hectare could be used compared to middle latitudes, but this advantage has to be paid by problems in the infrastructure, extremely high irradiation but in only a few hours during the day, and high temperatures. In mountains close to the equator the picture could be different with moderate temperature all through the year and during day and night.

For high value compounds productivity and production cost play a minor role. The high revenues in relatively small markets allow the application of closed photobioreactors on small areas. Activities in some countries in the middle latitudes are promising in this concern. Further north other points apply like the long days with ideally distributed light intensity during the summer, possibilities for temperature control by low temperature waste heat, and the short distance to CO_2-sources. Studies have shown that here business cases are realistic as production is possible from early spring to late autumn, even if the plant is switched off during winter to save maintenance energy. For further processing a powerful industry is waiting.

Large scale commodities like biofuels are facing a strong cost pressure. Large production capacities are necessary to reach industrial relevance. To fit these constraints large cultivation areas of many square kilometers with high solar irradiation are necessary and access to cheap CO_2 and nutrient sources. Such applications are expected to emerge typically in the southwest of the USA, in the Middle East, in some parts of Asia, or in Australia. One interesting idea are marine photobioreactors. While the availability of salt water inclusive cooling option and free space is obvious, at least in sea areas remote from heavy shipping or sensible fishery areas, wind and waves are challenges.

Regulations: What We Can and What We are Allowed to Do

Just like any other new products, products based on microalgae require approval according to regulations of the respective country. This approval focuses on two levels. First, it is to be demonstrated that the production process does not endanger health of the people working at the production facilities and not adversely affect the environment. Depending on the tonnage produced, comprehensive studies and data sheets have to be submitted according to the pertinent regulations, such as "Registration, evaluation, authorisation, and restriction of chemicals" and "Classification, labelling, and packaging" in the EU. Second, consumer protection has to be guaranteed. Subcategories have been defined depending on the market (food, food supplements, novel food, cosmetics, pharmaceutical products, feedstuff, animal health products). Various requirements have to be met. Allocation to one of these groups may be a problem already. The "EU Novel food regulation“ and the "EU Cosmetic regulation“ are relevant to algae. In a simplified procedure, for instance, the microalga *odontella aurita* and *astaxanthin* extracts from *haematococcus pluvialis* were approved of as novel food. The (mostly medium-sized) industrial companies consider such approval procedures a high obstacle. Support by politics is needed urgently.

For the transformation into energetic compounds and the envisaged reduction of carbon dioxide emissions, clear regulations and provisions will have to be adopted.

In the transport sector, in which biofuels represent an indispensable element of the sustainable fuel and mobility strategy, many problems have not yet been solved and lead to uncertainties in industry. To meet the political targets and to eliminate uncertainties for the producers of alternative fuels and automotive industry, some points have to be settled by policy, including: Which specifications and minimum requirements have to be met by microbial fuels with respect to adaptation of standards for gasoline and diesel? What are the legal specifications for blending quotas and carbon savings for the envisaged applications and what are the consequences when they are not reached? Such decisions are important for any investigation in algae plants.

Before these points have not been settled, no big change in the transport sector is to be expected.

International Cooperation: Development of Strategic Alliances

Despite all progress in algae-based biotechnology and the current installation of pilot plants to supply biofuels based on ethanol and lipids in the USA, the need for basic and applied research remains in this area. For a holistic use of algae at biorefineries, various biotechnological and process technology disciplines have to cooperate closely. Possibilities of cooperation in research alliances on the national level, however, are limited due to the interdisciplinary character of the topic. While the establishment of research clusters in the European Union is supported under the corresponding research framework programmes, such alliances can hardly be initiated with partners beyond the borders of the European Union and in research-focused nations, such as the USA. Due to the apparently lacking coordination of the funding institutions, hardly any project proposals of this type are invited. Different funding conditions and review procedures exist on the national levels. Applicants would prefer calls to be published not only on a national basis, but by all funding institutions of the target nations at the same time. Proposal, review, and funding could take place in parallel. Establishment of transnational research alliances, including the drivers of the international research community, would result in an innovation boost in the medium and long term. However, efforts to establish such international cooperative ventures by the funding institutions would have to be increased considerably.

Man: Part, Target, and Meaning of the Value Added Chain

Large-scale microalgae production will change the face of the Earth. For this, civil society has to be taken along. Anybody will welcome secure mobility in the coming decades and reduced famine in the world. But where will new jobs be created? In many regions in the world, where hardly any farming is done due to draught and where no mineral resources are found except for solar energy, microalgae will be a big opportunity. Establishment and operation of the facilities will create jobs and, hence, economic growth. Industrialised countries may contribute their strengths and provide the required process technology. The main concern of industrialised countries is the availability of high-quality biomass for bioeconomy. In addition, it is hoped that production will be distributed over many regions of the world. This will reduce not only material dependence, but also political dependence on fossil resources. For this to come true, the right steps have to be taken today. Technology assessment studies should include this aspect with the balance limits being defined accordingly. Not just since the speech of Obama, microalgae research has moved from science into the focus of the public. Many countries have already taken decisive steps towards creating a future with microalgae on the level of research, also with public funding. Politics can now continue on this way and define framework conditions for research, economy, society, and international relations.

Commercialisation of microalgal biotechnology will go along stepping stones from high value products in small amounts over the medium priced segment to bulk products in plants with increasing size and finally renewable energy. Some of the current trends are outlined in a study of dechema, on which this preface is based. This book will give views to some of the mentioned aspects and will encourage further reading and contributing to bring microalgal biotechnology further forward to make it a benefit for our society.

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