Industrial biotechnology: a challenging change to the raw material base

Biogenic raw materials have never been as popular as they are now. Efforts to tap renewable carbon resources are already underway, despite the fact that new oil drilling technologies are boosting fossil fuel stockpiles. In the medium term, industry will have to expand its raw materials base, and in the long term it may have to renew it completely. Industrial biotechnology is one of the key technologies in the transition from an economy based on fossil fuels to one based on renewable resources. The microbes that produce renewable resources need access to a sufficient supply of biomass. But what kind of biomass will they use and do we have enough of it?

How coveted biomass is depends a great deal on the type of biomass we are talking about. Although a battle is already raging about wood, we still have a rather relaxed attitude when it comes to biological waste. However, it is realistic to assume that the competition for renewable raw materials will intensify in the future. The world's population is growing, and along with it, so is the demand for food and animal feed. This creates a dilemma: grazing areas and agricultural and forest areas are limited, and the demand for biomass is enormous if it is to be used to (partially) replace fossil raw materials in industry.

But that's not all. As land is limited and there is a large number of competitive applications biomass can be used for, it is important to set priorities. Experts have defined a priority list for the different applications of biomass (OECD, 2011, p. 16) called 5F Cascade, which suggests that priority should be given to food and feed, followed by specialty and bulk chemicals and ingredients for medicines, then fibres and biomaterials (wood, pulp and paper), and then fuels and energy. Fertilizers and soil conditioners come at the end of the list.

However, all this is still a vision of the future. The idea behind the 5F Cascade is that the material use of renewable resources (biomass) before they are used to produce energy saves fossil fuels, cuts greenhouse gas emissions because CO_2 is bound for longer, and keeps biomass in a longer recycling chain, which therefore delivers greater added value. Biomass is currently predominantly used to make bioethanol and wood pellets, which means that it is combusted very early on in the recycling process. The cascading resource-efficient and sustainable use of biomass is currently not yet standard. At present, it is basically only used for energy production. Material flows (i.e. raw materials, biomass, water, waste, energy, etc.) need to be reorganised and new technologies need to be found that enable the effective conversion of biomass into valuable materials.

Biomass – should it be used for energy or materials?

Around 110 million tons of crude oil were used in Germany in 2012 for industrial processes and the production of energy. Crude oil is used for the production of fuels, lubricants, chemicals and plastics – modern life is inconceivable without crude oil.

Biomass is currently the only renewable carbon source. Maybe one day it will also be possible to use carbon dioxide or carbon monoxide from industrial processes, i.e. a large proportion of our exhaust gas emissions, for producing carbon compounds for use in industry. However, this pathway is far from sustainable because the carbon in this case would still derive from fossil resources such as crude oil, gas or coal. The first generation of biobased chemicals employs resources that are also used as food and feed. The second generation of biobased chemicals uses non-food biomass that mainly contains cellulose, hemicellulose or lignocellulose. Having said that, edible biological resources are still the principal resources used for the production of chemicals. However, the ongoing debate on sustainability is bringing biogenic residues and industry waste and its elusive material flows more into the spotlight (Raschka and Carus, 2012). In future, it is highly likely that a thing like biological waste will no longer exist. It can safely be assumed that the barriers to the material use of biomass will be removed and biomass will be turned into products and become the basis of value-added processes.

Biomass should be available, competitive and sustainable. In Europe, this applies for example to residues from the harvesting of round timber or material from landscape management (i.e. plants pulled up or pruned on streets and in parks and meadows, etc.). Nevertheless, round timber is a special case: the demand from the traditional wood industries is so high that there is very little wood available to produce anything else. Moreover, the potential for using wood residues from the forestry sector is already fully exploited.

So what about algae? Will they become the major suppliers of biomass? They take up CO_2 and convert it into hydrocarbons.

Whether they will become an alternative to land plants is difficult to say because methods that enable large-scale cultivation of algae are still in their infancy. However, they are certainly excellent candidates, due in particular to their CO_2-based metabolism and to the fact that they can be cultivated on areas that cannot be used for forestry or agriculture.

Lignocellulose – a challenge

The sustainability debate clearly affects first-generation (1G) biofuels which are produced from starch contained in foods like corn, sugar crops, wheat or oil from oilseeds such as rapeseed. A transition to using other renewable resources that are not starch-based and hence do not compete with food and feed is immanent. However, this transition to non-food renewables is a difficult one. "Lignocellulose, which is a renewable resource used for the production of second-generation biofuels, is still difficult to process and the appropriate technologies are still not mature enough," says Hartmut Grammel, Professor for Industrial Microbiology at the Biberach University of Applied Sciences. Bacteria and yeasts that are traditionally used in biotechnological applications are unable to metabolise hemicellulose, which is a major component of lignocellulose. This is due to the composition of the molecule. Hemicellulose is a polymer of sugars containing five carbon atoms each (C5 sugars). However, the microorganisms used in the field of biotechnology prefer glucose, a sugar with six carbon atoms that is contained in cellulose and starch. Nevertheless, some microorganisms are able to metabolise C5 sugars.

Lignin is a relatively complex biopolymer that is associated with even greater problems. This is another case where the microorganisms that are traditionally used in biotechnological applications struggle to break it down. Some fungi are able to break down lignin, but they are unsuitable for mass culture in bioreactors. Researchers are working intensively on the development of enzymes that can break down lignocellulose, and lignin in particular.

Once it is broken down, lignin can be used by microorganisms that are able to metabolise the C5 sugars of hemicellulose and transform them into products or product precursors. The goal is not only to find ways that enable the chemical transformation of the molecules, but also to find enzymes and organisms that are suitable for large-scale production. The latter is a huge challenge that will be difficult to achieve.

There is almost four times more global bioethanol production than biodiesel (fatty acid methyl ester) production (Pöyry Management Consultant Oy, p. 22). Some second-generation pilot- and demonstration-scale bioethanol plants (2G ethanol plants) that are able to use non-food substrates already exist and further large-scale plants are under construction. The only commercial-scale plant, which has an annual production capacity of 75 million litres, is located outside the city of Crescentino (Italy) and is able to produce bioethanol from rice straw and energy crops through enzymatic conversion. The specialty chemicals company Clariant operates a demonstration-scale (1.26 million litres) cellulosic ethanol production plant in the Bavarian town of Straubing.

Some 2G plants that are able to produce biobased fuels are operated – some on a trial basis - overseas. Proof of their cost-effectiveness is not yet available (Krieger, 2014). The competitiveness of 2G fuels heavily depends on the price and efficiency of enzymes and microbes (Pöyry Management Consultant Oy, p. 21). The microbial production of biodiesel (ed. note: previously done using a chemical process called transesterification), which is the most common type of biofuel used in the European countries, has not yet emerged from the development stage.

Interesting alternative: synthesis gas fermentation

Syngas fermentation, also known as synthesis gas fermentation, is an alternative to biofuel production. All types of biomass can be broken down thermochemically into a mixture of hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2). Some anaerobic bacteria, Clostridium species for example, use syngas, i.e. CO, CO_2 and H_2, as carbon and energy sources to produce ethanol, butanol or chemicals such as acetic acid, butyrate, 2,3 butanediole and acetone. Various Clostridium strains with modified metabolic pathways are used for example in the commercial conversion of syngas in pilot and demonstration plants (Coskata, INEOS Bio and LanzaTech).

At present, CO, CO_2 and H_2 are produced from fossil resources, crude oil and gas. Biomass or organic waste currently account for only 0.5 percent of the raw material base worldwide. The greatest challenge associated with the industrial application of syngas fermentation is the transfer of the gases from the gas into the liquid phase. The gases need to dissolve efficiently in a liquid medium, which is an important prerequisite to allow microorganisms to take up sufficient quantities of gaseous nutrients.

Syngas can also be converted into liquid hydrocarbons in Fischer-Tropsch reactors and subsequently used in existing refineries in the same way as fossil oil. The one-step pyrolysis process is still regarded as a relatively immature process. Organic biomaterial is decomposed at elevated temperatures in the absence of oxygen. Pyrolysis produces gas and liquid organic products.

The global biofuels market is expected to double to 136 billion euros by 2021. On the basis of products that are due to enter the market, the production of 2G ethanol will by then represent around six percent of current 1G ethanol production (Pöyry Management Consultant Oy, p. 23). The future of the biofuel industry depends heavily on political conditions. The new

regulations on ways to reduce CO_2 emission from transport fuels attach increasing importance to 2G fuels as they are rated higher than 1G fuels in terms of CO_2 reduction. This will result in rising demand for renewable raw materials, which in the case of 2G fuels, do not compete with food and feed.

Biogas is also a 2G energy carrier. Decentralized biogas production in Germany, which is regarded as a technology leader, covers four percent of gross electricity consumption (German Biogas Association, 7th July 2014). Anaerobic fermentation of biomass is commercially available. However, the construction of biogas plants has stagnated due to the amendments to the Renewable Energy Law (EEG). The law has further reduced feed-in tariffs, causing biogas plant operators to fear that new plants will no longer pay off.

Biogas nevertheless plays an important role in the current energy mix. According to calculations by the Agency of Renewable Resources (14th June 2014), biogas, when cleaned and upgraded to natural gas standards when it becomes biomethane, will be in a position to cover 10 percent (and in 2020, 15 percent) of our gas consumption and replace a lot of fossil gas.

First biobased platform chemicals are placed on the market

The production of polylactic acid, which is used for bioplastics, is an early example of success. The photo shows IngeoTM biopolymer pellets.

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The key molecules that might be the basis of a future green chemistry industry have already been identified. These molecules possess several functional groups that open up numerous reaction pathways and enable the production of intermediary products, which, due to their possible combinations, can be turned into a number of subsequent and final products. Laboratory processes that can be applied to C3, C4, C5, C6, C10 and C12 compounds are already available.

It is becoming apparent that in the near future it will be possible to produce highly pure renewable platform chemicals such as succinic acid, 1,4-butanediol (BDO), isobutanol, acetic acid or isoprene using specifically engineered microbes that are able to ferment sugar. It is expected that the methods will be in a position to compete with petrochemical processes. 2G conversion processes are still an exception in the chemical industry, such as for example the biotechnological production of citric acid and amino acids.

In addition, enzymes are widely used in the industry and the global market for industrial enzymes is growing rapidly. Many enzymes are derived from renewable resources and produced by fermentation. Two-digit growth rates (Erickson, 2012, p. 180 ff.) suggest that the demand for biobased resources will also continue to rise in this segment. The microbes that produce renewable resources will also in the future need access to a sufficient supply of biomass.

Early success trio: economy, environment, sustainability

Bioproducts produced on an industrial scale and that have achieved early success – 1,3 propanediol (PDO) produced by fermenting corn-sugar mixtures (DuPont Tate & Lyle Bio Products Company LLC) – have shown that competitive pricing and performance are equally as important for commercial success as environmental benefits and sustainability. The biotechnological synthesis of PDO requires much less energy and emits fewer greenhouse gases than the petrochemical method.

The same is true for polylactic acid (PLA, e.g. produced by NatureWorks LLC), polyhydroxyalkanoates or polyethylene (Erickson, 2012). However, the sustainability of production only becomes commercially relevant when customers are prepared to pay more for green methods or when the price of CO_2 certificates significantly increases.

Over the last few years, Europe has promoted the production of bioenergy rather than the production of materials from renewable resources. However, in order to facilitate the commercialization of biobased products, the European Commission has launched a public-private initiative (BIC; Biobased Industries Consortium) which has 3.8 billion euros – around 2/3 from private investors – to spend on the development of methods for converting biological residues and waste into greener everyday products. This initiative will run until 2020.

High expectations

The biobased economy is largely based on expectation (as are bioplastics), since the commercialization of some industrial biotechnology products has to overcome several hurdles before it can provide low cost, environmentally friendly products that are partially able to replace petrochemical products (Chen, 2012: "high volume and low price" strategy). Macroeconomist Dr. Sven Wydra from the Fraunhofer Institute for Systems- and Innovation Research (ISI) has just completed an innovation report on behalf of the Office for Technology Assessment at the German Bundestag: "We are still at the very beginning of the material use of biomass and we have much potential still ahead of us.

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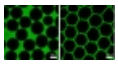

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