Catalysis – a Key to Sustainability

Matthias Beller

Catalysis is the science of accelerating chemical transformations. In general, readily available starting materials are converted to form more complex molecules using versatile applications. These conversions enable the creation of a large range of products for different industries, as well as products that can be used directly in the fields of health, environment, and nutrition. Catalysts ensure that reactions proceed in a highly efficient manner, are high yielding and avoid unwanted by-products. Importantly, they often allow for a more economical production compared to classical stoichiometric procedures.

Over the course of their synthesis, more than 80 percent of all chemical products come into contact with catalysts, thus rendering catalysts indispensable for the needs of today's society. Consequently, they are a key factor to sustainability and profitability of chemical production processes.

According to the North American Catalysis Society, 15 to 20 percent of the economies of the developed western nations rely directly or indirectly on catalytic processes. It is, therefore, not surprising that without catalysis many of the things we take for granted in daily life – petrol or plastics, dyes and clothing, automobiles or computers, medicines or cosmetics – would be either impossible or suffer in quality.

The economic value of catalysis is enormous. According to the market analyses of various experts, the value of goods manufactured with the aid

Fig. 9: Catalysts play an important role during the production process of many goods, for instance of cars, plastics and pharmaceuticals.

of catalysts amounts to between US $500 and US $2,500 billion per year. In 2004 the market for catalysts itself had a volume of approximately US $10 billion per annum – a figure that clearly shows the striking power of catalysis. The rate of growth in the catalyst market is 5 percent annually, with North America, Europe, and recently China contributing the largest share. In general, catalysts are used in four major areas: environmental protection (35%), chemicals (23%), oil processing in refineries (22%), and polymers (20%). Several different catalysts are available for the great variety of end uses.
Traditionally, catalysts are divided into homogeneous and heterogeneous catalysts, biocatalysts (enzymes), photo catalysts, and electro catalysts. The main areas of interest of the "Leibniz-Institut für Katalyse e.V. an der Universität Rostock (LIKAT)" are homogeneous and heterogeneous catalysis. Comparing the different sub-areas of catalysis, all have common characteristics, but also significant differences are visible. While homogeneous catalysts (most often the pre-catalyst) are molecularly defined and work at lower temperature (<200°C) and more selectively, heterogeneous catalysts are in general easily recycled and allow for high temperature processes.
Due to the specific characteristics of homogeneous and heterogeneous catalysis, the application and use of these systems have been performed in the past in different chemistry communities. In this regard, the LIKAT is bridging this gap in order to make full use of the potential synergism of the two fields.

Problems and challenges

In general, the goal of sustainable chemistry is to develop technologies that use fewer raw materials and less energy, that maximise the use of renewable resources, and minimise or eliminate the use of dangerous chemicals. In Germany, for instance, 1,000 people used 158 terajoules of energy in 1999. Among the substances released were 13,700 metric tonnes of greenhouse gases. They used 655 metric tonnes of steel and drive 443 cars. The same statistics for a less developed country like Egypt are 22 terajoules, 1,300 litres of gases, 5 metric tonnes of steel, and six cars. These figures make our future problems strikingly clear when rapidly developing countries with high populations such as China and India reach the same standard of living that we now enjoy. Since there is no reason why these nations should not reach a similar level of prosperity, we need to find the ways and means of ensuring that this development is environmentally sound – a task in which catalysis must and will play a decisive role.
Even now, many syntheses of chemical products are still carried out via classical organic reactions that are more than 100 years old. These include nitrations, Friedel-Crafts reactions, and halogenations. The disadvantage of these methods is occurrence of stoichiometric – frequently even overstoichiometric – quantities of salts that have to be separated and discarded. They also often require complicated protective group techniques, such as

Fig. 10: Catalysts also help processing food. Here catalyst's reaction is tested during the production of ice cream

halogenations and dehalogenations that are needed for the regionally specific activation of a functional group. This is why these conventional production processes often generate several metric tonnes of waste per metric tonne of target product. With active ingredients for medicines or crop-protection agents, the amount of waste produced can sometimes exceed the target product by a factor of tenths to one hundred. Given these facts, there is no doubt of the need for the most innovative and versatile catalytic methods for new environmentally safe chemical processes.
Providing enough energy is one of the most important tasks for the future of our society, the aim being to replace fossil resources in the transportation sector as well as in the generation of electricity and heat. Here, hydrogen as a future source of energy poses significant challenges. In this regard, catalytic processes play a decisive role in two areas: in mobile reformer units for producing hydrogen and in the conversion of chemical energy into electrical energy with the aid of fuel cells. However, there are still important problems to be solved. More efficient catalysts are needed for fuel cells and there is an additional need for catalytic processes to make hydrogen available as a sustainable and cost-effective raw material. Here, a major challenge for the next decades will be providing cost and energy-efficient artificial photosynthesis systems.
In the area of health and nutrition, catalytic processes form the basis for the production of fertilisers, agricultural additives, and pharmaceuticals currently used. In the past, pharmaceutical products have been produced using predominantly stoichiometric organic syntheses. However, since the 1990's, homogeneous catalysis is being used

on an increasingly frequent basis for the production of current drugs. The only way we will be able to manufacture new ingredients in a sustainable manner, especially chiral and enantiomerically pure products, is by an increased use of catalytic processes, because catalytic reactions offer the opportunity of shorter and more selective routes for a number of future drugs. In addition, catalytic innovations will contribute to the next level of development of the life sciences. We will need to provide more active drugs with less toxic side-effects. In this respect, catalytic reactions are one tool to open up new substance classes for pharmaceuticals.

In conclusion, it should be clearly stated that Germany continues to hold a leading position in the field of basic and applied catalysis and is well positioned to make major contributions to the aforementioned innovations. With two Max Planck Institutes (the Max Planck Institute for Carbon Research in Mülheim an der Ruhr and the Fritz Haber Institute in Berlin), and the Leibniz-Institut für Katalyse in Rostock and Berlin, as well as leading chemical and engineering departments in different universities, e.g. Aachen, Berlin, Heidelberg, and Munich, Germany has a competitive research infrastructure in this very important field.

Policy advice and research necessities

- the development of new environmentally safe (sustainable) processes, at best so-called "zero-pollution processes"
- the opening up of new raw materials, for the future especially the use of renewable resources
- energy technology, with an emphasis on hydrogen technology

Yet more specifically, some priorities should be:

- Improved solutions for direct regioselective introduction of amino, hydroxyl, carbonyl, and carboxyl groups
- Avoiding by-products of conventional methods, including Friedel Crafts-type reactions
- Developing new convenient catalysts – with inexpensive metals and ligands
- Achieving novel transformations that would not be possible without catalysts, e.g. useful conversions of carbon dioxide, nitrogen, etc.
- Developing synthetic processes that combine bio catalytic and conventional catalytic steps in useful ways.

Contact:
Prof. Dr. Matthias Beller
University of Rostock and
Leibniz-Institut für Katalyse (LIKAT)
Albert-Einstein-Straße 29a
18059 Rostock/Germany
Phone: + 49 (381) 1281-113
Fax: + 49 (381) 1281-5000
E-mail: matthias.beller@catalysis.de
www.catalysis.de