Green chemistry: a tool for the sustainable development of the chemical industry

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Most manufactured products involve one or more chemical processes. We cannot imagine what our life will be like without the products produced by the chemical industry. However, on average, only a small proportion of the resources we take from the Earth is converted into the desired products in current chemical processes, and large amounts of wastes and hazardous materials are generated. How to supply humanity with enough food, energy, chemicals and materials sustainably, without damaging our planet, is an unavoidable issue.

Green chemistry, which was established about two decades ago, has attracted much attention [1–3]. It reflects the efforts of academia and industry to address the challenges related to sustainable development of the chemical industry, and continuous progress is being made, both in academia and industry. Briefly, green chemistry is the utilization of a set of principles to reduce or eliminate the use or generation of hazardous substances in the design, manufacture and applications of chemical products [4]. Green chemistry is a multidisciplinary field and covers areas such as synthesis, solvents, catalysis, raw materials, products and efficient processes, as shown in Fig. 1.

EFFICIENT SYNTHETIC ROUTES
Most current chemical production processes lack efficiency in using feedstocks and produce large amount of wastes. Increasing atom economy [5] is crucial for reducing both the depletion of raw materials and the generation of waste. Ideally, all the atoms in reactants should be transformed into the desired products. However, the achievement of 100% atom economy in all industrial chemical processes is not realistic. Another way to eliminate waste is integration of different reactions and processes, in which the by-product in one reaction is the feedstock of another. Exploration of atom-economic synthetic protocols and routes to increase the synthetic efficiency and reduce or eliminate wastes is a long-term task.

GREENER AND FUNCTIONAL SOLVENTS
Huge amounts of toxic, flammable and volatile organic solvents are used in chemical processes to prepare chemicals and materials. About 20 million tons of organic solvents are released to the atmosphere each year [6], leading to solvent waste and environmental pollution. The use of greener solvents such as water, supercritical fluids, ionic liquids, non-toxic liquid polymers and their various combinations in chemical processes has become a major focus of research in academia and industry. A green solvent should meet some basic requirements such as low toxicity, ease of availability and recycling, and high process efficiency. It is known that the efficiency of a process usually depends strongly on the properties of the solvents used. Because of their special properties and functions, green solvents can be used to optimize chemical processes, decrease solvent usage and processing steps, and develop new routes and technologies that meet the requirements of sustainability.

GREENER CATALYSIS
Catalysis plays a key role in the chemical industry [7] because most chemical processes need catalysts to accelerate reactions, enhance selectivity and lower energy requirements. Current catalysts are often based on expensive, toxic, harmful or noble metals. Green catalysts should have some common characteristics such as high activity, selectivity, and stability, and ease of separation and reuse; they should be based on environmentally benign and widely available raw materials such as abundant metals, organic compounds and enzymes. The exploration
and development of new synthetic routes and chemical processes rely strongly on progress in catalysis. The design and use of green catalysts and catalytic systems to achieve the dual goals of environmental protection and economic benefits is an important task, and is essential for the sustainability of the chemical industry.

USE OF GREEN AND RENEWABLE FEEDSTOCKS

Currently, our energy supply and the feedstocks for producing organic chemicals and materials are mainly based on fossil resources, which are not renewable and are diminishing. The use of renewable carbon resources, i.e. biomass and CO₂, in the chemical and energy industries is extremely important, and different routes and processes have been developed [8]. However, we face thermodynamic, kinetic and technical challenges in the conversion of biomass and CO₂ into fuels and chemicals. Many current routes are technically feasible, but economically prohibitive, and only very small proportions of the resources are currently used. The development of efficient methods for converting biomass and CO₂ into useful chemicals and liquid fuels through energetically and economically viable industrial processes is of great importance, but is challenging. Moreover, the use of greener, cheaper, safer reactants and sustainable energy sources, such as oxygen, hydrogen peroxide and solar energy, in chemical processes is also an interesting area [9].

GREEN ENGINEERING AND PRODUCTS

It should be emphasized that green chemistry covers engineering aspects and green products [10]. Chemicals and materials are produced by industrial chemical processes, and therefore, clean, energy-efficient and mass-efficient processes and technologies are essential tools for achieving the goal of maximizing efficiency and minimizing wastes. Many current pharmaceuticals, fine chemicals, commodity chemicals and polymers are harmful. Products that are benign to human health and the environment need be designed and produced to replace hazardous products. Clearly, the exploration of synthetic routes, design of sustainable products and solvents, and exploration of new catalysts and chemical processes are closely related, and should be integrated. In addition, economic benefits are the central driver for the development of green chemistry and technology.

OUTLOOK

Green chemistry will be one of the most important fields in the future. Although this field has developed rapidly in the last 20 years, it is still at an early stage. Promoting green chemistry is a long-term task, and many challenging scientific and technological issues need to be resolved; these are related to chemistry, material science, engineering, environmental science, physics and biology. Scientists, engineers and industrialists should work together to promote the development of this field. There is no doubt that the development and implementation of green chemistry will contribute greatly to the sustainable development of our society.

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