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EDITORIAL

CHEMISTRY GOES GREEN

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Green chemistry emerged in the 1990s when research increasingly focused on the development of environmentally benign alternatives to hazardous chemical processes. This was prompted by a rising awareness of the costs of waste in industries, and the need for cleaner chemical manufacturing in governments. Through a combination of targeted research funding, tougher legislation and awards for best practice, the green chemistry movement quickly gained momentum and helped nurture what are now well-recognized clean technologies in process chemistry. Wasteful separations, for example, were addressed through the use of supercritical CO_2; atmospherically damaging volatile organic solvents were replaced by non-volatile ionic liquids; and heterogeneous reagents and catalysts were introduced to avoid the use of soluble reagents and other process additives that were hazardous or difficult to separate.

The importance of new metrics for measuring process greenness, championed by the pharmaceuticals industry, also became recognized. One of the earliest and most popular–the ratio of waste to product, or 'E factor' – highlights the wastefulness of many chemical processes. More recent assessments have also shown the need to consider a wider set of metrics across a product's life-cycle.

The legislative, economic and social drivers for change now influence all the stages of a chemical product's life-cycle. Diminishing reserves and marked price fluctuations have been highlighted for oil – the main raw material for chemicals – but in reality the problem is much wider. Resource depletion of many key minerals and price increases for commodities affect almost all chemicals and jeopardize the survival of manufacturing in its present form. At the other end of the life-cycle, mounting pressure from the public as well as non-governmental organizations (NGOs) has led to an exponential growth in product-focused legislation (notably the European Registration, Evaluation, Authorization and Restriction of Chemical substances, or REACH) and a degree of consumer choice that is threatening the continued use of countless chemicals. These challenges can only be embraced with a combination of pure, discovery-oriented research and translational, application-focused research.

Chemists working with biologists and engineers will learn how to make greater use of the only practical sustainable source of carbon: non-food biomass. This includes agricultural, food and forestry wastes, as well as the co-products from some large-scale processes such as biofuel manufacturing. Large volumes of consumer and industrial wastes, such as discarded electrical and electronic equipment, can also be exploited by using the low-environmental-impact technologies developed in the 1990s. This will not only be a major step towards the creation of a new generation of green and sustainable chemicals, but will also help solve the escalating waste problems faced by modern society.

In particular, we can make more imaginative use of the extracts from biomass: cellulose, starches and chitin can act as a source of small molecules, but they could also become the building blocks of new macromolecular materials. Compounds such as ethanol, lactic acid, succinic acid and glycerol would then replace – or at least reduce our reliance on – fossil-based compounds such as ethene, propene, butadiene and benzene. The future green chemistry toolkit thus needs to be flexible and versatile as well as clean, safe and efficient.
Here the chemistry–biology and chemistry–(bio) chemical engineering interfaces are crucial: we need to develop synthetic pathways starting from the oxygenated and hydrophilic molecules produced through most current biomass conversions. That also means we cannot afford to include wasteful and costly steps before these synthetic transformations. A wider range of chemistry in water will help (and often make processes safer), as will the further development of other important synthetic strategies such as reducing processes through telescoped reactions, which combine several reactions into one process step. At the chemistry–engineering interface, catalytic membranes, intensive processing techniques and more energy-efficient reactors will also become more important. Fermentation technology will remain an important route for the decomposition of complex biomass to small molecules, but with better control of pyrolysis–through catalysis and alternative activation methods (such as microwaves) – we should also be able to develop parallel routes to different molecules, which would give us a much wider range of

building blocks. Finding new, sustainable and cost-effective routes to aromatics is proving to be especially difficult: we need better ways of opening up the structures of nature's aromatic stores, such as lignin and suberin.

The challenge for green chemistry is not just to replace undesirable chemicals such as chromates and polyhaloaromatics but also to make sure that, wherever possible, the substitutes and the chemistry used to manufacture them are green and sustainable. More research is currently needed to address the challenges that REACH and other product-focused legislation present – safer, more environmentally benign products are required in just about every commercial sector, with particular emphasis on flame retardants, plasticizers, adhesives and primers.

This new century will see a gradual transfer from a petroleum-based chemistry to a chemistry based on a wide diversity of feedstocks. Although virgin fossil-derived and mineral-derived resources will continue to be important for the foreseeable future, chemicals and materials derived from non-food biomass and from the increasing mountain of what we still refer to as 'waste' must take over: today's waste will be tomorrow's resource. Green chemistry can help in converting these feedstocks into resources through low-environmental-impact technologies, processes and methodologies. In this way we will be able to achieve the essential goal for future generations of green and sustainable products.