Part 1
Green Chemistry for Sustainable Development

Green Separation Processes. Edited by C. A. M. Afonso and J. G. Crespo

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1.1 Green Chemistry and Environmentally Friendly Technologies

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1.1.1 Introduction

“Green Chemistry” is the universally accepted term to describe the movement towards more environmentally acceptable chemical processes and products [1]. It encompasses education, research, and commercial application across the entire supply chain for chemicals [2]. Green Chemistry can be achieved by applying environmentally friendly technologies – some old and some new [3]. While Green Chemistry is widely accepted as an essential development in the way that we practice chemistry, and is vital to sustainable development, its application is fragmented and represents only a small fraction of actual chemistry. It is also important to realize that Green Chemistry is not something that is only taken seriously in the developed countries. Some of the pioneering research in the area in the 1980s was indeed carried out in developed countries including the UK, France, and Japan, but by the time the United States Environmental Protection Agency (US EPA) coined the term “Green Chemistry” in the 1990s, there were good examples of relevant research and some industrial application in many other countries including India and China [4].

The Americans launched the high profile Presidential Green Chemistry Awards in the mid-1990s and effectively disclosed some excellent case studies covering products and processes [5]. Again, however, it is important to realize that there were many more good examples of Green Chemistry at work long before this – for example, commercial, no-solvent processes were operating in Germany and renewable catalysts were being used in processes in the UK but they did not get the same publicity as those in the United States [2, 4].

The developing countries that are rapidly constructing new chemical manufacturing facilities have an excellent opportunity to apply the catchphrase of Green Chemistry “Benign by Design” from the ground upwards. It is much easier to build a new, environmentally compatible plant from scratch than to have to deconstruct before reconstructing, as is the case in the developed world.

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In this chapter I shall start by exploring the drivers behind the movement towards Green and Sustainable Chemistry. These can all be considered to be "costs of waste" that effectively penalize current industries and society as a whole. After a description of Green Chemistry I will look at the techniques available to the chemical manufacturers. This leads naturally into a more detailed discussion about methods of evaluating "greenness" and how we should apply sustainability concepts across the supply chain. It is important that, while reading this, we see Green Chemistry in the bigger picture of sustainable development as we seek to somehow satisfy society's needs without compromising the survival of future generations.

1.1.2
Objectives for Green Chemistry: The Costs of Waste

Hundreds of tonnes of hazardous waste are released to the air, water, and land by industry every hour of every day. The chemical industry is the biggest source of such waste [3]. Ten years ago less than 1% of commercial substances in use were classified as hazardous, but it is now clear that a much higher proportion of chemicals presents a danger to human health or to the environment. The relatively small number of chemicals formally identified as being hazardous was due to very limited testing regulations, which effectively allowed a large number of chemicals to be used in everyday products without much knowledge of their toxicity and environmental impact. New legislation will dramatically change that situation. In Europe, REACH (Registration, Evaluation, Assessment of Chemicals) will come into force in the first decade of the twenty-first century and whilst, at the time of writing, the final form of the legislation has yet to be decided, it is clear that it will be the most important chemicals-related legislation in living memory and that it will have a dramatic effect on chemical manufacturing and use [6]. REACH will considerably extend the number of chemicals covered by regulations, notably those that have been on market since 1981 (previously exempt), will place the responsibility for chemicals testing with industry, and will require testing whether the chemical is manufactured in Europe or imported for use there. Apart from the direct costs to industry of testing, REACH is likely to result in some chemical substances becoming restricted, prohibitively expensive, or unavailable. This will have dramatic effects on the supply chain for many consumer goods that rely on multiple chemical inputs.

Increased knowledge about chemicals, and the classification of an increasing number of chemical substances as being in some way "hazardous", will have health and safety implications, again making the use of those substances more costly and difficult. Furthermore, it will undoubtedly cause local authorities and governments to restrict and increase the costs of disposal of waste containing those substances (or indeed waste simply coming from processes involving such substances). Thus, legislation will increasingly force industry and the users of chemicals to change – both through substitution of hazardous substances in their processes or products and through the reduction in the volume and hazards of their waste.

The costs of waste to a chemical manufacturing company are high and diverse (Fig. 1.1-1) and, for the foreseeable future, they will get worse.

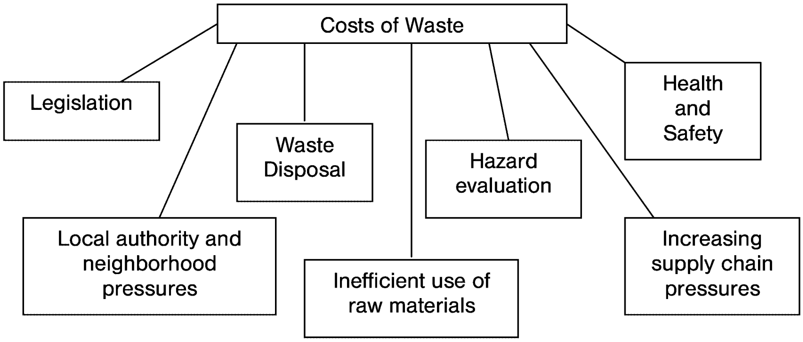


Fig. 1.1-1 The costs of waste.

These costs and other pressures are now evident throughout the supply chain for a chemical product – from the increasing costs of raw materials, as petroleum becomes more scarce and carbon taxes penalize their use, to a growing awareness amongst end-users of the risks that chemicals are often associated with, and the need to disassociate themselves from any chemical in their supply chain that is recognized as being hazardous (e.g. phthalates, endocrine disrupters, polybrominated compounds, heavy metals, etc.; Fig. 1.1-2)

1.1.3 Green Chemistry

The term Green Chemistry, coined by staff at the US EPA in the 1990s, helped to bring focus to an increasing interest in developing more environmentally friendly chemical processes and products. There were good examples of Green Chemistry research in Europe in the 1980s, notably in the design of new catalytic systems to replace hazardous and wasteful processes of long standing for generally important synthetic transformations, including Friedel–Crafts reactions, oxidations, and various base-catalyzed carbon–carbon bond-forming reactions. Some of this research had led to new commercial processes as early as the beginning of the 1990s [4].

In recent years Green Chemistry has become widely accepted as a concept meant to influence education, research, and industrial practice. It is important to realize that it is not a subject area in the way that organic chemistry is. Rather, Green Chemistry is meant to influence the way that we practice chemistry – be it in teaching children, researching a route to an interesting molecule, carrying out an analytical procedure, manufacturing a chemical or chemical formulation, or designing

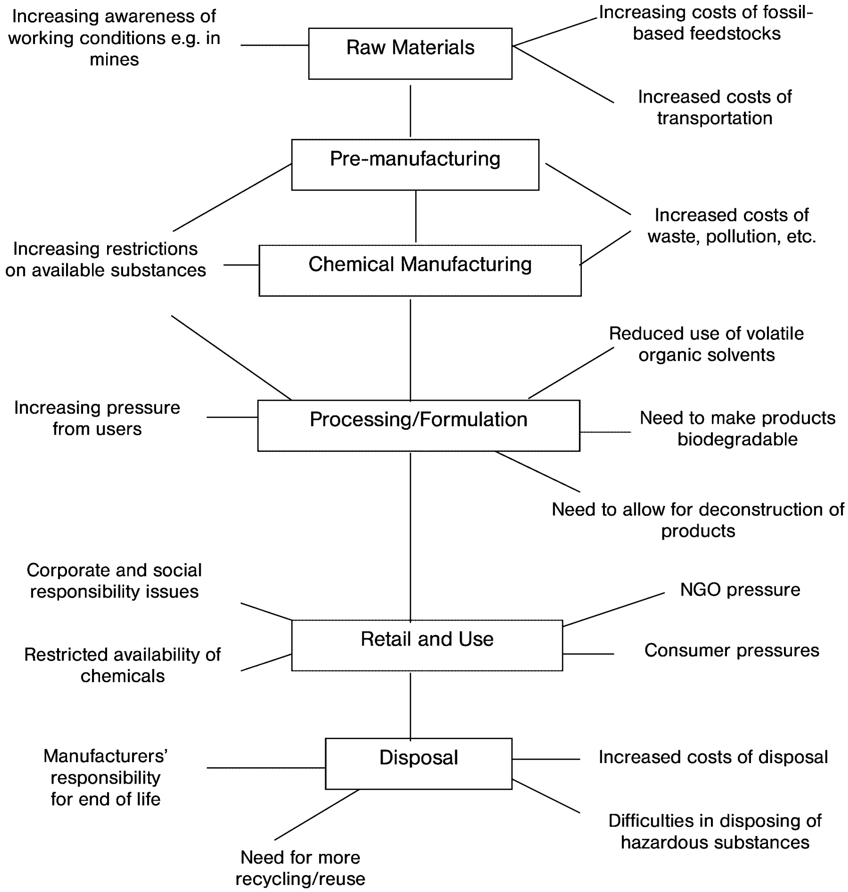


Fig. 1.1-2 Supply chain pressures.

a product [7]. Green Chemistry has been promoted worldwide by an increasing but still small number of dedicated individuals and through the activities of some key organizations. These include the Green Chemistry Network (GCN; established in the UK in 1998 and now with about one thousand members worldwide) [8] and the Green Chemistry Institute (established in the USA in the mid 1990s, now part of the American Chemical Society and with "chapters" in several countries around the world) [9]. Other Green Chemistry Networks or other focal points for national or regional activities exist in other countries including Italy, Japan, Greece and Portugal and new ones appear every year. The GCN was established to help promote and encourage the application of Green Chemistry in all areas where chemistry plays a significant role. (Fig. 1.1-3)

At about the same time as the establishment of the GCN, the Royal Society of Chemistry (RSC) launched the journal "Green Chemistry". The intention for this journal was always to keep its readers aware of major events, initiatives, and edu-

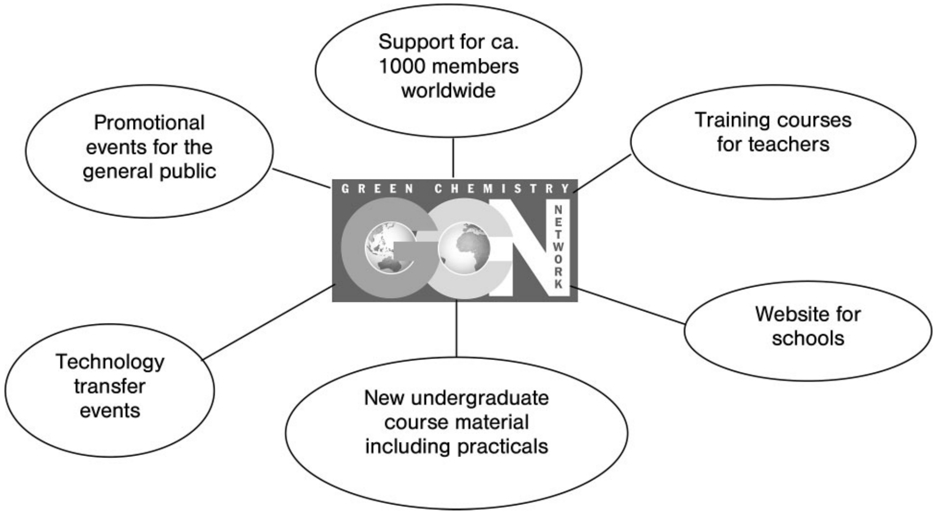


Fig. 1.1-3 The roles of the Green Chemistry Network.

cational and industrial activities, as well as leading research from around the world. The journal has gone from strength to strength and has a growing submission rate and subscription numbers, as well as having achieved one of the highest impact factors among the RSC journals (Fig. 1.1-4).

Green Chemistry can be considered as a series of reductions (Fig. 1.1-5). These reductions lead to the goal of triple bottom-line benefits of economic, environmental, and social improvements [11]. Costs are saved by reducing waste (which is becoming increasingly expensive to dispose of, especially when hazardous) and energy use (likely to represent a larger proportion of process costs in the future) as

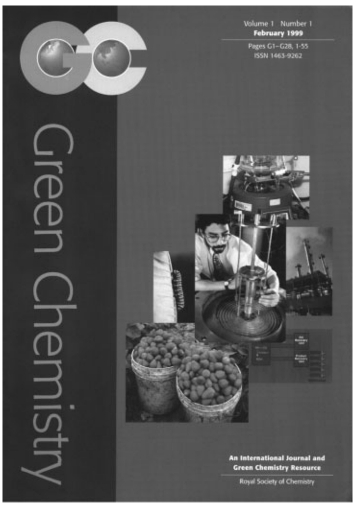


Fig. 1.1-4 The first issue of *Green Chemistry*.

well as making processes more efficient by reducing materials consumption. These reductions also lead to environmental benefit in terms of both feedstock consumption and end-of-life disposal. Furthermore, an increasing use of renewable resources will render the manufacturing industry more sustainable[12]. The reduction in hazardous incidents and the handling of dangerous substances provides additional social benefit – not only to plant operators but also to local communities and through to the users of chemical-related products.

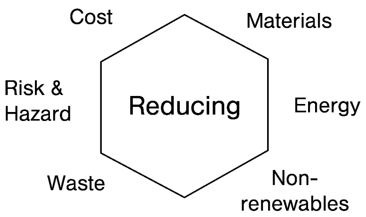


Fig. 1.1-5 “Reducing”: The heart of Green Chemistry.

It is particularly important to seek to apply Green Chemistry throughout the lifecycle of a chemical product (Fig. 1.1-6) [13, 14].

Scientists and technologists need to routinely consider lifecycles when planning new synthetic routes, when changing feedstocks or process components, and, fundamentally, when designing new products. Many of the chemical products in common use today were not constructed for end-of-life nor were full supply-chain issues of resource and energy consumption and waste production necessarily considered. The Green Chemistry approach of “benign by design” should, when applied at the design stage, help assure the sustainability of new products across their full lifecycle and minimize the number of mistakes we make.

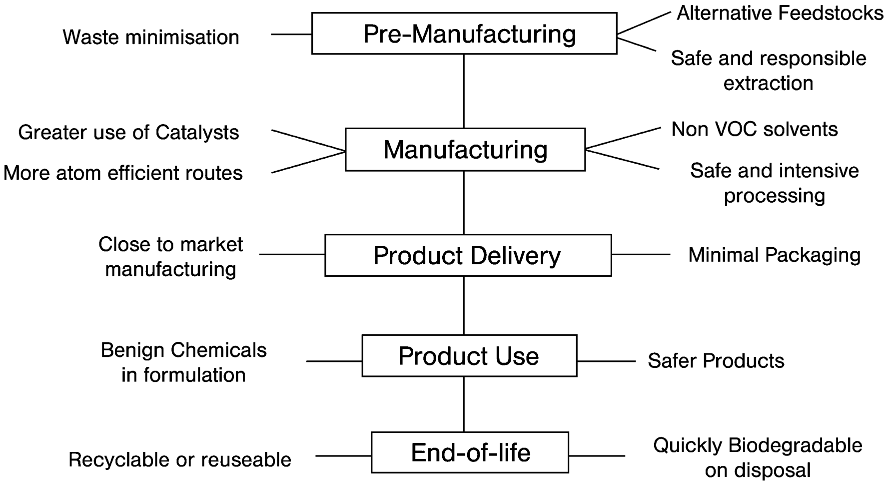


Fig. 1.1-6 Green Chemistry in the lifecycle of a product.

Much of the research effort relevant to Green Chemistry has focused on chemical manufacturing processes. Here we can think of Green Chemistry as directing us towards the "ideal synthesis" (Fig. 1.1-7) [3, 15].

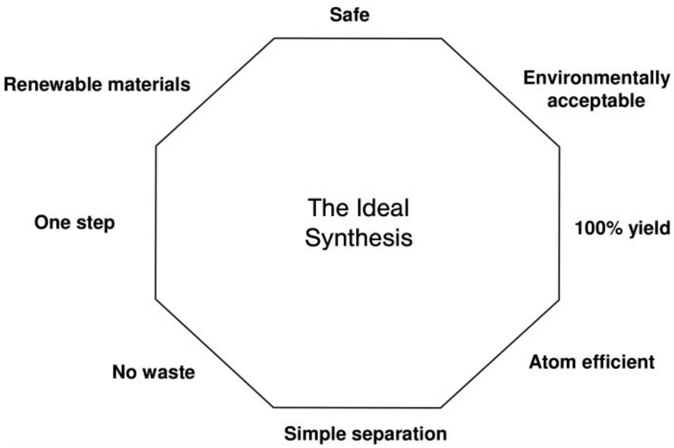


Fig. 1.1-7 Features of the "ideal synthesis".

Yield is the universally accepted metric in chemistry research for measuring the efficiency of a chemical synthesis. It provides a simple and understandable way of measuring the success of a synthetic route and of comparing it to others. Green Chemistry teaches us that yield is not enough. It fails to allow for reagents that have been consumed, solvents and catalysts that will not be fully recovered, and, most importantly, the often laborious and invariably resource- and energy-consuming separation stages such as water quenches, solvent separations, distillations, and recrystallizations. Green Chemistry metrics [16] are now available and commonly are based on "atom efficiency" whereby we seek to maximize the number of atoms introduced into a process into the final product. These are discussed in more detail later in this chapter. As indicated, simple separation with minimal input and additional outputs is an important target. An ideal reaction from a separation standpoint would be one where the substrates are soluble in the reaction solvent but the product is insoluble. The process would, of course, be further improved if no solvent was involved at all! Some of the worst examples of atom inefficiency and relative quantities of waste are to be found in the pharmaceutical industry. The so-called *E* factor (total waste/product by weight) is a simple but quite comprehensive measure of process efficiency and commonly shows values of 100+ in drug manufacture [17]. This can be largely attributed to the complex, multistep nature of these processes. Typically, each step in the process is carried out separately with work-up, isolation, and purification all adding to the inputs and amount of waste produced. Simplicity in chemical processes is vital to good Green Chemistry. Steps can be "telescoped" together for example, reducing the number of discrete stages in the process [18].

To achieve greener chemical processes we will need to make increasing use of technologies, some old and some new, which are becoming proven as clean technologies.

1.1.4 Environmentally Friendly Technologies [3]

There is a pool of technologies that are becoming the most widely studied or used in seeking to achieve the goals of Green Chemistry. The major "clean technologies" are summarized in Fig. 1.1-8. They range from well-established and proven technologies through to new and largely unproven technologies.

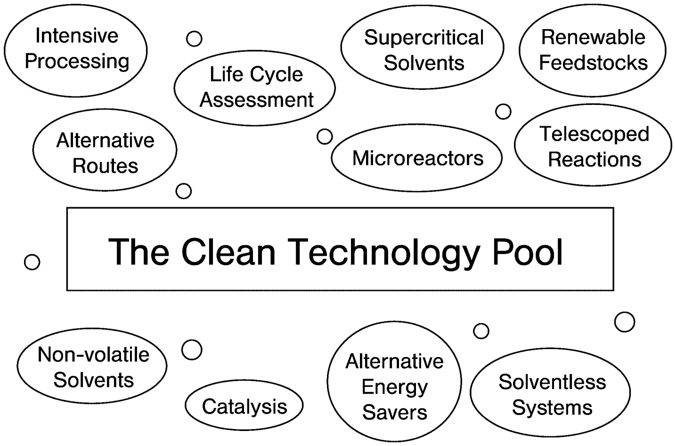
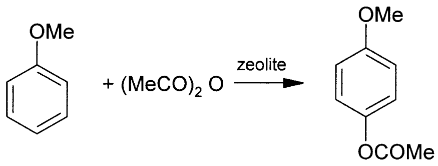


Fig. 1.1-8 The major clean technologies.

Catalysis is truly a well-established technology, well proven at the largest volume end of the chemicals industry. In petroleum refineries, catalysts are absolutely fundamental to the success of many processes and have been repeatedly improved over more than 50 years. Acid catalysts, for example, have been used in alkylations, isomerizations and other reactions for many years and have progressively improved from traditional soluble or liquid systems, through solid acids such as clay, to structurally precise zeolite materials, which not only give excellent selectivity in reactions but are also highly robust, with modern catalysts having lifetimes of up to 2 years! In contrast, the lower volume but higher value end of chemical manufacturing – specialties and pharmaceutical intermediates – still relies on hazardous and difficult routes to separate soluble acid catalysts such as H_2SO_4 and $AlCl_3$ and is only now beginning to apply modern solid acids. Cross-sector technology transfer can greatly accelerate the greening of many highly wasteful chemical processes [19]. A good, if sadly rare, example of this is the use of a zeolite to catalyze the Friedel–Crafts reaction of anisole with acetic anhydride (Scheme 1.1-1).

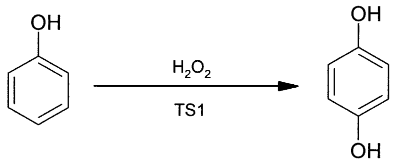


Scheme 1.1-1

In comparison to the traditional route using $AlCl_3$, the zeolite-based method is more selective. However, anisole is highly activated and the method is not applicable to most substrates – zeolites tend to be considerably less reactive than conventional catalysts such as $AlCl_3$.

Many specialty chemical processes continue to operate using traditional and problematic stoichiometric reagents (e.g. in oxidations), which we should aim to replace with catalytic systems. Even when catalysts are used, they often have low turnover numbers due to rapid poisoning or decomposition, or cannot be easily recovered at the end of the reaction. Here we need to develop new longer-lifetime catalysts and make better use of heterogenized catalysts, as well as considering alternative catalyst technologies (e.g. catalytic membranes), and to continue to improve catalyst design so as to make reactions entirely selective to one product [20].

Another good example of greener chemistry through the use of heterogeneous catalysis is the use of TS1, a titanium silicate catalyst for selective oxidation reactions [21] such as the 4-hydroxylation of phenol to the commercially important hydroquinone (Scheme 1.1-2).

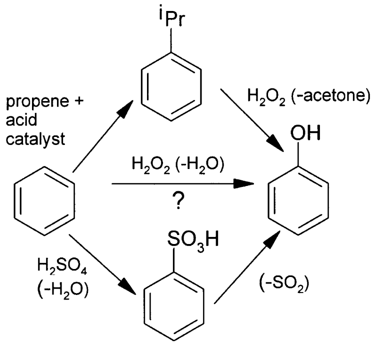


Scheme 1.1-2

TS1 has also been used in commercial epoxidations of small alkenes. A major limitation with this catalyst is its small pore size, typical of many zeolite materials. This makes it unsuitable for larger substrates and products. Again like many zeolites, it is also less active than some homogeneous metal catalysts and this prevents it from being used in what would be a highly desirable example of a green chemistry process – the direct hydroxylation of benzene to phenol. At the time of writing, commercial routes to this continue to be based on atom-inefficient and wasteful processes such as decomposition of cumene hydroperoxide, or via sulfonation (Scheme 1.1-3).

Of course, the direct reaction of oxygen with benzene to give phenol would be 100% atom efficient and based on the most sustainable oxidant – truly an ideal synthesis if we can only devise a good enough catalyst to make it viable!

The increased use of catalysis in the manufacture of low volume, high value chemicals will surely extend to biotechnology and, in particular, the use of enzymes



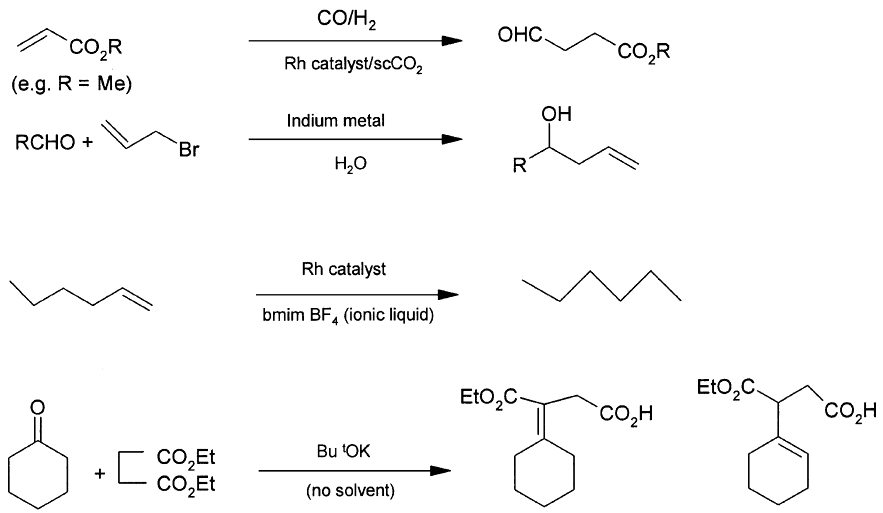
Scheme 1.1-3

[3, 22]. Enzymes provide highly selective routes to chemical products, often under mild conditions and usually in environmentally benign aqueous media. Drawbacks to their more widespread introduction include slow reactions, low space–time yields and, perhaps most importantly, a lack of familiarity with and even suspicions of the technology from many chemical compounds.

The replacement of hazardous volatile organic compounds (VOCs) as solvents is one of the most important targets for countless process companies including those operating in chemical manufacturing, cleaning, and formulation [23]. Some VOCs such as carbon tetrachloride and benzene have been widely prohibited and replaced but other problematic solvents, notably dichloromethane (DCM), continue in widespread use. While in many cases other, less harmful, VOCs are used to remove the immediate problems (e.g. ozone depletion) due to such compounds as DCM, more fundamental technology changes have included the use of non-organic compounds such as supercritical carbon dioxide or water, the use of non-volatile solvents such as ionic liquids (molten salts), and the total avoidance of solvent (e.g. through using a surface-wetting catalyst in a reaction, or simply relying on interfacial reaction occurring between solids). All of these alternative technologies have been demonstrated in numerous organic reactions such as those examples shown in Scheme 1.1-4.

Carbon dioxide has also been successfully introduced into some dry-cleaning processes and various consumer formulations now no longer contain a VOC solvent.

Green Chemistry needs to be combined with more environmentally friendly technologies if step-change improvements are to be made in chemical manufacturing processes. Synthetic chemists have traditionally not been adventurous in their choice of reactors – the familiar round-bottomed flask with a magnetic stirrer remains the automatic choice for most, even when the chemistry they plan to use is innovative e.g. the use of a non-volatile ionic liquid solvent or a heterogeneous catalyst as an alternative to a soluble reagent. However, an increasing number of research articles describing green chemical reactions are based on alternative reactors including· [3, 24].



Scheme 1.1-4

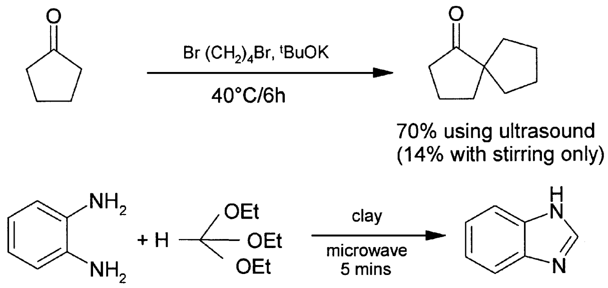
- continuous flow reactors (a technology that dominates the petrochemical industry but is little utilized in specialty chemical manufacturing)
- microchannel reactors whereby reaction volumes are kept small and scale is highly flexible thus reducing hazards and risk
- intensive processing systems such as spinning disc reactors which combine the benefits of low reaction volumes with excellent heat transfer and mixing characteristics
- membrane reactors that can maintain separation of aqueous and non-aqueous phases, hence simplifying the normally waste-intensive separation stages of a process

These alternative reactor technologies can be combined with Green Chemistry methods including, for example, catalytic membrane reactions and continuous flow supercritical fluid reactions.

Energy has often been somewhat neglected in the calculations of resource utilization for a chemical process. Batch processes based on scaled-up reaction pots can run for many hours or even days to maximize yield and often suffer from poor mixing and heat transfer characteristics. As the cost of energy increases and greater efforts are made to control emissions associated with generating energy, energy use will become an increasingly important part of Green Chemistry metrics calculations. This will open the door not only to better designed reactors such as those described earlier but also to the use of alternative energy sources. Of these, two of the more interesting are:

- ultrasonic reactors
- microwave reactors[25].

Both are based on the use of intensive directed radiation that can lead to very short reaction times or increased product yields and also to more selective reactions [3]. Examples of the use of these reactors are shown in Scheme 1.1-5.



Scheme 1.1-5

A lifecycle approach to the environmental performance and sustainability of chemical products demands a proper consideration of pre-manufacturing and specifically the choice of feedstocks. Today's chemical industry is largely based on petroleum-derived starting materials, a consequence of the rapid growth in the new petroleum-based energy industry in the early twentieth century. This industry was based on an apparently inexhaustible supply of cheap oil, which we could afford to use on a once-only basis for burning to produce energy. Petrochemicals was a relatively small (around 10%) part of the business, generating a disproportionately high income and helping to keep energy costs down, which in turn maintained ultra-high demand for the raw material even when extraction became more difficult and transportation more controversial. The parallel and mutually supportive growth in petro-energy and petrochemicals from the petro-refineries of the Middle East, Americas, Africa, and elsewhere is surely past its peak. It now seems likely that as we try to tackle the inevitable decline of oil as an energy source, so shall we attempt to seek alternatives for the manufacture of at least some of the many chemicals we use today. While forecasts seem to change every day and political parties can selectively use bits of the overwhelming amount of conflicting data to suit their own agenda, no one will argue that these changes must occur in the twenty-first century – "one hundred years of petroleum" is beginning to look about right.

The use of sustainable, plant-based chemicals for future manufacturing can involve several approaches (Fig. 1.1-9)' [3, 7 14].

Many of the earlier plans in this area were based on the bulk conversion of large quantities of biomass into the type of starting materials that the chemical industry has grown up on (CO, H_2, C_2H_4, C_6H_6, etc.). On one hand the logic behind this approach is clear – the manufacturing industries are equipped to work with such simple small molecules. On the other hand, it is perverse to consume resources and generate waste in removing functionality from albeit a soup of molecules, just so that we can then apply our chemical technology toolkit to consume more resources and generate more waste in converting the intermediate simpler molecules into ones we can use in the many industries that use chemicals. The scale of operation,

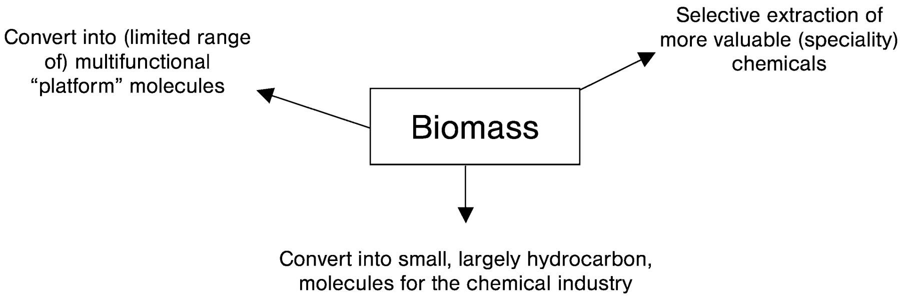


Fig. 1.1-9 Approaches to the use of plant-based chemicals.

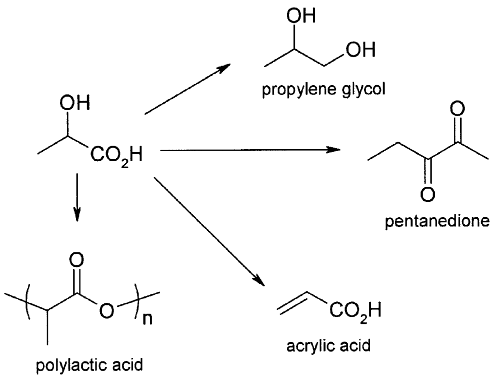
and the added costs of the extra steps, will always make this technology expensive and of limited appeal except in those situations where a large volume of waste biomass is in close proximity to suitable industrial plant.

Nature manufacturers an enormous array of chemicals to perform the many functions that its creatures need to survive, grow, and propagate. A tree contains some 30 000 different molecules ranging from simple hydrocarbons to polyfunctional organics and high molecular weight polymers. Many of these molecules have immediate and sometimes very high value, for example as pharmaceutical intermediates. The selective extraction of compounds from such complex mixtures is, however, often impractical and uneconomic and may lead to a very high environmental impact product as a result of enormous inputs of energy and outputs of waste. The extraction of families of compounds with high value themselves or through Green Chemistry modification is a more likely approach to take advantage of some of nature's gifts of sustainable and interesting molecular entities.

The third approach of using a large proportion of biomass to produce so-called "platform molecules" is worth close consideration. Here, we need to learn how to make best use of a number of medium-sized, usually multifunctional, organic molecules that can be obtained relatively easily by controlled enzymatic fermentation or chemical hydrolysis. The simplest of these is (bio) ethanol; others include levulinic acid, vanillin, and lactic acid. These are chemically interesting molecules in the sense that they can be used themselves or can quite easily be converted into other useful molecules – building on rather than removing functionality – as can be seen, for example, with lactic acid (Scheme 1.1-6).

One of these products, polylactic acid, has become the basis of one of the best recent commercial illustrations of the potential value of this approach. Cargill-Dow now manufacture polylactic acid polymer materials using a starch feedstock. The materials are finding widespread use as versatile, sustainable, and (importantly) biodegradable alternatives to petro-plastics. [14, 26].

Making more direct use of the chemicals in biomass and the functionality they contain, rather than reducing them to simpler, smaller starting materials for synthesis, makes sense from a lifecycle point of view as well as economically (Fig. 1.1-10).



Scheme 1.1-6

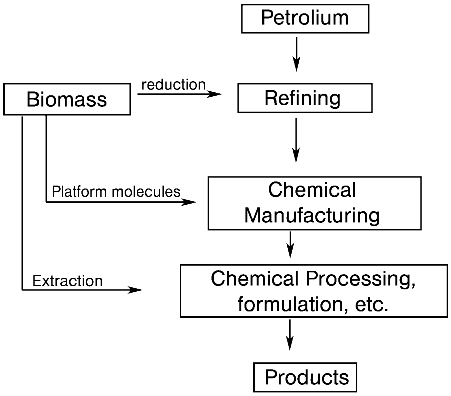


Fig. 1.1-10 The use of biomass chemicals in traditional chemical industry processes.

1.1.5
Green Chemistry Metrics

In its short history, Green Chemistry has been heavily focused on developing new, cleaner, chemical processes using the technologies described earlier in this chapter. Increasing legislation will force an increasing emphasis on products but it is important that these in turn are manufactured by green chemical methods. Industry is becoming more aware of these issues and some companies can see the business edge and competitive advantage that Green Chemistry can bring. However, the rate of uptake of Green Chemistry into commercial application remains very small. While the reasons for this are understandably complex, and also dependent on the economic vitality of the industry, it is important that the advantages offered by Green Chemistry can be quantified. Legislation or supply-chain pressures may persuade a company that the use of a chlorinated organic solvent is undesirable, but how can they select a genuinely "greener" alternative? How can a company add environmental data to simple cost and production factors when comparing routes to a particular compound? Can the environmental advantages of using a renewable feedstock compared to a petro-chemical be quantified? In order to make Green Chemistry happen, we need to see the concept mature from an almost philosophical belief that it is the "right thing to do" to one that can give hard, reliable data to prove its merits.

These needs and "reality checks" have led to the emergence of Green Chemistry-related metrics, although they are very new and by no means widely applied or tested. The ultimate metric can be considered to be lifecycle assessment (LCA), but full LCA studies for any particular chemical product are difficult and time consuming.[13, 14]. Nonetheless we should always "think LCA", if only qualitatively, whenever we are comparing routes or considering a significant change in any product supply chain. Green Chemistry metrics [16, 25] are most widely considered in comparing chemical process routes, including limited, if easy-to-understand, metrics such as atom efficiency and attempts to measure overall process efficiency such as *E* factors, mass intensities, and mass efficiency [27]. As with LCA, these metrics have to be applied with definite system boundaries, and it is interesting to note that for process metrics these boundaries generally do not include feedstock sources or product fate. Energy costs and water consumption are also normally not included, although given the increasing concerns over both of these it is difficult to believe that they can be ignored for much longer. At the product end of the lifecycle we are used to testing for human toxicity and this will become much more prevalent through REACH [6]. We will also need to pay more attention to environmental impact, and here measures of biodegradability, environmental persistence, ozone depletion, and global-warming potential are all important metrics. Last, but not least, we are moving towards applying Green Chemistry metrics to feedstock issues. As we seek "sustainable solutions" to our healthcare, housing, food, clothes, and lifestyle needs, so we must be sensitive to the long-term availability of the inputs that go into the supply chain for a product [14]. With increasing pressures from the feedstock and product ends, and increasing restrictions and controls on the intermediate processing steps, chemistry must get greener!

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1.2 Sustainable Development and Regulation

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1.2.1 Introduction

Sustainable development has become the accepted orthodoxy for global economic development and environmental protection since the end of the twentieth century.

Sustainable development means many things to many people and the range of actions and their implications is as varied. This work uses the most often quoted and accepted definition from the report *Our Common Future* [1] (also know as the Brundtland Report): "Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

This definition leads to the consideration of three major aspects of sustainable development: environment, economy, and community. The UK's headline indicators (see Appendix to this chapter) adopted as part of the country's Sustainable Development Strategy in 1999 [2] give a good indication of the breadth of the scope of sustainable development.

This sets global society a number of challenges as to how to balance the competing needs of feeding, clothing, and housing a growing global population, whilst managing limited resources efficiently and generating sufficient wealth to meet the reasonable economic aspirations of the societies at large. This must all be done without damaging the earth's eco-system. There is overall consensus on the objectives, with passionate debate [3] about the actual steps that are needed to achieve them.

The achievement of sustainable development will require action by the international community, national governments, commercial and non-commercial organisations, plus individual action by citizens. The international community has passed a number of milestones in moving forward the sustainable development agenda. The most notable are:

1987: The World Commission on Environment and Development (The Brundtland Commission chaired by Gro Harlem Brundtland) produced the report *Our*

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Common Future. That report produced and popularized the current sustainable development definition that is quoted above.

1992: The Earth Summit, also known as the UN Conference on Environment and Development (UNCED), was held in Rio de Janeiro to reconcile worldwide economic development with protecting the environment. The Summit brought together 117 heads of states and representatives of 178 nations, who agreed to work towards the sustainable development of the planet.

2002: A further meeting, The World Summit on Sustainable Development, was held in Johannesburg (South Africa) to review progress in the ten years since UNCED.

These meetings produced statements of intent from the world's political leaders and other stakeholders. The basic questions still remain:

– How to create wealth without permanently damaging the environment?
– How to enable a fair distribution of wealth, with equality of access to health and education?

The outcome of each society's response to these questions is its laws, regulations and other government interventions.

This chapter examines whether regulation is aiding or hindering the goal of sustainable development in relation to its environmental aspects. It focuses primarily on the European Union (EU), whilst also drawing on examples from the other areas of the world.

1.2.1.1 Sustainable Development and the European Union

The prime function of the EU was to create a common market for goods and services. This role has grown as the necessary rules to enable a common market to operate have developed. The EU has well-developed economic, social, and environmental policies, which require that environmental protection must be integrated into other EU policies. This is with the overt objective of promoting sustainable development. The economics and corresponding policies of the EU are described elsewhere [4].

The inclusion of environmental protection is particularly relevant when considering a common market or identifying potential conflict between environmental protection and economic growth. In fact one of the objectives of the EU's Sixth Environmental Action Programme is the decoupling of economic growth from resource usage.

1.2.1.2 Why Regulation is Required to Achieve Sustainable Development

In order to appreciate the need for regulations in relation to achieving sustainable development, it is necessary to explore briefly the link between the environment and some of the basic features of the operation of a market economy. This section highlights the main features that underpin the need for regulation, and explores some of the instruments that governments use to achieve the goals of sustainable development. Other authors discuss this topic more fully [5]. Later sections comment on how different approaches can aid or hinder sustainable development.

The underlying principle behind the operation of a market economy is that the market provides all the incentives to the participants to operate as efficiently and effectively as possible. However, this is not always the case; a market can be "imperfect" and this is particularly so for the environment. Externalities (where the full costs of an operation are not included in the price of the goods or services) are often viewed as the most widespread cause of market failures in relation to the environment. In such situations market prices often do not reflect the full cost of the environmental resources. Such externalities can be either negative or positive.

A typical example of a negative externality is the situation where the discharge of industrial wastewater from a manufacturing operation into a watercourse results in a downstream user incurring extra costs for a situation that is beyond his control. Unless there is government intervention, the upstream manufacturer does not have to pay the full costs of his operation.

This is the basis of the "polluter pays principle", which was incorporated into the Maastricht Treaty and states that those who are responsible for environmental pollution, resource depletion, and social cost should pay the full cost of their activities. If these costs are ultimately passed on to the consumer, then there is an incentive to reduce the levels of environmental damage and resource depletion.

It thus becomes essential to internalize the full environmental cost into the price of goods and services in order to achieve sustainable development. Government intervention, in the form of regulations, and a variety of economic instruments aim to enable this process by ensuring that the social costs and benefits are included in the prices that are charged.

The environment also has many of the features of a "common" or "public good" in economic terms. Overall, society would be better off with clean air and water and abundant natural resources, but in a market economy this does not occur without some form of intervention. In most situations in a market economy, people who have not paid for goods do not receive them; it is not possible to exclude people from the benefits of clean air because they have not paid for it.

Governments may also intervene by supplying information on the better use of environmental resources in situations where producers lack the knowledge to make the best business decisions in relation to the environment. The UK government's "Envirowise" scheme is a typical example.

1.2.1.3
Environmental Policy and Innovation

One of the most serious implications of the fact that goods and services frequently do not bear the full environmental costs of their production is the effect on innovation in environmental technologies that could contribute to sustainable development. There is less incentive for firms to undertake research and development into technologies, process improvements, or systems that could contribute to sustainable development if the rate of return on the investment does not reflect fully the costs involved i.e. the costs are still externalized. This can result in a vicious circle of under-investment that market forces alone cannot resolve. A related argument is that dischargers will do the minimum to meet the enforced standards rather than look further to see what else could be done to reduce their environmental impact.

Conversely, there are also situations where tight environmental regulation has forced the development of new technology to enable the standards to be met; for instance fuel additives and water-treatment processes.

There is also a view that regulation stifles innovation in general. However the authors of a report [6] to the UK Royal Commission on Environmental Pollution recently explored the claim that EU legislation put the European chemical industry at a disadvantage compared with the US and Japanese industries. The report concluded that in most cases regulation plays a "modulating role" and can both inhibit and stimulate innovation. It is thus the *rate* of innovation rather than the *quantity* of innovation that appears to be affected.

As well as the investment in the innovation activity itself, there is also the issue that even when new environmental technologies are launched, their uptake is slow [7]. The European Commission feels that economic barriers are a particular problem unless true environmental costs are taken into account. They also cite poor access to finance, long investment cycles, and poor dissemination of new technologies as issues. The Commission has now adopted an action plan [8] to overcome the perceived barriers, including utilizing financial instruments to share the risks of investing in environmental technologies.

1.2.2
Environmental Policy Instruments

This section briefly examines the range of policy instruments that might be used to achieve a particular objective or counterbalance a perceived market failure.

1.2.2.1
"Command and Control" Regulation

Environmental policy instruments in the Organization for Economic Co-operation and Development (OECD) countries have, historically, been typified by "command and control" regulation, such as the European Union's Integrated Pollution Prevention and Control Directive (IPPC) regulations. Under such regulations, potential polluters are "commanded" to comply with particular standards and then "controlled" by tight monitoring and enforcement activity. Such approaches have been successful in reducing air and water pollution: for instance in greenhouse gas and sulfur dioxide emissions and in the improvement in the level of treatment and the proportion of the population connected to wastewater treatment plants [9]. However, concerns have been raised about their effectiveness in other areas.

As well as the concerns discussed above in relation to the effect on innovative activity, the OECD [10] comments that such regulations are costly to implement and enforce. Typically, they also do not take into account the broader environmental impacts that result from general patterns of production and consumption and how these change.

They are also relatively ineffective in controlling diffuse sources of pollution (such as the effect of agricultural fertilizers on surface water quality and consequently drinking water quality). Some regulations are perceived to work well and in a cost-effective manner. The Montreal Protocol, aimed at phasing out all the main ozone-depleting chemicals, has achieved nearly a 90% reduction in the production of ozone-depleting substances in Western Europe and also reductions in their production and use in Central and Eastern Europe. These achievements are reflected in a gradual fall in the concentration of chlorine-containing ozone-depleting substances in the troposphere [9].

IPPC addresses the effects of pollution once a manufacturing process has been carried out. However, sustainable development also needs to address the control of substances in the overall supply chain. These are both the substances that are used as raw materials for the manufacture of other substances and the resulting products themselves. Controlling the input and use of chemicals in the environment is a central theme of a holistic view of sustainable development and has key implications for the social aspects of sustainable development.

The EU is, at the time of writing, reviewing its regulatory control of chemicals with its REACH (Registration, Evaluation, Authorization and Restriction of Chemical) proposals [11]. Although the current EU system is often seen as fragmented and cumbersome, even the amended proposals published in October 2003 have prompted vigorous debate. Arguments on the one hand center again on the perception that the proposals will have a negative impact on innovation, will be costly to implement, and damage the competitiveness of the European chemical industry. Environmental organizations, however, counter that REACH will result in significant environmental and health benefits and encourage innovation. UK retailers [12] also welcome the REACH proposals, despite the imperfections in the regulations, because they see that they could provide a single robust system that both suppliers and customers can use and that will share the burden of the costs involved.

1.2.2.2 Government Subsidies

Government intervention in the form of subsidies to particular industries and the impact of such subsidies on sustainable development is contentious. The OECD [10] highlights subsidy policies such as those to agriculture, fisheries, and peat and coal production as having a particularly harmful environmental impact. Similarly, if subsidies are used instead of taxes to try to reduce a particular pollution, then these can distort the polluting industry by attracting an inefficient high level of new entrants.

However, in some situations the source of pollution is so diffuse and comes from such a wide variety of sources that the "polluter pays" principle is not practical and therefore society at large has to pay. On a related aspect, although subsidies are not allowed for pollution abatement technologies in general in the EU, there are exceptions. A positive use of subsidies permits assistance to encourage Small and Medium Size Enterprises (SMEs) in particular to go beyond mandatory standards, use renewable energy and/or install energy-saving equipment.

1.2.2.3
Alternative Approaches

As well as regulations, governments are now using and developing more innovative and effective means of intervention to achieve environmental policy requirements. Economic instruments such as taxes and trading schemes are designed to change behavior by giving industrialists a financial incentive to operate differently and more flexibility in how they achieve the required environmental objectives. Table 1.2-1 summarizes some examples of the tools available to governments and their relationship to the market failures discussed above.

Taxes and trading schemes These are designed to internalize environmental costs and send the message that if sustainable development is to be achieved then the polluter and ultimately the user of the products and services concerned must pay the full cost of the goods or services. These include those associated with the previously hidden environmental costs. It would be unreasonable to implement the full environmental costs through such systems immediately, principally because of

Table 1.2-1 Examples of policies to address market failures.

Market failure	Tax	Trading schemes	Tax credits/ Public spending	Voluntary agreements	Regulation
Negative Externalities	Climate-change levy Landfill tax Fuel duty	Emissions trading scheme Landfill permits	Reduced rate of VAT on grant-funded installation of central heating and heating appliances	Pesticides EU CO_2 from cars agreement	Integrated pollution prevention and control Water quality legislation
Positive Externalities or Public Good			Tax relief for cleaning up contaminated land		Habitats and species protection legislation
Information Failures	Differential rates of fuel duty				Environmental impact assessment directive

costs sunk into existing capital equipment. Hence the timescale for adjustment is likely to be lengthy. The phasing in of the Climate Change levy and Landfill Tax in the UK are examples of this approach.

Although environmental taxes and trading schemes are similar in many respects, there are some key differences:

- Taxes fix the value assigned to pollution, but do not specify the amount.
- Trading schemes operate the other way round by fixing the amount that can be discharged, but enable the market to put a value on the pollution load.

Both approaches should allow the market to find the cheapest way of meeting the environmental objectives. The EU will be ready to implement trading schemes in 2005.

The perception of environmental taxes and trading schemes amongst industrialists is often that they are simply more measures imposed by governments to raise revenue rather than to achieve particular environmental policy objectives or replace inefficient regulations with more effective alternatives. They thus need to be accompanied by appropriate targeted information to ensure industrialists understand the reasons behind the schemes.

The OECD [10] feel that there is little evidence that such taxes reduce international competitiveness, although they qualify their view with the comment that the sectors most exposed to competition often receive exemptions and reductions.

Tax credits and public spending Schemes utilizing tax credits typically offer tax incentives to industrialists to invest in sustainable and resource-efficient technologies. Public spending is often used to encourage directly specific environmental innovation and to promote relevant research and development. Another facet of this is the deliberate utilization of green procurement policies by local and national governments to drive the market towards sustainable development.

Voluntary agreements These are agreements between industry and public authorities to meet environmental objectives. They often contain an element of coercion in the form of a threat of tax or regulation, and the OECD [10] regards voluntary agreements as ineffective on their own and recommends reassessing such practices. The UK government has a voluntary agreement with the pesticides sector to reduce the impact of pesticides on the environment, and feels that good progress is being made against the targets. However, the UK government has continued to investigate the use of economic instruments that could be used if the voluntary agreement fails or takes too long.

Another aspect of voluntary agreements is the voluntary action undertaken by individuals, typically in the recycling of household waste. Voluntary actions by individuals are also more successful in solving significant environmental problems when they are backed up by a cost implication. The recent introduction of a pilot program in the Republic of Ireland that involves householders paying for the disposal of household waste by weight has seen a 50% reduction in the weight of household refuse to be disposed of.

There is thus a balance to be achieved between intervention and non-intervention and the type of intervention to be used. There is no single solution and the optimum approach aims to mix and balance the tools available to match the economies and circumstances of the country in question.

This section has set the scene principally in the European arena on the relationship between the desire for sustainable development and the broad regulatory means by which governments pursue their objectives for sustainable development in a market economy. It has also highlighted the strengths and weaknesses of different tools and how these can help or hinder sustainable development. The next section examines what these authors judge to be the likely challenges and trends in the future for the environmental aspects of sustainable development and regulation.

1.2.3 Future Trends and Challenges

This section summarizes some key areas in the future relationship between sustainable development and regulation and their implications for producers, researchers, and society as a whole.

There will be a continuing balance between the needs of the environment and the social and economic needs of society.

Although the OECD [10] stated that environmental performance in OECD countries had improved in several respects since 1990, it argued that this improvement had come at the expense of the economic aspects of sustainable development. The OECD also argued that the cost of achieving these improvements could have been less (or the scale of improvements greater) if more cost-effective means of government intervention had been used. Industrialists will increasingly be expected to offer cost-effective proactive solutions to the environmental consequences of their operations rather than simply minimizing the negative effects. Balanced against this is the view that it is neither possible nor economically desirable to achieve zero environmental impact.

Government intervention is likely to make use increasingly of a variety of economic instruments as well as "command and control" regulations.

The latter will probably principally be confined to controlling localized point sources of pollution where it is important that emissions are kept below particular levels. "Command and control" regulations, by relying on fixed emission standards, do not take account of the fact that the costs of reducing pollution are different for different firms. They are thus inefficient in achieving the overall aim of reducing pollution whilst retaining economic and social development. Similarly, governments will need to resolve conflicts in some areas of environmental policy, typically for subsidies, and review other less-effective policy instruments such as voluntary agreements.

There are price implications for both producers and consumers as environmental costs continue to be included in the price of goods and services.

As government economic instruments and regulations force producers throughout the supply chain to consider the environmental costs of their operations, producers have to contend with several challenges. How do they cost these aspects into goods and services using a traditional accounting system that is not designed to cope with such costs? This basic problem is frequently the reason why projects with an environmental benefit do not get taken up. Producers also have to contend with the sunk costs of existing capital equipment, which means that investing in new equipment needs to take place at the appropriate point in the investment cycle.

There is then the challenging issue of how much of these costs can be passed on as a price rise in the supply chain, ultimately to the domestic consumer. The domestic consumer may not appreciate the environmental implications or accept the price rise as their contribution in overall responsibility for improving the environment. The implications here are for education throughout the supply chain.

Ultimately price elasticity comes into play. The fall in revenue of around 8% since 1999 (OECD [10]) from environmental taxes is an interesting illustration of how environmental taxes can result in a change in consumer behavior. The OECD attribute about a third of this decrease to a decrease in the sale of petrol because of higher prices.

The general public and NGOs tend to distrust the chemical industry and the use of chemicals and this is likely to increase unless there is action by industries that use chemical themselves.

In many parts of the world, the public perceive the chemical industry as polluting and are concerned about the impact of chemical products on health, safety, and the environment [7]. This poor perception has become more significant since the mid-1980s. This is despite the fact that measurable improvements have been achieved in the reduction of emissions. There is thus a link between the public's attitude and their behavior as consumers. A further contributor here is the increase in freedom of environmental information: for instance easier access to public registers of pollutants.

There is a complex set of issues here in relation to sustainable development. Stakeholder pressure could force the removal of some substances or products such that the outcome is perceived overall as a positive contribution towards sustainable development. Conversely, stakeholder behavior could force the continued use of substances or practices that are not sustainable in the long term.

Similarly, pressures from retailers reacting to consumers could have an impact on REACH and its implementation. This was summed up [12] by one retailer who, although recognizing the economic success of the chemical industry, felt "it has mismanaged the whole concept of trust in the last twenty years".

There is a continuing need for the development of green metrics that demonstrate to all where progress is being made and where further action is required.

Table 1.2-2 (in the Appendix to this chapter) describes the headline indicators that the UK government uses to measure the country's progress towards sustainable development. Whatever the merits or otherwise of these chosen indicators, they start to track and highlight the complexities of sustainable development. Although the European Environment Agency measures numerous parameters to track environmental performance, the European Commission is still developing a set of metrics comparable to those used by the UK to track sustainable development. Measures that are developed need to be based on outcomes, i.e. environmental quality objectives. In the short and medium term, it may be necessary to control specifically some inputs: for example emissions of greenhouse gases.

Operators of industrial concerns in the European Union will shortly find themselves specifically liable under the "polluter pays principle" when the European Environmental Liability Directive is implemented.

The EU Environmental Liability Directive [13] came into force in 2004 and member states have three years to implement it into national law. This Directive holds operators whose activities have caused environmental damage financially liable for remedying the damage. It also has a preventative benefit as well in that operators whose activities are deemed to have caused an imminent threat of environmental damage are also liable to take preventative action.

Although existing policy instruments and some national civil liability laws already cover some aspects of this Directive, this is the first comprehensive approach and one that in particular will cover damage to biodiversity that has not previously had protection. It is wide ranging in its implications and is likely to result in greater involvement by citizens and NGOs, who will now be able to require the competent authorities to act.

Again, the underlying principle behind this Directive is to move the financial expenditure associated with environmental protection and sustainable development to the operator responsible rather than the costs being met by society in general. In terms of a market economy, the costs have been internalized.

European Union industrialists will come under increasing pressure to consider the environmental lifecycle of their products "from cradle to grave".

The EU is committed to introducing an Integrated Product Policy (IPP [14]) which aims to promote sustainable development by reducing the negative environmental impacts of products throughout their lifecycle "from cradle to grave".

Whereas until now much of the effort related to environmental policies has concentrated on large point sources of pollution either at the start of the product's life (manufacturing) or its end (waste disposal), IPP aims to integrate policies across the whole lifecycle. It is market orientated and aims to use incentives to move the market towards more sustainable options.

One of the first areas that the EU is working on is the provision of lifecycle information and a handbook (due 2005) on best practice in lifecycle analysis (LCA) along with a gradual expansion of environmental labeling. At the moment there is no commitment to create regulations for IPP. However, regulation is likely to remain a potential tool, in addition to the range of economic instruments discussed above along with various guidelines.

The timescale for the implementation of IPP is long and the impact of the current proposals reduced from the original intentions. However, the successes achieved in dealing with major point sources of pollution have enabled the scope of environmental policy to be broadened to cover the whole lifecycle of a product. This introduces new challenges and opportunities to achieve sustainable development.

Producers will see more end-of-life Directives such as The Waste Electrical and Electronic Equipment Directive (2002/96/EC) plus the End of Life Vehicles Directive (2000/53/EC). There will be mounting pressure for LCAs to be carried out on all new products and substances. Not only will the manufacturing process have to be green but also the use and disposal of the product or substance will have to be benign. As a result of this, the growing science of green product design is likely to spread from overtly consumer goods to all aspects of the supply chain.

Table 1.2-2 UK headline indicators for sustainable development.

Indicator	Description
Economic output	GDP per head (UK) measured against an index based on 1970 figures
Investment	Total (measured against an index based on 1970 figures) and social (railways, hospitals schools, etc.) investment (UK)
Employment	Percentage of people of working age in work measured against an index based on 1970 figures (UK)
Poverty and social exclusion	Selected indicators of poverty and social exclusion
Education	NVQ Level 2 qualifications measured as percentage of population at age 19 (UK)
Health	Life expectancy (years) and expectancy of good or fairly good health (GB)
Housing conditions	Percentage of households in non-decent housing both social and private sector (England)
Crime – robbery, vehicle and burglary	Number of recorded crimes (England and Wales)
Climate change	Emission of greenhouse gases measured in million tonnes C both as a basket of six gases and carbon dioxide (UK)
Air quality	Days when pollution is moderate or higher (UK), measured for both rural and urban sites
Road traffic – total traffic volumes	– Measured in billion vehicle kilometers
Traffic per unit of GDP	– Vehicle kilometers per unit of GDP
River-water quality	Rivers of good or fair chemical quality
Wildlife – farmland birds – woodland birds	Population of wild birds (UK) measured against an index based on 1970 figures
Land use	Percentage of homes built on previously developed land (England)
Waste – Household waste – All arisings and management	Measured in kg per person

1.2.4
The Implications for Green Separation Processes

The European Commission takes a broad view of what constitutes “environmental technologies”. It includes integrated technologies that prevent pollutants being generated in the production process as well as new materials, energy- and resource-efficient processes, environmental know-how, and new ways of working. The preceding sections in this chapter have identified that environmental policy instruments in OECD countries and Europe are moving in the future towards a greater use of economic instruments and less reliance on “command and control” regulation that specify the use of a particular technique. Thus green separation processes that enable a greater degree of environmental control to take place as part of the manufacturing process are likely to be more attractive.

As producers start to realize the financial implications of green taxes such as those aimed at reducing the amount of waste that goes to landfill, separation processes that enable producers to reduce, recycle, or not produce the waste in the first place, become more viable.

Separation processes that enable valuable materials to be recovered from waste streams, especially as fossil fuels and primary ores are exhausted, are also likely to be in increasing demand. A similar logic applies to technologies that maximize yields and recoveries of target materials for minimum input of fossil fuels and other utilities or can lead to the use of renewable or alternative feedstocks.

In the short and medium term, industry will still require end-of-pipe processes, but IPPC and IPP will encourage the use of in-pipe, in-process technologies and techniques along with appropriate management systems.

1.2.5
Conclusion

The way that regulation contributes to sustainable development is changing significantly. Europe and the OECD countries are moving towards a regulatory system that combines the historic “command and control” with a system that makes greater use of economic instruments. The debate is more about what economic instruments will be used for what pollution load and how quickly rather than whether it happens.

These regulatory strategies have the potential to help sustainable development by encouraging industrialists to take proactive steps to prevent pollution before it happens rather than by policing the pollution that has already occurred. This is likely to be balanced with a greater use of consumer-based environmental taxes to encourage individual citizens to appreciate the real costs of sustainable development.

Whether or not one signs up to sustainable development as a politically desirable policy, there is a belief among the G7 countries that the global demand for oil will increase by 50% between 2004 and 2025. Those same commentators believe that the perceived gap between oil supplies and demand will be met by technology, some of which has not yet been invented!

These technologies might fall within the definition of "Green Chemical Technologies". They may use alternative feedstocks to synthesize existing desirable molecules, make more efficient use of fossil-fuel (oil) derived materials, and/or, finally, create substances which give the same effect (utility) than those used currently but with less environmental or public health impact.

Whatever the consequences of regulation, stakeholder pressure driven by rising oil prices, will create a greater demand for green product design. Manufacturers will seek greater resource efficiency, reuse/recyclability and alternative feedstocks. This is likely to happen long before any regulation on IPP is enshrined in legislation.

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