

# The Role of Biopesticides as a Challenge and Opportunities in the Field of Agriculture: A Review and Study of Green Chemistry

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## Abstract

Green chemistry and sustainable agriculture are inherently intertwined; farmers need green chemists to make safe agricultural chemical inputs. Green chemists need farmers practicing sustainable agriculture to provide truly "green" bio-based raw materials to process into new products. Green Chemistry connects with sustainable agriculture as a consumer of agricultural products, as a source for remediation technologies, and as a producer of inputs. In very general terms, according to the US EPA, biopesticides are pesticides derived from natural materials such as animals, plants, bacteria, and minerals. The two key categories focused on in this report include biochemical and microbial pesticides (reviewing the third category of biopesticides, transgenic crops, was outside the scope of this report). The subcategories of biochemical pesticides introduced in this report include insect pheromones, plant extracts and oils, plant growth regulators and insect growth regulators. Microbial pesticide subcategories discussed include bacteria, virus, fungus, and other less common microorganisms. Biopesticide solutions often require the grower to learn new application techniques and new ways of thinking about pest management. As noted, biopesticides are often highly specific and have very precise modes of action. This specificity can mean that workers can enter fields quickly after use, thus cutting wait times and offering more flexibility to the user. Specificity also means, however, that growers may need to purchase several different kinds of product to meet their pest management needs; this is a potential cost concern for growers. Biopesticides also require new skills and understanding of pests, their life cycles and how to use biopesticides to intercede effectively. This is both a challenge but also an opportunity for expanding a new category of skilled labor in the farm sector.

## 1. Introduction

The green chemistry revolution is providing an enormous number of challenges to those who practice chemistry in industry, education and research. With these challenges however, there are an equal number of opportunities to discover and apply new chemistry, to improve the economics of chemical manufacturing and to enhance the much-tarnished image of chemistry. In this article which is based on his Inaugural Lecture at the University of York in 1998, Professor Clark reviews some of the challenges, considers some of the new and successful "greener" chemistry in practice and uses two areas of chemistry to examine the scale and diversity of current problems and the exciting opportunities for innovative chemistry research and application. Pesticides may disturb the normal plant growth and development. Pesticides are not destroyed by the soil microbes and accumulate near the plant roots making the supply of Nitrogen, Phosphorous, and Potassium ineffective. This results in the growth restriction of the crops and diminishes the soil fertility. Pesticides decrease plant resistance against other harmful microbes. Pesticides permeate into the soil with rains and mix with ground waters contaminating them. Pesticides may drain into the streams, rivers, and lakes polluting the water sources and killing living organisms in water reservoirs.

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Abuse of pesticides contributes the development of pesticide resistance. The pests that are resistant to pesticides are able to survive. Resistance has a genetic basis and pests can pass modified genes of resistance to the progeny. Thus, the pest populations become more resistant to the applied pesticides. Pesticides often kill the beneficial organisms as well. Useful pollinators such as bees and valuable predators such as ladybirds may become innocent victims of pesticide application. Pesticides are also toxic for wild animals and plants or for pets. Pesticides can possibly destroy beneficial organisms and thus damage fields, gardens, orchards, and the environment. Pesticides may cause a range of acute and chronic detrimental health effects. Spraying of pesticides produces suspensions of toxic compounds in the air. These suspensions may cause respiratory affections in workers who inhale these pesticides. The harmful effects of pesticides may begin with the irritation of the skin and end with severe affection of the nervous system, hormonal breakdown, loss of fertility, and cancers. Agricultural workers may become victims of severe pesticide poisoning. Numerous cases of birth defects, fetal death, neurologic and developmental disorders are also associated with the use of pesticides.

## 2. The challenges for green chemistry to scientists

Sustainable development is now accepted by governments, industry and the public as a necessary goal for

achieving societal, economic and environmental objectives. Within this, chemistry has a key role to play in maintaining and improving our quality of life, the competitiveness of the chemical industry and the natural environment. This role for chemistry is not generally recognized by government or the public. In fact chemicals, chemistry and chemists are actually seen by many as causes of the problems. The European Chemical Industry Council (CEFIC) survey in 1994 showed that 60% of the general public had an unfavorable view of the chemical industry and in the USA, a survey carried out for the Chemical Manufacturers Association (CMA) in 1993 showed that only 26% were favorably disposed towards the industry. The pharmaceutical and plastics sectors scored better than the chemical industry as a whole, possibly because the general public are more aware of their products and their benefits. The chemical industry is consistently regarded less favorably than the petroleum, gas, electricity, lumber and paper industries. The main reasons given for unfavorable opinions of the chemical industry are concerns over adverse environmental impact, transport, safety and waste. Less than one third of those interviewed believed that the chemical industry is concerned about protecting the environment and less than one half believed that the chemical industry is working hard to develop techniques to solve environmental problems. The negative public opinions of the chemical industry can in some ways be contrasted with the tremendous economic success of the industry. It is one of the most successful and diverse sectors of manufacturing industry in many regions of the world. The range of chemical products is enormous and these products make an invaluable contribution to the quality of our lives with manufacturing plants having capacities ranging from a few tonnes per year in the fine chemicals area to 500,000 tonnes per year in the petrochemicals area. However, these manufacturing processes also lead to millions of tonnes of waste, and the reduction or elimination of this waste is now a central issue for the industry, the authorities, and the general public. There is a danger that if the economic success of the industry is not matched by a clearly perceived improvement in environmental performance then, at best, the industry will be regarded by the general public as a necessary evil.

The challenge for chemists and others is to develop new products, processes and services that achieve the societal, economic and environmental benefits that are now required. This requires a new approach which sets out to reduce the materials and energy intensity of chemical processes and products, minimize or eliminate the dispersion of harmful chemicals in the environment, maximize the use of renewable resources and extend the durability and recyclability of products—in a way which increases industrial competitiveness.

Some of the challenges for chemists include the discovery and development of new synthetic pathways using alternative feed stocks or more selective chemistry, identifying alternative reaction conditions and solvents for improved selectivity and energy minimization and designing less toxic and inherently safer chemicals. In chemical synthesis, the ideal will be a combination of a number of environmental, health and safety, and economic targets (Fig.1)

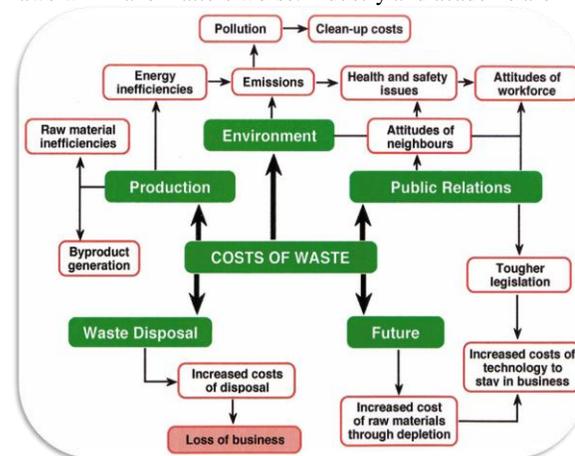
Although many chemists, and some large and smaller companies, are actively pursuing 'green chemistry' there are still many barriers to progress. These include a general lack of awareness and training in schools, universities and industry and a management perception that green chemistry is a cost without benefits. The drive towards clean technology in the chemical industry with an increasing emphasis on the reduction of waste at source will require a level of innovation and new technology that the chemical industry has not seen in many years. Mature chemical processes, which are often based on technology developed in the first half of the 20th century, may no longer be



Fig: 1

acceptable in these environmentally conscious days. 'Enviro-economics' will become the driving force for new products and processes. This can be seen by considering the ever-escalating and various 'costs of waste' (Fig. 2).

The costs of waste can truly be enormous. It has been estimated that compliance with existing environmental laws will cost new EU member states \$130 billion. In the US, \$115 billion was spent in 1992 on waste treatment and disposal. New European legislation and tighter national laws will make matters worse. Industry and academe are



now reacting to these challenges and many are seeing the opportunities—be they in winning research funding, unprecedented opportunities for translating new, greener chemistries from the research bench to the production plant or in gaining commercial advantage from the application of new low-waste processes or the marketing of new environmentally friendly products or technologies. The

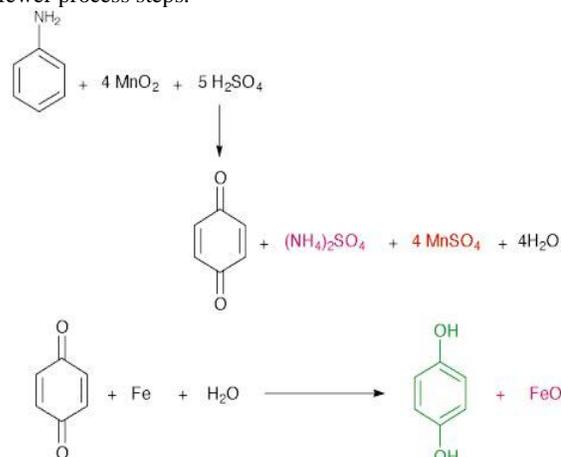
rapidly growing interest in green chemistry is partly witnessed by the growth in relevant conferences with regular events now being held in the USA, Europe and Asia. The Gordon Green Chemistry conferences (held alternately in the USA and Europe since 1995) along with other recent international meetings are good examples of effective meetings of industrial, academic and governmental chemists and engineers with a variety of backgrounds, interests and areas of expertise but with the common goal of seeing

The application of green chemistry throughout the chemical and allied industries. Additionally, the emergence of Green Chemistry organizations in the USA, Italy and the UK are indications of the growing interest in the concept and the recognition of the value of networking such diverse activities. It is particularly significant to note that many of these organizations place education as high on their agenda as research—the long term future of the subject and indeed of the industry will depend on future generations. In the US, a particularly important and strategic development was the emergence of the Presidential Green Chemistry Challenge awards. These have had numerous benefits, not least the open disclosure of many new and exciting products and processes that will be of real benefit to the environment and to the image of chemistry.

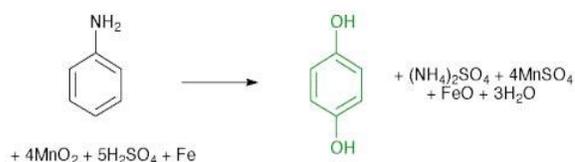
### 3. Green chemistry and public awareness

Through the US Presidential Green Chemistry Challenge awards, other promotional initiatives and a general increase in public awareness, an increasing number of headlines have drawn attention to scientific and commercial breakthroughs in reducing the environmental impact of chemical products and processes. These include: new marine antifouling to replace tributyltin oxide (Rohm and Haas); environmentally friendly high solid coating reduces VOCs (Bayer); new route to a steroidal intermediate involving catalytic oxidation with no heavy metal waste (Pharmacia and Upjohn); new micro emulsion based solvent for industrial cleaning (Dow); full plant trials for a new polymerization catalyst that gives a 90% reduction in waste (GE Plastics); new commercial hydrogenation process based on supercritical fluid technology promises to be greener and safer than existing processes (Thomas Swan); new environmentally friendly route to herbicide intermediate (Monsanto); envirocatalysts launched as environmentally friendly replacements for hazardous reagents and catalysts (Contract Chemicals). Some individual case studies can be used to illustrate the environmental advantages that are being achieved in some chemical processes. 1-Disodium aminodiacetate (DSIDA) is a key intermediate in the manufacture of Roundup TM, the environmentally friendly herbicide. The traditional manufacturing route to DSIDA was based on old Stricker chemistry and suffered from numerous serious environmental and health and safety problems: the use of the highly toxic hydrogen cyanide which requires special handling and gives rise to operator, environmental and local community risks; the exothermic generation of unstable intermediates requires special care to avoid runaway reactions; the process generates at least 1 kg of waste per 7 kg of product; the waste contains cyanide and formaldehyde and needs treatment prior to disposal.

The new DSIDA manufacturing process is cleaner and safer. It is based on the catalytic dehydrogenation of diethanolamine and involves: less toxic and less volatile starting materials; endothermic and inherently safer chemistry; a 'zero waste' route: after removal of the catalyst, no further purification is required before the intermediate is used in the next stage of the herbicide manufacture; a new active and reusable solid catalyst which has applications wider than in this process. Overall the new catalytic process gives higher product yields and involves fewer process steps.



Overall the chemistry involved can be represented as:

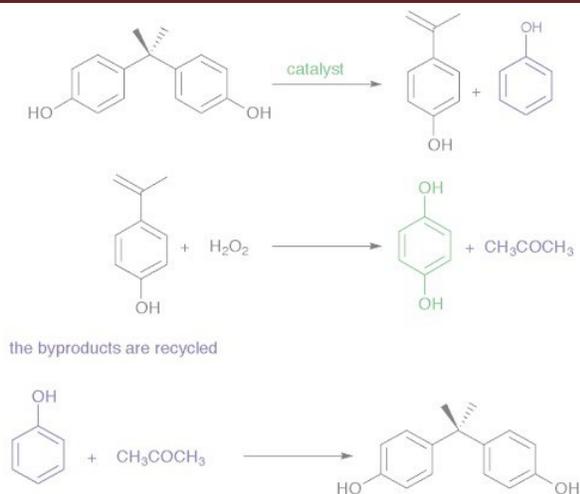


The classical route to hydroquinone, a very useful intermediate in the manufacture of polymeric materials, suffers from very poor atom utilization (*i.e.* a small fraction of the atoms consumed in the process end up in the final product) and leads to the production of enormous volumes of waste. The manufacturing method is shown in Fig. 3.

As can be seen, the production of one mole of hydroquinone leads to the production of mole equivalents of ammonium sulfate and iron (ii) oxide and more alarmingly 4 mole equivalents of manganese sulfate. This is an example of a process with a poor environmental acceptability factor (high waste to product ratio) 3 made worse by the hazardous nature of the waste. 4 The poor atom efficiency of the process is best illustrated by some simple atom economy calculations (Table 1).

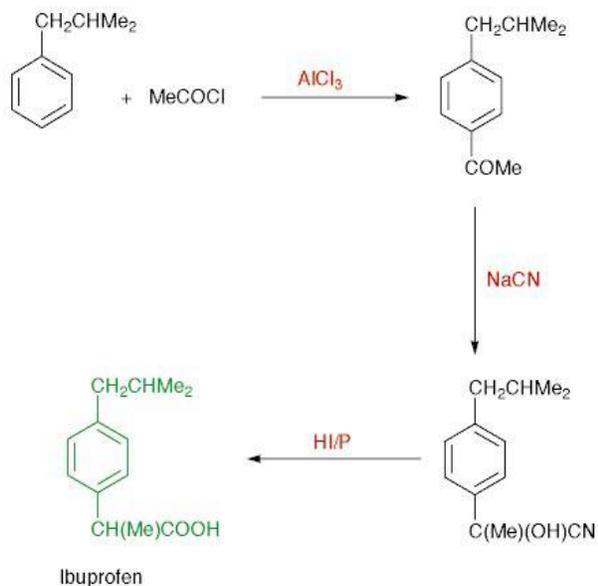
**Table: 1.** Atom Accounts for the Classical Route to Hydroquinone

Element	Fate	Atom Utilization
Carbon	Product(s)	Up to 100%
Hydrogen	Product and waste	Up to 33%
Oxygen	Product and waste	Up to 13%
Manganese	Waste	0%
Sulfur	Waste	0%
Iron	Waste	0%



**Fig. 4.** The new Upjohn route to hydroquinone

Overall only 3 kg of acetone waste are produced per 10 kg of hydroquinone product, and there are no significant amounts of salt waste. 4-Isobutylacetophenone is a key intermediate in the manufacture of the bulk active pharmaceutical ibuprofen.



**Fig. 5** The Traditional Manufacturing Route to 4-Isobutylacetophenone

The conventional method of preparation is based on a Friedel-Crafts acylation, which uses greater than stoichiometric quantities of  $\text{AlCl}_3$ . To produce 1000 tonnes of 4-isobutylacetophenone, 760 tonnes of  $\text{AlCl}_3$  are required and a corresponding amount of Aluminum waste in the form of aluminous water is generated when the product catalyst (Lewis base-Lewis acid) complex is broken down by quenching with a large volume of water. In addition, large amounts of acidic gaseous emissions have to be scrubbed from the off-gas stream. Later stages in the process involve cyanide and elemental phosphorus (which does not end up in the final product) making the whole

manufacturing process extremely hazardous and wasteful (Fig. 5).

Increasing pressure from generic competition (as the product came off patent) and to reduce the environmental impact led to Boots, in collaboration with Hoechst Celanese, developing a new cleaner process based on the use of HF as the Friedel-Crafts catalyst. Hydrogen fluoride is extremely corrosive and requires quite expensive plants for safe handling. The dangers resulting from any escape into the environment are also considerable. However, while the use of HF presents serious difficulties, unlike  $\text{AlCl}_3$  it can be separated and recycled and the process is run continuously with complete containment. The total removal of catalyst waste in this step is an important development in the pursuit and application of green chemistry. In the overall process 6 stoichiometric steps with <40% atom utilization have been replaced by 3 catalytic steps with ca. 80% atom utilization.

#### 4. Important Generic Areas of Chemistry

To help illustrate the many challenges ahead and the opportunities for new greener chemistry, two very broadly based generic areas of chemistry can be at least superficially examined in terms of their scope, the environmental unacceptability and poor atom economics of typical processes, and the goals and possible approaches of green chemistry. The emphasis will be on batch type processes involving liquid phase reactions as practiced by fine, specialty chemical and chemical intermediate manufacturers around the world.

#### 5. Acid Catalyzed Reactions

Acid catalysis is the most widely used type of catalysis with applications in all sectors of the chemical, pharmaceutical and allied industries, although the largest scale use is in the petrochemical industries where the processes are largely quite efficient and the use of solid acids is well established. Traditionally most liquid phase organic reactions have been catalysed by strong Brønsted acids such as  $\text{H}_2\text{SO}_4$  and HF and by soluble Lewis acids such as  $\text{AlCl}_3$  and  $\text{BF}_3$ .

These acids have many important advantages—they are cheap, readily available and very active. Unfortunately, they also suffer from some serious disadvantages, which are becoming increasingly prominent in these environmentally conscious days—they are difficult to separate from the organic products and their use leads to large volumes of hazardous waste. In the petrochemical industry, where acid catalysis is vital to many of the business areas, solid acids including zeolites have become established in the large-scale vapour phase processes. Continuous processes operating in contained plants can involve solid catalysts running for greater than a year before being removed and replaced. The efficiency of such processes is very high and the relative quantities of waste can be impressively low. Solid acids are only beginning to impact non-petrochemical process chemistry.

Friedel-Crafts acylations (including benzoylations and sulfonylations) are real and alarming examples of very widely used acid-catalysed reactions which are based on 100 year old chemistry and are extremely wasteful. The reaction of an acid chloride with an aromatic substrate requires a greater than stoichiometric quantity of aluminium

chloride as the 'catalyst' (>2 mole equivalents in sulfonylations). Every molecule of the ketone product forms a complex with one molecule of the catalyst, effectively removing it from the reaction. The organic product is released by using a water quench with the resulting emission of about 3 equivalents of HCl which need to be scrubbed from the off gases leading to the production of 3 equivalents of salt waste. Once the organic product has been recovered, aluminous water remains, which must be disposed of. The overall process generates considerably more waste than product

Many other industrial processes are catalysed by AlCl<sub>3</sub>. These include alkylations and the production of resins *via* cationic polymerisation. While these reactions do not require the use of stoichiometric quantities of the Lewis acid, none of the catalyst is recovered and all such processes show the same atom accounts (Table 2).

**Table: 2** Atom accounts in a typical AlCl<sub>3</sub>-Catalysed Friedel–Crafts Acylation

Element	Fate	Atom Utilisation
Carbon	Products and by-products	Up to 100%
Hydrogen	Products, by-products and waste (from quench)	<<100%
Aluminium	Aluminous water/ aluminium salts	0%
Chlorine	Waste water (from quench) and salt (from HCl scrubbing)	0%
Oxygen	Waste water	Down to 0%

The green chemistry goal for such reactions should be to remove all elements from the accounts other than those involved in the organic chemistry and, of course, to push the organic chemistry towards 100% selectivity to the desired product. A number of new, more environmentally friendly acids for liquid phase organic reactions, notably solid acids (which are generally easier and less energy and resource consuming to recover than soluble acids), have been discussed and are beginning to find their way into industrial usage. These include zeolites,<sup>7</sup> clays and other mixed metal oxides, inorganic–organic composite materials, functionalised polymers and supported reagents<sup>8,9</sup> as well as lanthanide triflates.<sup>10</sup> Other interesting 'green' solutions to the problem include the use of ionic liquids.

Bromination chemistry is a relatively small area of organic chemistry but one with many useful applications (including photographic chemicals, pharmaceutical and agrochemical intermediates) and an international specialty chemical industry based on it. The chemistry is largely based on the use of elemental bromine and the problems associated with the use of traditional acid catalysts are compounded by the low atom utilisation of the bromine. The most important bromination reactions include aromatic bromination, bromide hydroxylation and the  $\alpha$ -bromination of carboxylic acids.

Aromatic bromination reactions are typically catalysed by Lewis acids such as FeCl<sub>3</sub> and AlCl<sub>3</sub> which present the familiar environmental problems of separation difficulties usually leading to HCl emissions and the production of large volumes of aqueous and salt waste. In the case of the aliphatic brominations phosphorus and sulfur reagents are

commonly used. The  $\alpha$ -bromination of carboxylic acids is carried out using red phosphorus, in some cases in near stoichiometric quantities. The phosphorus ends up as a cake of phosphates and other phosphorus species containing bromine and organic contaminants. It can only be disposed of after treatment. Additionally, all of the above reactions usefully employ no more than 50% of the bromine with an equivalent amount being converted to HBr which needs to be scrubbed from the off gases and removed as NaBr. The atom accountability in such reactions again tells a story of inefficiency and waste

In reactions using stoichiometric levels of phosphorus and with a substrate molecular weight of 100, even 100% efficient organic chemistry only gives 40% of the final mass as product, with 60% being waste. At a more likely level of 80% efficient organic chemistry, the figures change to 31% product and 69% waste.

A clean synthesis approach to bromination reactions should be able to greatly improve their environmental performance and atom efficiency. It is now known for example, that aromatic brominations, at least for other than strongly deactivated substrates, can be effectively catalysed by solid acids (including supported mild Lewis acids that are easily recovered and can be reused many times). It should also prove possible to replace the phosphorus in aliphatic brominations. Furthermore, it should be possible to devise economical methods for oxidatively regenerating the bromide side-product to bromine ideally using oxygen, which will lead to water only as a side product. The effect of these improvements on the atom accounts would be dramatic

The effect on the mass efficiency is equally impressive with 100% efficient organic chemistry leading to 94% of the final mass as product and only 6% as waste. Even at 80% efficient organic chemistry, the figures are 75% product and only 25% waste respectively.

## 6. Partial Oxidations

The partial oxidation of organic molecules (typically hydrocarbons) is a diverse and widely used area of chemistry with applications in almost all of the important fine and speciality chemicals industries including the manufacture of pharmaceuticals, agrochemicals and monomers (some of the most important transformations are shown in Fig. 9). Established manufacturing methods include those based on cobalt–acetic acid–bromide systems (*e.g.* for the side chain oxidation of alkylaromatics). While these are catalytic in cobalt the corrosive nature of the systems and the large reaction volumes are drawbacks. These coupled with the high temperatures and pressures that are often required give rise to problems for the operator and the plant, and improved catalytic reaction systems need to be developed. Peroxide reagents are useful in many partial oxidation reactions including epoxidations, Baeyer–Villiger reactions and hydroxylation's. Peroxides can be hazardous however, and the more reactive organic peroxides such as percarboxylic acids do present serious difficulties to the operator especially in large scale processes. Stoichiometric metal oxidants such as chromium (vi) and manganese (vii) are perhaps the best known oxidising agents in chemistry. While they are commonly associated with volumetric analysis and bench scale reactions, their use on a large scale

leads to large volumes of toxic metal waste.<sup>1, 13</sup> Rather surprisingly, such reagents continue to be used in some industrial processes such as the conversion of secondary alcohol functions to ketones. In a typical reaction, the feed stocks are a source of chromium (vi), acid and an organic solvent as well as the organic substrate. The wasteful nature of such processes is evident when the work-up of the final reaction mixture is considered (Fig. 11). Typically, the mixture will undergo a water quench to liberate the product and considerably larger quantities of acid and chromium waste. The combination of toxic metal, acid and organic residues represents a particularly difficult form of waste, which must be treated before disposal. Even with 100% efficient solvent recovery, these processes will generate considerably larger volumes of waste than product. The high added value of partially oxidised products may continue to make the chemistry economically viable but it cannot be considered environmentally acceptable.

A simple exercise in atom accountability in the partial oxidation of an organic substrate with a stoichiometric chromium reagent system can also be used to highlight the problems of the input atoms in the case of a simple hydrocarbon oxidation, only carbon, hydrogen and oxygen are required in the final product. Chromium, sodium and sulfur are used yet do not appear in the final product. In the ideal synthesis, the only atoms that leave a process should leave in the form of useful product. The most environmentally acceptable source of oxygen is air, directly leading to only nitrogen as waste (of course, oxygen itself or oxygenenrichedair can also be used in the actual process). For most organic oxidations using air, a catalyst will be required to enable the reaction to occur at moderate temperatures and pressures (even with a catalyst many important partial oxidations currently require very forcing conditions suggesting the need for improved catalysis). Thus, in the ideal partial oxidation process, only the organic substrate, air and (a small amount of) catalyst should be introduced into the reactor. If the catalyst can be retained in the reactor in some way (and subsequently reused either *via* a continuous mode of operation, or *via* fresh charge of substrate), then the work up of the reaction mixture should only involve product recovery and unreacted substrate recycling. In some partial oxidations (*e.g.* the side chain oxidation of alkylaromatics), water will also be produced in the reaction but water is just about the most environmentally acceptable side product, at least when pure, and can be used as a source of energy if vented off as steam. This, of course, ignores any organic side products which commonly occur in many partial oxidations but these are also prevalent in the older and more wasteful processes, indeed the use of some newer forms of catalysis (*e.g.* those based on shape selective micro porous solids) can improve reaction selectivity. To keep such an ideal process as simple, efficient and clean as

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possible, an active and selective catalyst is required. Furthermore, to avoid any potentially difficult catalyst separation stages, it should remain in a separate phase from the organics (and, of course, not leach any of its component parts into the organic phase). In the case of a simple stirred reactor, a particulate solid catalyst could be used although the ultimate separation of such a material from a liquid (decantation, filtration, *etc.*) may not be a trivial exercise. For continuous flow reactions, catalyst pellets may be more appropriate. Fortunately, useful progress is being made in the discovery and application of solid catalysts for partial oxidation reactions. These include mixed metal oxides such as the titanium silicate 'TS1' (*e.g.* for the hydroxylation of small aromatic compounds) and supported reagent type catalysts (*e.g.* for alkene epoxidations).

## 7. Concluding Remarks

The drive towards clean technology in the chemical industry and the emergence of green chemistry related issues in chemical research and education are unlikely to be short term 'fashions'. In the future, the synthetic chemist will need to be as concerned about atom efficiency as the synthetic route and the process chemist will need to be as concerned about the waste produced as the product to be made. It is already becoming evident that the more successful chemical manufacturing companies of the future will be those that can exploit the economic, legislative and public image advantages that a clean technology approach to chemical manufacturing can provide. Also, the more successful chemistry researchers and educationalists will be those that can appreciate the value of green chemistry in innovation, application and teaching (as well as recognizing the important role that green chemistry can play in enhancing the attractiveness of chemistry as a discipline).

While many exciting new greener chemical processes are being developed it is clear that a far greater number of challenges lie ahead. In two of the largest generic areas of chemistry, acid catalysis and partial oxidations, there are countless processes operated by almost every type of chemical manufacturing company, producing products of incalculable value yet also producing almost immeasurable volumes of hazardous waste. New greener chemistry is needed. One of more important development areas in this context will be the more widespread use of heterogeneous catalysis in liquid phase organic reactions. The enormous range of reactions and the rapidly growing number of new catalysts will require the use of rapid screening methods and the use of innovative engineering to fully exploit the new chemistry. Synthetic chemists must be more prepared to work with catalyst chemists who must in turn work more closely with chemical and process engineers. For every challenge offered by the green chemistry revolution there is also an exciting opportunity.

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