Catalysis for green chemistry*

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Abstract: The use of heterogenization as a method for achieving clean synthesis is discussed. The chemical modification of mesoporous solids can be used to make a range of catalysts, including solid acids and bases, and stable metal complexes for selective oxidations and other reactions. By avoiding an aqueous quench stage in the separation, the heterogenization of catalysts and reagents can lead to substantial reductions in waste produced in organic chemical manufacturing processes.

INTRODUCTION

In order to achieve the "triple bottom line", we need to develop new, more environmentally friendly, chemical products and processes [1]. Catalysis, which has played such a vital role in the success of the industry in the 20th century, will also play a very important role in the new greener industry of the new century. Catalysis can not only help to green chemical processes (e.g., by replacing reagents or by enabling more efficient processes) but the demonstration of their value—to reduce the environmental impact of processes and reduce the costs of the processes—will catalyze the greening of chemistry.

ATOM EFFICIENCY

The concept of atom efficiency has proven to be a popular tool in the evaluation of the "greenness" of a chemical process [2]. It is also revealing to compare sectors of chemical manufacturing. Most people would associate oil refining more than pharmaceutical manufacturing with dirty processes and waste, yet, while the sheer scale of the former leads to the largest volume of waste, the ratio of waste to product is greater for the latter by a factor of 10^2–10^3. In pharmaceutical and fine chemicals manufacturing, the high value of the product has been a particularly significant feature in the establishment of many highly (atom) inefficient processes. Stoichiometric reagents (e.g., chromate oxidants), catalysts that cannot easily be recovered and reused, and large volumes of volatile organic solvents are routinely used with all the consequential waste at the end of the reaction when the organic products need to be separated from the inorganic reagents, catalysts, and solvents (typically by an aqueous quench). Some of the biggest problem areas in synthetic methodology in this context are:

- acid-catalyzed reactions
- selective oxidations
- halogenations
- base-catalyzed reactions
- reductions
- metal-catalyzed reactions
- phase-transfer-catalyzed reactions

In tackling these problem areas, we should not be afraid to strive toward the "ideal synthesis" which would be

- atom efficient,
- safe,
- one step,
- involving no wasted reagents,
- based on renewable resources, and
- environmentally acceptable (including product fate considerations).

Step changes that move toward the ideal synthesis can be achieved with the application of several technologies including catalysis, process intensification, alternative energy sources, and supercritical fluids. Since the major source of waste from a chemical process is the reparation stage, it would seem sensible to focus heavily on that. The heterogenization of catalysts (and, where appropriate, reagents) so that they can easily be separated (and reused) at the end of a process, is a logical and versatile approach to simplifying the process, removing the need for an aqueous quench (or other destructive separation step) and reducing the demand for raw materials [3].
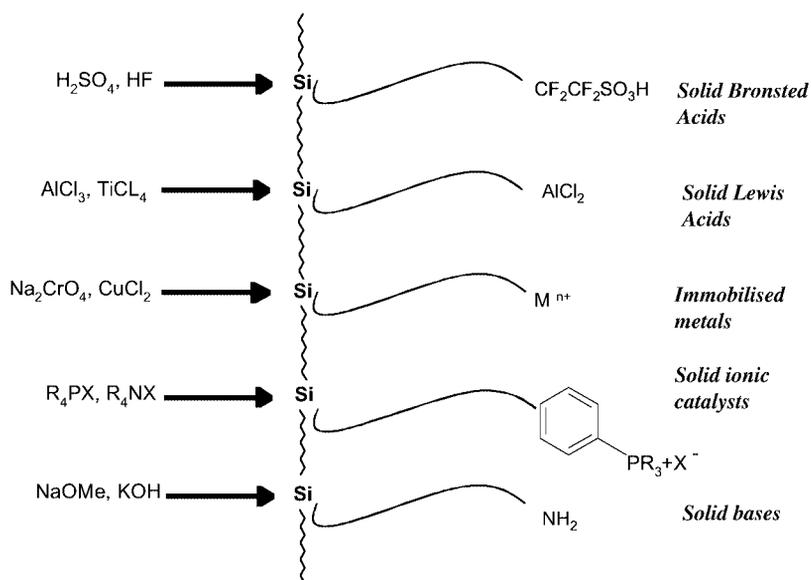
CATALYST HETEROGENIZATION

It is possible to prepare heterogeneous analogs of most, if not all, of the most commonly used soluble and homogeneous catalysts. Heterogenization through chemical surface modification is most conveniently carried out using a silica (or silica-rich) backbone (Fig. 1) [4].
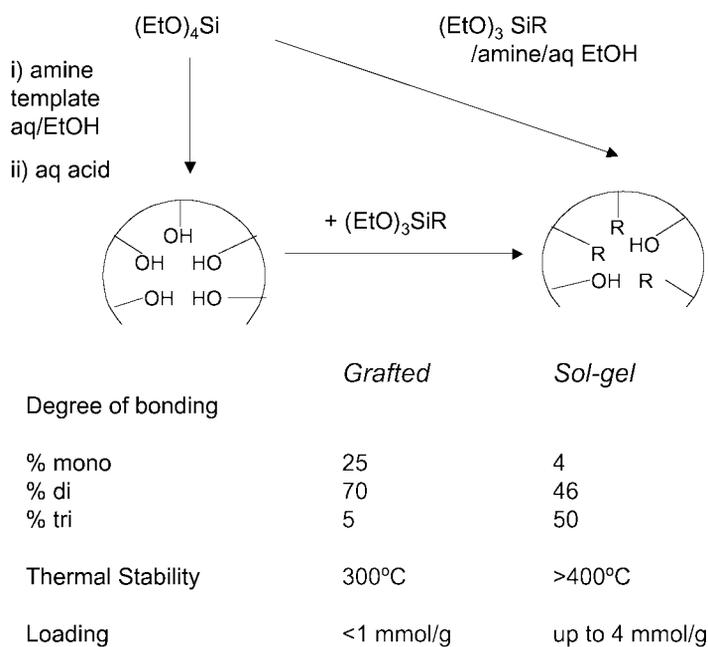
There are essentially two methods for preparing organically modified materials—grafting and *in situ* sol-gel (Fig. 2).

We have found the latter to be preferable in terms of thermal stability and, in particular, in terms of loading. Ultrahigh loaded materials prepared by this method of >3 mmole g^{-1} are not uncommon and these can be considered as inorganic–organic hybrids with organic contents reaching 50% [5].
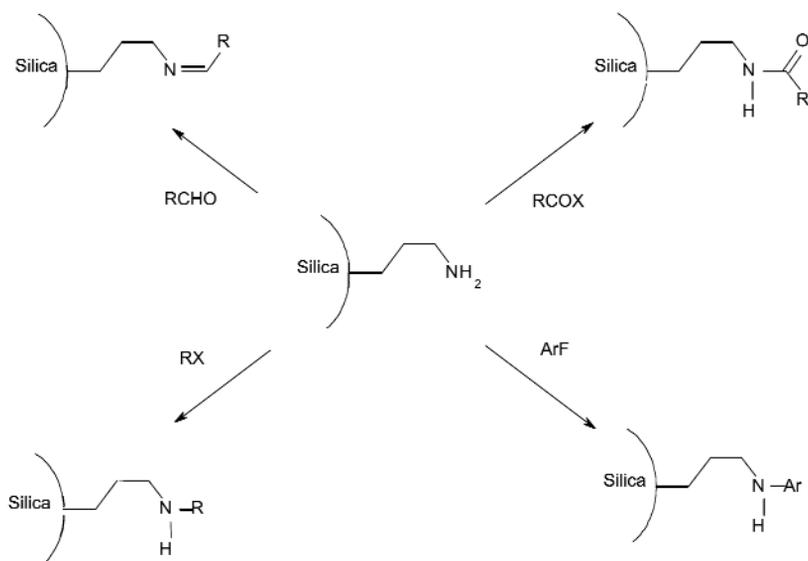
The main disadvantage of the sol-gel-based materials such as these is the potential sensitivity of the sol-gel process to the functional group R. This can be a problem if relatively well-ordered materi-

Fig. 1 Catalyst heterogenization.

Fig. 2 Grafting vs. sol-gel.

Degree of bonding

	Grafted	Sol-gel
% mono	25	4
% di	70	46
% tri	5	50
Thermal Stability	300°C	>400°C
Loading	<1 mmol/g	up to 4 mmol/g

Fig. 3 Postmodification of an aminopropylsilica (AMPS).

als with narrow (meso)pore size distribution are required, although many successful examples have been reported. Some functional groups are particularly versatile as intermediates en route to other useful materials (Fig. 3).

REACTIONS CATALYZED BY SOLID ACIDS

Acid catalysis is by far the most important area of catalysis. It is employed by industries in all sectors of chemical manufacturing, but suffers from the use of traditional Brönsted and Lewis acids that are hazardous to use and give rise to enormous volumes of dangerous effluent. We have studied the use of mesoporous solid acids based on silica and zirconia in many important organic reactions, examples of which are shown in Fig. 4.

A particularly interesting challenge in this context is to try to design purely Lewis and purely Brönsted solid acids as well as those that show both characteristics. Variable strength of acidity is also important. There are some important organic reactions where careful control of the type and strength of acidity is very important if high reaction selectivity is to be achieved. In this context, we have been working for several years on developing controlled acidity (Fig. 5) [6].

Early research at York, and in collaboration with a UK specialty chemical manufacturer, led to the discovery of clay-supported zinc chloride ("clayzic"). Clayzic became the basis of a commercial "Envirocat" [7] catalyst which has proven to be useful for typically Lewis acid-catalyzed reactions, including benzylations, olefinations, and some cyclizations. More recently, we have extended this concept to a new solid Lewis acid, HMS-supported zinc triflate which shows reasonable selectivity in the rearrangement of ∝-pinene oxide to campholenic aldehyde (a reaction that rapidly loses selectivity with any Brönsted acidity in the system) and excellent reusability compared to conventional homogeneous processes [8].

Solid Brönsted acids based on mesoporous inorganic solids have only become available quite recently [9]. HMS-sulfonic acid is a particularly interesting material and can be prepared at high
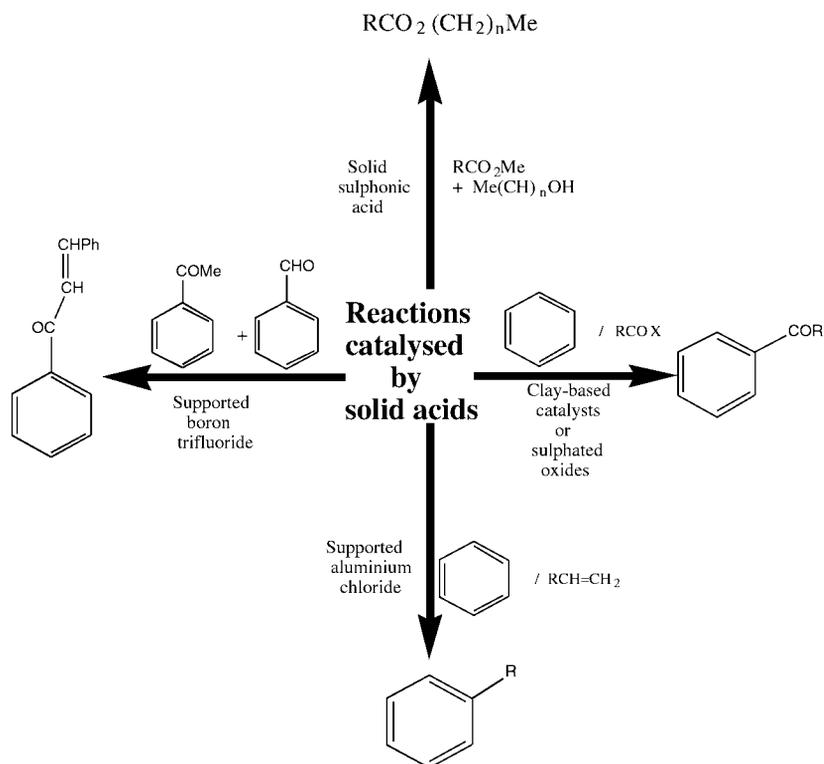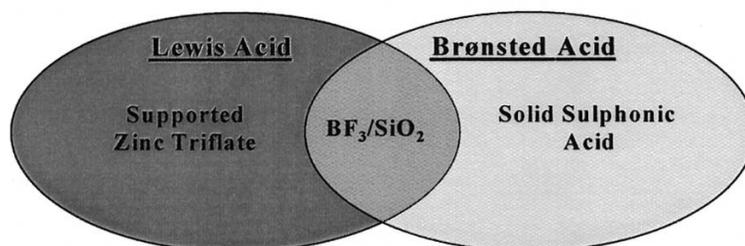

Fig. 4 Some reactions catalyzed by solid acids.

Fig. 5 Controlled acidity in solid acids.

(ca. 3 mmole g^{-1}) loadings and with very high surface areas (>1000 $m^2 g^{-1}$). The material behaves like a solid form of methanesulfonic acid, yet it is safe to handle, recoverable, and reusable in reactions including transesterifications. A simplified one-step procedure for making some mesoporous solid sulfonic acids has recently been reported [10] and lends weight to the belief that materials of this type have a very promising future as environmentally friendly replacements for traditional acids such as sulfuric acid and its organic derivatives. The main restriction to the widespread use of these solid acids is cost, as is the case for many heterogenized analogues of commercial catalysts and reagents. This will become less of an obstacle as environmental cost factors represent an increasingly high fraction of total process costs.

We have also been able to demonstrate that it is possible to prepare solid versions of strong Lewis acids such as $AlCl_3$, BF_3, and SbF_3 [6]. These have generally been prepared in forms which show mixed Lewis–Brönsted acid characteristics, and successful applications in organic synthesis include selective alkylation of aromatics and hydrocarbon polymerizations. The concept can be extended to zirconia as a support material especially after sulfation to increase its acidity. Sulfated zironia is an excellent catalyst for aromatic alkylations and, when used in its mesoporous form, is also reusable.

PARTIAL OXIDATION

The partial oxidation of hydrocarbons and the selective oxidation of fuctionalized organic compounds are reactions of diverse importance. Application areas include pharmaceuticals, agrochemicals, and polymers. Traditional synthetic methods employ a variety of reagent and catalyst systems including stoichiometric high-oxidation-state metals (highly toxic and leading to large volumes of waste at the separation stage), catalytic metal-acid-bromide systems (used in the manufacturing of aromatic carboxylic acids but leading to emissions due to solvent burning and corrosion problems for the reaction vessels) and hazardous organic peroxides which give organic waste byproducts.

Hydrogen peroxide is a safer alternative to its organic derivatives and has only water as a byproduct (although this can be problematic in organic processing) and genuinely catalytic no-solvent air/oxygen systems would seem to be particularly attractive from an environmental perspective.

It is particularly revealing and disturbing to study the atom efficiency of, for example, chromate oxidation systems where the substrate to be oxidized is typically the minor component in a complex brew including chromate, organic solvent, and acid. These inevitably lead to high byproduct (waste)product ratios.

We are studying a variety of novel oxidation systems based on the use of immobilized metal complexes and recyclable solid peroxy systems. One example of the former is a novel form of cobalt (III). Cobalt is one of the most useful redox metal systems. It is normally used in its more common +2 oxidation state which can lead to rate-limiting +2 to +3 oxidation steps (e.g., using O_2 as the oxidant) and induction periods. By designing an appropriately chemically modified mesoporous silica, it is possible to stabilize Co (III) (Fig. 6) in a form which is active in the side-chain oxidation of alkylaromatics [11].
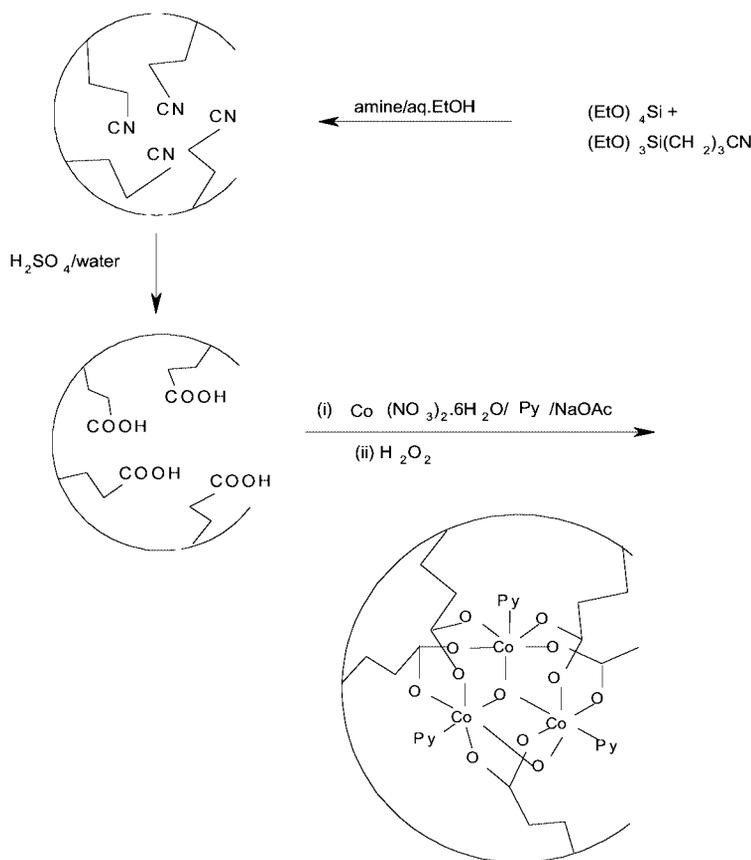
Characterization of the catalytic material shows that it is a high surface area mesoporous material lacking in long-range order and with reasonably high cobalt loading (0.68 mmolg^{-1}).

We have also been able to develop catalytic systems based on immobilized metal complexes that are capable of catalyzing reactions of pharmaceutical value including the selective oxidation of steroidal compounds [12].
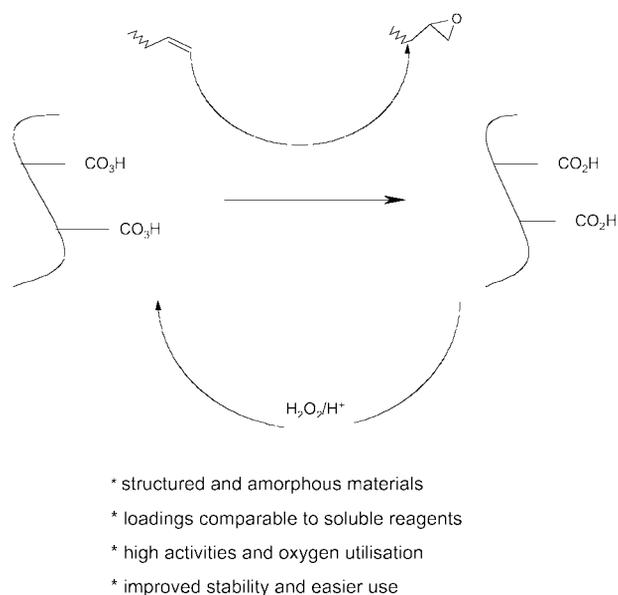
An alternative approach to the utilization of mesoporous solids in liquid-phase selective oxidation reactions is to use solid peracids. Here, the material may not strictly act catalytically but may be easily recycled (Fig. 7).

We have been able to prepare suitable materials by chemical modification of sol-gel synthesized cyanoalkylsilicas (Fig. 8).

These are good examples of materials that can be made with ultra-high loadings and are effectively inorganic-organic hybrids. Their high loadings and good diffusional characteristics make them realistic substitutes for traditional organic peracids. On a weight-for-weight basis, their activity in typical peroxide reactions (epoxidations, Baeyer–Villiger reactions, etc.) is usually somewhere in between that of commercial metachloroperbenzoic acid and peracetic acid. The solid reagents offer significant advantages over their soluble counterparts—they have good shelf-life, reasonable thermal (up to ca. 150 °C) and shock stability, and can be easily recycled at very high oxygen efficiencies [13]. Chemically modified mesoporous materials based on silicas, aluminosilicates, zirconias, and many other environmentally compatible materials have enormously diverse potential as benign replacements
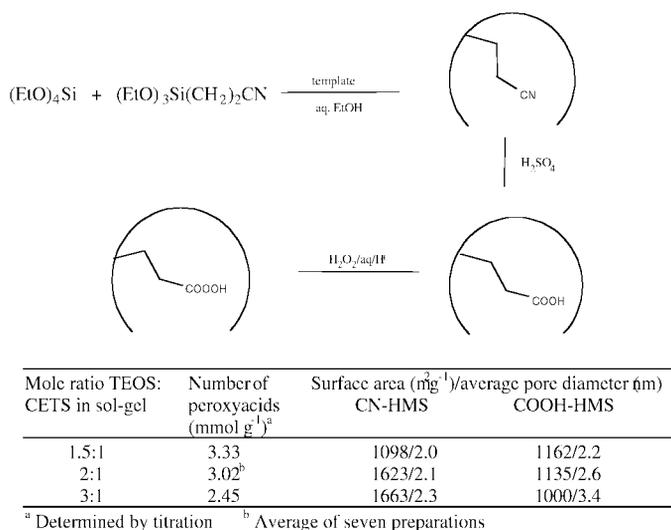

Fig. 6 Immobilized Co(III).

* structured and amorphous materials
* loadings comparable to soluble reagents
* high activities and oxygen utilisation
* improved stability and easier use

Fig. 7 Supported peracids.

Stable inorganic-organic hybrids can be prepared with ultrahigh loadings based onmesoporous solids with very high surface areas

$(EtO)_4Si$ + $(EtO)_3Si(CH_2)_2CN$

Mole ratio TEOS: CETS in sol-gel	Number of peroxyacids $(mmol\ g^{-1})^a$	Surface area (m^2g^{-1})/average pore diameter (nm)	
		CN-HMS	COOH-HMS
1.5:1	3.33	1098/2.0	1162/2.2
2:1	3.02^b	1623/2.1	1135/2.6
3:1	2.45	1663/2.3	1000/3.4

^{a} Determined by titration ^{b} Average of seven preparations

Fig. 8 Mesoporous solid peroxycarboxylic acids via sol-gel technology.

for the many hazardous and environmentally threatening chemicals that we have built our chemical manufacturing on. We have extended this principle to numerous solid bases, for example (Fig. 9).

Palladium, a highly versatile metal for organic synthesis, can be effectively immobilized on chemically modified mesoporous materials that provide the right ligand geometry. We have proven the activ-
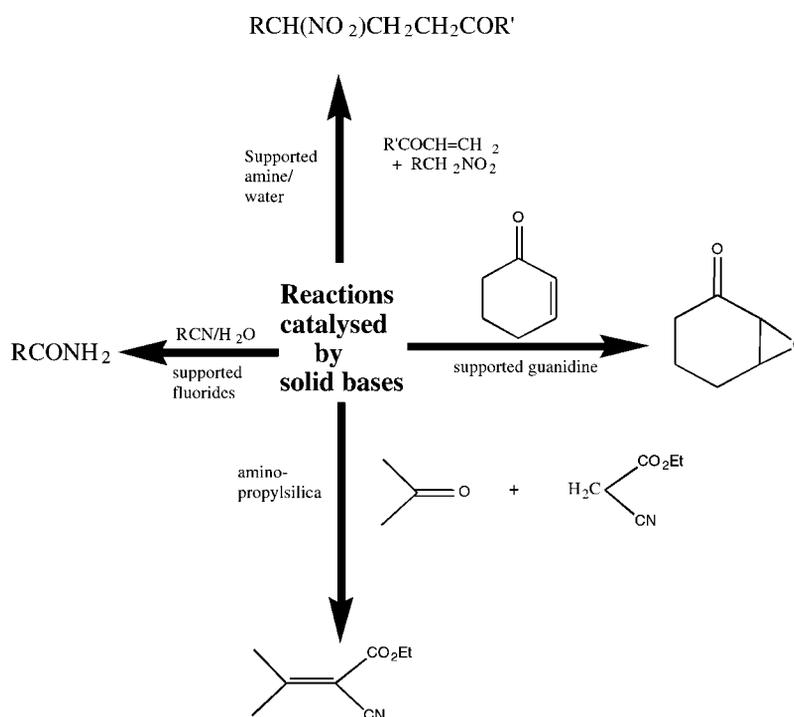
$$RCH(NO_2)CH_2CH_2COR'$$

Fig. 9 Some reactions catalyzed by solid bases.

GREEN CHEMISTRY AT YORK
CENTRE FOR CLEAN TECHNOLOGY
THE UNIVERSITY *of York*

WHAT IS GREEN CHEMISTRY?
Green Chemistry is the design, manufacture, and use of environmentally benign chemical products and processes that prevent pollution and reduce environmental and human health risks.

GREEN CHEMISTRY GROUP

The *York Green Chemistry Group* works at the frontiers of modern chemical research and seeks to:

■ develop new chemical processes to replace unacceptable methods

■ apply innovative catalyst technology to established industrial processes

■ reduce waste through increased reagent and solvent efficiency

■ develop environmentally acceptable routes to important organic products

■ design new environmentally friendly materials and materials based on renewable resources

www.york.ac.uk/depts/chem/staff/Clark-home.html

The Green Chemistry Network is sponsored by the Royal Society of Chemistry and located at the University of York. The main aim of the GCN is to promote awareness and facilitate education, training and practice of Green Chemistry in industry, academia & schools.
www.chemsoc.org/gcn

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Fig. 10 Green chemistry at University of York.

ity of such materials in reactions including the important carbon–carbon bond forming Heck and Suzuki reactions [14].

It is also possible to build quite complex organic structures on the surfaces of mesoporous materials, including those active in typically phase-transfer-catalyzed processes where a membrane version could be used in an interfacial reaction system that keeps the organic and inorganic component of an organic process separate, hence alleviating separation difficulties and reducing waste [15].

The research described above has been carried out by, or in collaboration with, researchers based in the York Clean Technology Centre. This is also the hub of the Green Chemistry Network as well as other green chemistry-related activities. (Fig. 10).

What will the chemical industry of the near and far 21st century look like? The application of the principles of green chemistry and other aspects of clean technology will increasingly lead to more environmentally compatible manufacturing systems. "Just-in-time" manufacturing can ease transportation and storage problems with small, intensive plants replacing the giants of the 20th century. Looking further ahead, we can expect to see more chemical plants taking advantage of local resources including plant-based feedstocks, clay-based reagents, and catalysts, etc., and it is quite possible, as transport becomes a bigger issues, that manufacturing will be largely in response to regional needs rather than global market opportunities. We should seek to meet the needs, not the greed, of society.

ACKNOWLEDGMENTS

REFERENCES

1. R. A. Sheldon. *Chemistry & Industry* **1**, 12 (1997); J. H. Clark. *Green Chem.* **1**, 1 (1999).
2. B. M. Trost. *Angew. Chem. Int. Ed. Eng.* **34**, 259 (1995); R. A. Sheldon. *Chemtech* 38 (1994).
3. J. H. Clark and C. N. Rhodes. *Clean Synthesis Using Porous Inorganic Solid Catalysts*, RSC Clean Technology Monographs, Cambridge (2000).
4. P. M. Price, J. H. Clark, D. J. Macquarrie. *J. Chem. Soc.*, *Dalton* 101 (2000).
5. D. J. Macquarrie. *Phil. Trans. R. Soc. Lond.*, A **358**, 419 (2000).
6. K. Wilson and J. H. Clark. *Pure Appl. Chem.* **72**, 1313 (2000).
7. *Envirocats*, Contract Catalysts, Merseyside, England.
8. K. Wilson, A. Renson, J. H. Clark. *Catal. Lett.* **61**, 51 (1999).
9. W. M. VanRhijn, D. E. DeVor, B. F. Sels, W. D. Bossaert, P. A. Jacobs. *Chem Comm.* 317 (1998).
10. D. Margolese, J. A. Melers, S. C. Christiansen, B. F. Chmelka, G. D. Stucky. *Chem. Mater.* **12**, 2448 (2000).
11. B. K. Das and J. H. Clark. *Chem. Comm.* 605 (2000).
12. J. A. R. Salvador and J. H. Clark, *Chem. Comm.* 33 (2001).
13. J. A. Elings, R. Ait-Meddour, J. H. Clark, D. J. Macquarrie. *Chem. Comm.* 2702 (1998).
14. J. H. Clark, D. H. Macquarrie, E. B. Mubofu. *Green Chem.* **2**, 53 (2000).
15. G. Grigoropoulou, J. H. Clark, D. W. Holland, K. Scott. *Chem. Comm.* (2001), In press.