EDITORIAL

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Guest editorial: Canada is greener this spring

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Canada is a nation known by its vast land, rich resources, and sparse populations. In spite of its small population, Canada has contributed to the advance of science and technology in the world in no small way. Some examples range from the invention of the world's first telephone by Alexander Graham Bell in a small town called Brantford in the province of Ontario, to the discovery of insulin by Frederick G. Banting and Charles Best at the University of Toronto, and to the invention of the world first "gene machine" by Kelvin Ogilvie at the Chemistry Department of McGill University. In environmental science, the 1987 Montreal Protocol is among the world's major international agreements on protecting the world environment and the Canadian industrial "Responsible Care" program pioneered by Jean M. Belanger of the Canadian Chemical Producers' Association has now been adopted by 45 other countries worldwide.

On the other hand, although green chemistry has been a rapidly growing field in the US and Europe for more than a decade, it has not had as high a profile among researchers in Canada until recently. Earlier sparse green chemistry activities in Canada were mostly associated with isolated researchers such as Murray Moo-Young at Waterloo and Ian Brindle of Brock University. In the Fall of 2000, T. H. (Bill) Chan of McGill University launched a major Canadian initiative on green chemistry (through the help of Paul Anastas) by establishing a Canadian Chapter of the Green Chemistry Institute and by setting up a nation-wide Canadian Green Chemistry Network in 2002 involving over 40 academic research scientists from across the country as well as research scientists from the National Research Council, the Natural Resources Canada and Environment Canada. This group of researchers applied for a National Center of Excellence with a long list of industrial partners. This first major initiative went through several stages of the reviewing process but lost in the final stage in 2003. Nevertheless, the process furthered the goal of organizing the community. During this time, the first "Green Chemistry" graduate/undergraduate course was also established by T. H. Chan at McGill University. Conferences on green chemistry in Canada started in earnest with a Green Chemistry Workshop at Regina, Saskatchewan in May of 2003, an International Green Chemistry Symposium within the joint IUPAC/CIC (Canadian Institute of Chemistry) Conference in Ottawa in August, and a workshop on biomass utilization led by Industry Canada in late 2003. The IUPAC/CIC conference provided the first international exposure of green chemistry activities in Canada. Also in 2003, three Canada Research Chairs in Green Chemistry (Chao-Jun Li of McGill University, Philip Jessop of Queen's University, and Tomas Hudlicky of Brock University) were appointed by the Government of Canada with all three researchers coming from the United States. Furthermore, in late 2003, a Canadian Green Chemistry Forum within the CIC was established by Roland Anderson (Executive Director of the CIC) and P. Sundararajan (Vice Chair of the CIC) in consultation with T. H. Chan and C. J. Li.

With the weather warming and snow melting, green chemistry in Canada is gaining new ground this Spring. Early in the year, the Federal Government set up a policy of focusing on Green and Sustainable Science and Technologies as a future focus of Canada by pledging a $500 million budget on innovative "Sustainable Technologies" to be dispensed in two years. In April, a special issue of the Canadian Chemical News was devoted entirely to green chemistry. The Canadian Green Chemistry Medal was also established this Spring to honor individual(s) for promoting green chemistry in Canada and internationally. Later in the Spring, high-profile green chemistry researchers from Canada, the US, and Europe met in Montreal in May for two conferences, both designed to raise the profile of green chemistry in the Canadian research community. The first of the two conferences, the 18th Canadian Symposium on Catalysis, had three half-day sessions dedicated to catalytic aspects of green chemistry, while the second, the Canada–US Joint Workshop on Innovative Chemistry in Clean Media, focused on the properties and uses of green solvents in chemical science and technologies. Only a week later, the national meeting of the Canadian Chemical Society, held in London, Ontario, included green chemistry events. By this summer, green chemistry activities have spread across most universities as well as governmental laboratories and industrial sectors in Canada. Looking toward the future, Canada is positioning to be a major player in this field in the world and Canadian researchers are actively involved in various international conferences such as the Gordon Research Conference on Green Chemistry, the 2nd International Green Chemistry Conferences in Washington DC, the Pacifichem Chemical Congress in Hawaii, and various international collaborations.

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Recent green chemistry development in Canada

High-profile green chemistry researchers from Canada, the US, and Europe met in Montreal in May for two conferences, both designed to raise the profile of green chemistry in the Canadian research community. The first of the two conferences, the 18th Canadian Symposium on Catalysis, had three half-day sessions dedicated to catalytic aspects of green chemistry, while the second, the Canada–US Joint Workshop on Innovative Chemistry in Clean Media, focused on the properties and uses of green solvents in chemical synthesis. Only a week later, the national meeting of the Canadian Chemical Society, held in London, Ontario, included green chemistry events.

Report on the meeting: Canada–US Joint Workshop on Innovative Chemistry in Clean Media

The presentation of the inaugural 2004 Canadian Green Chemistry Medal to Dr Paul T. Anastas, who is stepping down as the Assistant Director for environmental policies of the White House Office of Science and Technology Policy to become the new Director of the Green Chemistry Institute of the American Chemical Society, kicked off a two-day Canada–US Joint Workshop on Innovative Chemistry in Clean Media on the campus of McGill University in downtown Montreal on May 20–21 2004. The Canadian Green Chemistry Medal was created to promote the development of green chemistry in Canada as well as globally, and was coordinated by the Canadian Chapter of the Green Chemistry Institute. The medal is to recognize annually the outstanding contributions of individual(s) in the promotion and development of green chemistry internationally as well as in Canada. The nomination (to the Canadian Chapter Coordinator), which has an annual deadline on April 1, is open to individual(s) worldwide. Dr Paul T. Anastas, who coined the term “Green Chemistry” and defined the field as “the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances”, was selected for his long-term efforts in promoting and supporting the field of green chemistry worldwide and in Canada. He has been credited in helping the establishment of the Canadian Green Chemistry chapter. In his award lecture, Dr Anastas provided a historical overview of the field of green chemistry, the present accomplishments and activities in the field worldwide, and the future challenges in science and technologies facing mankind.

Fig. 1 Dr Paul T. Anastas receives the 2004 Canadian Green Chemistry Medal sculpture from T. H. Chan, the coordinator of the Canadian Green Chemistry Chapter.

The workshop program featured lectures and panel discussions by leading academic and industrial scientists from the US, Canada, and Europe on the frontiers and issues of using “greener” solvents in science and technologies. Ronald Breslow (Columbia University, USA) delivered the plenary lecture of the workshop on developing biomimetic catalytic reactions in water for site-specific reactions *via* hydrophobic effects. Breslow used three examples including a site-specific oxidation which defies chemical reactivity, the development of a catalyst having both strong acid and base properties, and the study of a dendrimeric catalyst for controlling site-selective reductions.

The first day of the workshop focused on the use of water and supercritical CO_2 in science and technologies. Eric Beckman (University of Pittsburgh, USA) described his efforts in developing catalytic *in situ* formation of H_2O_2 from H_2 and O_2 for oxidations in CO_2 and the utilization of CO_2 as a renewable material and as solvent for chemical and material synthesis. Philip Jessop (Queen’s University, Canada) presented methods that provide the advantages of heterogeneous catalysis for catalyst separation and the advantages of homogeneous catalysis for high efficiency by using “obedient solvents” (solvents which change their nature when a trigger is applied). Walter Leitner (RWTH Aachen, Germany) highlighted some recent accomplishments of his group on developing new catalysts for green chemical synthesis in CO_2. Examples described include the development of QUINAPHOS ligand for asymmetric C–C bond formations, methods for catalyst immobilizations, and ruthenium-catalyzed C–H activation reactions. Alan Weedon (University of Western Ontario, Canada) described the study of photochemistry in supercritical CO_2. The product yields, rates, and quantum yields of a number of photochemical reactions at a variety of pressures were presented. The reactions show interesting pressure effects on reaction rate, density effects on diffusion rate, and solvent and solute clustering effect.

Nicholas Leadbeater (University of Connecticut, USA) disclosed the development of catalytic transition-metal catalyzed C–C bond formation reactions without using transition-metal catalyst under microwave conditions in water. Potential mechanistic insights were discussed for these unconventional reactions. Paul Percival (Simon Fraser University, Canada) discussed the study of muons in high-temperature water. Muon

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was used as a spin probe in magnetic resonance to study transient free radicals under hydrothermal conditions. C. J. Li (McGill University, Canada) described his group's efforts in developing new fundamental C–C bond formation reactions in water that will lead to potentially "green" multi-step synthesis. The studies include aqueous organometallic reactions and C–C bond formations *via* the reaction of C–H bonds such as alkyne–aldehyde–amine coupling (A^3-coupling) and asymmetric alkyne–aldehyde–amine coupling (AA^3-coupling) in water. A poster session featuring contributed papers concluded the day.

On the second day, the morning session was devoted entirely to ionic liquids. Martyn Earle (Queen's University of Belfast, UK) overviewed the development of ionic liquids and their use as solvents in various chemical reactions. Examples include Friedel–Crafts reactions, nitrations, halogenations, and oxidations. It has been shown that by changing the anion of ionic liquids, completely different products have been obtained in the nitration of toluene. Robin Rogers (University of Alabama, USA) detailed a wide range applications of ionic liquids as "enabling solvents" in science and technologies. Examples include the use of ionic liquids in the separation of cellulose and biopolymers and catalytic reactions. He also vividly described some preliminary studies on the toxicity issue of ionic liquids. T. Mark McCleskey (Los Alamos National Lab, USA) discussed the use of ionic liquids, water, and CO_2 for making unique materials. The applications of such materials include a temperature sensor, chemical sensors, and electrochromic devices. T. H. (Bill) Chan (McGill University, Canada) described the development of ionic liquid supported synthesis (ILSS). Low molecular weight ionic liquids were proposed as soluble supports for organic synthesis. They have demonstrated such a concept with a Suzuki reaction and in the synthesis of oligopeptides, saccharides and nucleotides. Robert Singer (Saint Mary's University, Canada) concluded the session with a discussion of using ionic liquids as solvents in organic and organometallic reactions. Examples include Diels–Alder reactions, oxidations, Friedel–Crafts reactions, and bis-metalation of alkynes.

Rajender Varma (US EPA) started the afternoon session with a talk on microwave-assisted reactions under solventless conditions. These reactions provided better yields and cleaner products in a short period of time. Example reactions included Ugi and Biginelli reactions for rapid assembly of compound libraries and the synthesis of heterocycles. Christian Mehnert (ExxonMobil, USA) presented the use of ionic liquids for a number of practical catalytic reactions such as hydroformylations, hydrogenations, and aldol condensations. A concept of supported ionic liquids catalysis was also introduced.

The final session of the workshop featured a panel discussion including high level industrial representatives. They include Berkeley Cue (VP-retired, Pfizer Inc. USA), William Vladuchick (Executive Director of R&D, Eli Lilly Co. USA), S. Volante (VP of R&D, Merck Co. USA), Steven Horne (Director of Chemistry at Brantford Chemicals, Canada), Hadi Mahabadi (Associate Manager of Xerox Canada), and Richard Berry (Program Manager of PAPRICAN, Canada) discussed the challenges and opportunities of green chemistry in various industrial sectors ranging from pharmaceuticals, fine chemicals, to print and paper-making. P. (Sundar) Sundararajan (Vice Chair, The Chemical Institute of Canada) concluded the workshop with a strong endorsement on developing green chemistry in Canada.

The workshop was supported by the Green Chemistry Institute (ACS), Pfizer Inc (US), Eli Lilly and Company (US), Merck Frosst Therapeutics (Montreal), Brantford Chemical Company (Canada), McGill University, and the Canadian Chapter of the Green Chemistry Institute. Local organizing committee members included T. H. Chan, C. J. Li, Philip Jessop, Jean Lassard, and Robert Marchessault.

Report on the meeting: The 18th Canadian Symposium on Catalysis

The Canadian Symposium on Catalysis, held in Montreal from the 16th to the 19th of May, had three sessions on catalysis related to green chemistry. The first session was dedicated to biochemically-related topics. Keynote speaker François Jerome (CNRS-Université de Poitiers, France) reported the preparation and successful testing of silica- and polymer-supported amine catalysts for the esterification and etherification of sugars, leading to biodegradable emulsifiers. University of Guelph professor Marcel Schlaf has embarked upon an ambitious program to develop ionic hydrogenation/hydrogenolysis catalysts for the conversion of natural polyols, such as glycerol or sorbitol, to α,ω-diols. Speakers from CNRS at Montpellier described preliminary work towards the use of chitosan and alginate microspheres as chiral supports for heterogeneous catalysis. Although no significant enantioselectivity was observed, the catalysts were found to be stable and active for selected reactions. Sasha Omanovic, from McGill University, described a method for the regeneration of NADH by an electrocatalytic reduction of NAD+.

Biphasic catalysis and other methods for the recovery and recycling of homogeneous catalysts were introduced in a keynote presentation by Leitner. His group has prepared a poly(ethylene glycol)-supported phosphine ligand, which, when used as a component of a homogeneous hydroformylation catalyst in neat olefin, can be precipitated from the liquid aldehyde product by the application of supercritical CO_2 ($scCO_2$). The $scCO_2$ also serves as a medium for extracting the product out of the vessel. The catalyst can then be used again, for the same reaction or a different reaction. Related techniques were described by other speakers including homogeneous catalysis with a conventional catalyst dissolved in a liquid polymer–$scCO_2$ biphasic system (Yoon-Seo Uh, a graduate student at Queen's), a catalyst that reversibly converts from heterogeneous to homogeneous upon exposure to CO_2 (Colin Thomas, Georgia Institute of Technology), and an ionic liquid–water biphasic system for performing bacteria-catalyzed toxin degradation (Douglas Baumann, also from Queen's). In Baumann's system, the bacteria reside entirely in the aqueous phase. The ionic liquid dissolves the bulk of the toxin (phenol was used as an example) and slowly releases it to the aqueous phase, thereby protecting the bacteria from being exposed to a toxic concentration. Testing showed that two of the ionic liquids (donated by Cytec) were biocompatible with the bacterial catalysts used.

Carbon dioxide was found to have utility in other ways, in addition to its use in biphasic catalysis. Qinmin Pan (from the Rempel group at Waterloo) described the homogeneous hydrogenation of unsaturated polymers, such as nitrile butadiene rubber, with catalysts dissolved in $scCO_2$. CO_2 was also mentioned as a reagent for *in situ* creation of an acid catalyst, methylcarbonic acid, from methanol (Ross Weikel from the Eckert/Liotta group at Georgia Tech.). Even though the acid is not stable, it was found to be effective as a catalyst for several reactions, with the greatest effectiveness at 30–65 bar pressure, depending on the reaction and conditions. The acid can be neutralized by releasing the CO_2 pressure.

Solid acid catalysts, as green alternatives to conventional liquid acids, are the subject of research by Karen Wilson (University of York, England). She showed that the structural and chemical characteristics of sulfated zirconia catalysts, and the selectivity of reactions catalyzed by them, are a strong function of the concentration of sulfuric acid present during their preparation.

The conference was supported by local universities, the Canadian Catalysis Foundation, the Chemical Institute of Canada, the Petroleum Research Fund, and Nova Chemicals Ltd.

Fig. 2 L.-R. Philip Jessop (Queen's), Walter Leitner (RWTH), and Charles Eckert (Georgia Inst. of Tech.) at the banquet at the Canadian Symposium on Catalysis.

Report on the meeting: The 87th Canadian Chemical Society Conference and Exhibition

A week later (May 29–June 2), the 87th Canadian Chemical Society Conference and Exhibition (in London, Ontario), featured two green chemistry-related events. The "CIC Chair's Event" on Green Chemistry and Engineering Forum was organized by P. Sundararajan (Carleton University, the Vice Chair of CIC). This forum featured five speakers from academia, government and industry for a 15 min presentation of each on their vision and thoughts on green chemistry. Richard Puddephatt (Chair of CIC) opened the forum. C. J. Li (McGill University, Canada) discussed challenges and opportunities of green chemistry in academia in Canada. Joseph Cunningham (Industry Canada) overviewed the governmental initiatives and industrial opportunities of sustainable technologies in Canada. Dave Schwass (Senior Environment Officer, Nova Chemicals, Canada) discussed the needs, the challenges, and the benefits of implementing green chemistry technologies. Yves Deslandes (ICPET, National Research Council of Canada) presented the green chemistry research activities in National Laboratories to face sustainable challenges in Canada. Steve Horne (Director of R&D of Brantford Chemical, Canada) discussed the win–win opportunities of green chemistry in fine chemicals. The floor was then opened for discussions with many active topics ranging from the definition of green chemistry to technical details of implementing a particular green chemistry technology in industry.

On the following day (May 31) of the CSC Conference, a symposium on *Teaching Environmental and Green Chemistry and Environmental Science* was organized by Colin Baird (Queen's University, Canada) and Martin Stillman (University of Western Ontario, Canada). T. H. Chan (McGill University, Canada) discussed experience of teaching a graduate/undergraduate course entitled *Green Chemistry* at McGill University. John Andraos (York University, Canada) presented his experience of teaching a new third-year level course offered at York called *Applied Industrial Organic & Green Chemistry* to correlate organic synthesis with "green" metrics. The session was chaired by Dietmar Kennepohl (Athabasca University, Canada).

These Green Chemistry events also coincided with a new initiative by the federal government this Spring in the "Throng Speech" for pursuing green and sustainable science and technologies as a focus of industries in Canada in the next twenty years.

Green chemistry and engineering seem a natural fit for Canada, which has always had an image of being a vast and (mostly) unspoiled land. Even though organization of the green chemistry movement in Canada had a late start compared to those in the US and Europe, work presented at these conferences, and the attendance at the conferences themselves, demonstrated that research in this area is developing strongly in Canada, thanks in no small part to support from our international colleagues.

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Roger A. Sheldon†

A profile of Roger A. Sheldon, Professor of Biocatalysis and Organic Chemistry at Delft University of Technology, who developed the concepts of E factors and atom utilization for assessing the environmental impact of chemical processes.

Timeline

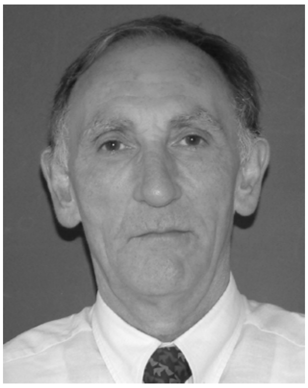
1967: PhD in Organic Chemistry, University of Leicester, UK. Research advisors: Professor Stuart Trippett and Dr. Stephen Davidson

1967–1969: Postdoc with Professor Jay Kochi, Case Western Reserve University, Cleveland and Indiana University, Bloomington, IN

1969–1980: Shell Research Laboratories Amsterdam (KSLA), The Netherlands

1980–1991: DSM- Andeno, Vice President of R&D

1991–present: Professor of Biocatalysis and Organic Chemistry, Delft University of Technology, The Netherlands



Roger Sheldon was born in Stapleford, near Nottingham on June 24, 1942. He was introduced to the wonders of organic chemistry at an early age. After just turning sixteen he left the Newark Magnus Grammar School to seek gainful employment as a technician in the research department of the Boots Pure Drug company. His first assignment involved the synthesis of the steroid hormone, progesterone, hardly the simplest of molecules to start with. Through diligent study, one day and three nights in the week at Nottingham Technical College, he obtained the title of Graduate of the Royal Institute of Chemistry in 1964. At this point, his thirst for knowledge unquenched, he enrolled as a PhD student at Leicester University where he conducted research on organophosphorus chemistry. His joint supervisors were Stuart Trippett and Stephen Davidson.

After being awarded a PhD in organic chemistry in 1967 he migrated to the United States to take up a postdoctoral appointment in the group of Jay Kochi at Case Western Reserve University in Cleveland and subsequently moved with Jay to Indiana University. Jay had an unmistakable influence in molding his scientific thinking and attitudes. Jay introduced him to the scientific rigors of physical organic chemistry and the fascinating world of one-electron transfer reactions between free radicals and transition metal ions. This provided the foundations for his long standing interest in catalytic oxidations and he has fond memories of his 'Kochi period'.

In 1969 he moved to the Shell Research Laboratories Amsterdam (KSLA) where he met Jetty Dijkstra who became his wife in 1970. They have two children. Their daughter, Annemarie, pursued a career in teaching handicapped children and their son, Frank, is a graduate in chemical engineering from Delft University.

At Shell he continued to apply what he had learnt with Jay in his studies of industrial catalytic oxidations, in particular epoxidations with alkyl hydroperoxides; research which underlies the Shell SMPO process for the coproduction of styrene and propylene oxide. In recognition of his pioneering work in catalytic oxidations he was awarded the Royal Society of Chemistry Award in Hydrocarbon Oxidation Chemistry in 1979 and the Berzelius Medal in Catalysis from the University of Lund, Sweden in 1982. During his Shell period he also investigated the application of various catalytic methodologies, such as olefin metathesis and hydroformylation, to the synthesis of fine chemicals, a theme which has pervaded much of his subsequent research. Processes which he developed for the manufacture of pyrethroid insecticides are still in use today.

He also took an avid interest in what has now become known as Green Chemistry at an early point in his career. In the late sixties and early seventies he was profoundly influenced by reading books such as Rachel Carson's 'Silent Spring', Barry Commoner's 'The Closing Circle' and E. F. Schumacher's 'Small is Beautiful'. This new found knowledge prompted him to write an essay on 'Chemistry and the Quality of Life' which won him the Royal Society of Chemistry Essay Prize in 1974. He has fond memories of being presented the prize by Sir Derek Barton, then President of the RSC. This later developed into a long standing friendship and correspondence on oxidation matters. It also marked the beginning of his commitment, over the last three decades, to the development of clean catalytic technologies for the production of (fine) chemicals.

In 1980 he was enticed away from Shell to become Vice President of R&D of the fine chemical company, Oce Andeno, which later became part of DSM Fine Chemicals. He was rather surprised to discover that, in contrast to his experiences at Shell, very few catalytic methodologies were applied in the manufacture of fine chemicals. Hence, he made it his business to change this sorry state of affairs. He was fortunate to have a boss, Joop Jacobs, who was forward-looking and encouraged him to run R&D as he saw fit (as long as some cash was generated at the end of the day). Based largely on his experience at Andeno/DSM he developed, in the late 1980s, the concept of the E Factor and the EQ (Environmental Quotient) for assessing the waste generation and environmental impact of chemical manufacturing processes, highlighting the pressing need for cleaner catalytic processes to replace classical 'stoichiometric' technologies in the fine chemical and pharmaceutical industries. His E Factor concept, first published in 1992, was subsequently accepted worldwide (he is widely known as 'Mr. E Factor) and many companies now use it for assessing the potential environmental impact of their processes. Over the last decade or more he has, through his publications and many invited and plenary lectures at international conferences, drawn attention to the need for cleaner technologies in the fine chemical and pharma industries and been a

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†The opinions expressed in the following article are entirely those of the author and do not necessarily represent the views of either the Royal Society of Chemistry, the Editor or the Editorial Board of *Green Chemistry.*

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staunch advocate of Green Chemistry.

His important role in promoting the concepts of Green Chemistry to a generation of chemists is underscored by, *inter alia*, his co-chairing, with James Clark, of the 2000 Gordon Conference on Green Chemistry. He was also intimately involved, as the first Chairman of the Editorial Board, in establishing the successful journal, *Green Chemistry*. More recently, he was Chairman of the International Symposium on Catalysis Applied to Fine Chemicals, which focused on the use of sustainable catalytic technologies for fine chemicals manufacture.

While at Andeno in the mid 1980s he was inspired by the seminal papers of Alex Klibanov on enzymatic conversions in organic media and developed a strong interest, which continues to this day, in biocatalysis, Research under his direction at Andeno led to the commercialization of various biocatalytic processes for the manufacture of pharma intermediates as pure enantiomers. His book, ‘Chirotechnology’, published in 1993, stems from this period and has become a classic in the field, leading to the widespread adoption of the term. It is worth noting, in this context, that most pharma companies were not convinced, back in the mid-eighties, that the synthesis of drugs as pure enantiomers would ever be an economically viable option. This sounds familiar and reminiscent of initial resistance to the concept of Green Chemistry and the underlying concepts of atom economy and E Factors. It is a common reaction to new technologies and is symptomatic of not looking further than the proverbial end of one’s nose. Similarly, a decade earlier, in the mid-seventies, most oil companies were of the opinion that unleaded petrol was an economic non-starter.

In 1991 he moved to the Delft University of Technology, where he is currently Professor of Biocatalysis and Organic Chemistry. At Delft he has continued to promote the concepts of Green Chemistry, both in his publications and his teaching. Green chemistry features prominently in his undergraduate teaching, *e.g.* one course is entitled Green Chemistry and Sustainable Technology. A major theme of his research in Delft is the integration of the subdisciplines of catalysis—homogeneous, heterogeneous and enzymatic—in organic synthesis, with the ultimate goal of designing multi-step catalytic cascade processes which emulate the metabolic pathways in the living cell. He has made important contributions to the development of green catalytic oxidations and carbonylations and novel enzymatic methods for the synthesis of pure enantiomers. Much of his biocatalysis research is guided by the concept of non-natural reactions of enzymes. Another major theme is catalysis in novel media, such as oxidations and carbonylations in aqueous biphasic media and (bio)catalysis in ionic liquids. The common thread in this research is a drive to achieve precision and elegance in chemicals production *via* atom efficient, low E Factor processes in which a catalyst, if needed, exhibits high activity, selectivity and stability, and is readily separated and recycled. With regard to the latter, effective methods for immobilization of homogeneous catalysts and enzymes are required and this features prominently in his research. For example, his group invented a novel and extremely effective method for the immobilization of enzymes as Cross-Linked Enzyme Aggregates (CLEAs). The commercial potential of the technique is currently being exploited by a spin-off company, CLEA Technologies.

In his Delft period his group has produced about 300 scientific papers and twenty patents and he is a regular invited speaker at international conferences on homogeneous, heterogeneous and biocatalysis, and chirotechnology. He is a frequent publisher in the journals *Green Chemistry* and *Advanced Synthesis and Catalysis*, flagships of the new era of sustainable technologies. He has been a visiting professor at the universities of Osaka (Japan), Campinas (Brazil) and Pierre and Marie Curie (Paris). In recognition of his many contributions to catalysis and green chemistry he was awarded an honorary doctorate of the Russian Academy of Sciences in 1999.

Summarizing, Roger Sheldon’s commitment to, and promotion of, what has now become known as Green Chemistry spans a period of three decades. He has experienced the subject from both an industrial and an academic vantage point. He has witnessed the gradual acceptance, by chemical companies, that Green Chemistry and Sustainable Technologies not only are good for the environment and quality of life but also make good economic sense and, by academics, that Green Chemistry can be good science that is published in premier scientific journals. He takes great satisfaction in the thought that the concept of Green Chemistry is firmly implanted in the consciousness of the current generation of chemists and chemical engineers, both in industry and academia, and that he may have played a role in putting it there. With regard to his Delft period he has much to thank, and gratefully acknowledges, the important contributions of his steadfast coworkers, Fred van Rantwijk and Isabel Arends, and the many PhD students and postdocs whose hard work and dedication has made it all possible. He is also grateful to his many mentors who have helped shape his professional career and to his wife, Jetty, for her continued support, encouragement and understanding.

Highlights

Markus Hölscher reviews some of the recent literature in green chemistry.

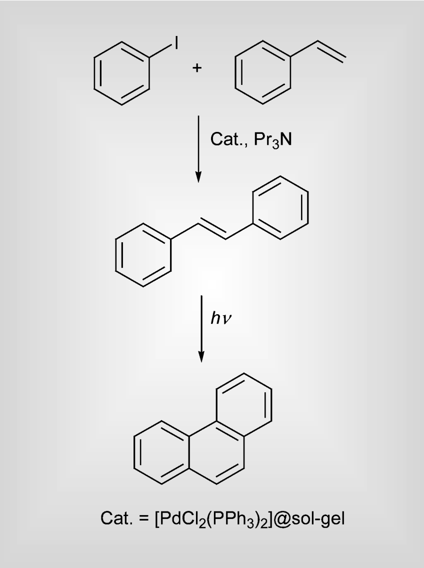
Apo-ferritin cages as carriers for Pd-nanoclusters—catalytic size selective hydrogenation

The immobilization of metal nanoclusters in different types of supramolecular assemblies has recently attracted much interest. Ferritin, an iron storage protein with a cagelike structure, is one of the hosts with promising features for incorporating guests. Ueno and Watanabe *et al*. from Nagoya University used the three- and fourfold channels located at the junctions of the 24 protein subunits to introduce Pd^{2+} ions which subsequently were reduced to Pd-nanoclusters by $NaBH_4$ (*Angew. Chem.*, 2004, **116**, 2581–2584). Different analytical techniques proved the Pd-nanoclusters to be monodispersed particles of approximately spherical shape with the protein shell intact and surrounding the metal core. The diameter of the metal particles is *ca*. 2.0 nm and they consist only of Pd.

Hydrogenation of acrylamide derivatives was accomplished in aqueous solution with no by-products. The TOFs obtained varied quite substantially between 72 and 6.3 depending on the substrate. The Pd-apo-ferritin was shown to be stable during and after the catalytic reactions. By blocking the threefold channels with Tb^{3+} ions the TOF for hydrogenation of acrylamide decreased drastically to *ca*. 7% of its original value, indicating the anionic hydrophilic threefold channels to be the pathway for the substrates. Also, substrate sizes influenced the TOF to a high degree suggesting size selective processes to be operative.

Sol–gel-catalysts for the Heck vinylation of aryl iodides with subsequent photocyclization

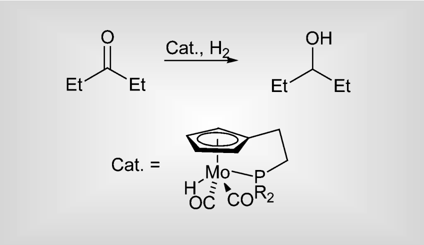
The Heck coupling of aryl halides with olefins has developed into such a powerful tool for the formation of C–C bonds that cost reduction of the relatively expensive reaction (palladium, solvents) is mandatory to achieve the next step in overall performance. One of the strategies used is the heterogenization of the catalyst, which has been investigated extensively by many different approaches. A novel leach proof method was added recently by Blum *et al*. from Hebrew University (*Org. Lett.*, 2004, **6**, 925–927). In a unique procedure the catalyst ($PdCl_2(PPh_3)_2$) was immobilized in a silica based sol–gel, which in contrast to many others can be synthesized very easily. Tetramethoxysilane was simply hydrolyzed with water and a THF solution of the Pd complex was added. Gelation was induced by tetrabutylammonium fluoride and after being aged for 16 h some quick washing, sonicating and drying procedures were applied, resulting in the ready to use sol–gel entrapped catalyst.



Iodobenzene couples with styrenes and acrylic acid derivatives (yields up to 89%), whereas bromobenzenes react very slowly. Recycling experiments showed the catalyst's activity to be hardly affected. Also, one-pot two-step syntheses are possible without affecting the catalyst's activity and recyclability: when iodobenzene and styrene were reacted to stilbene in the first step (reflux, ambient pressure, 12 h) a photocyclization to phenanthrene could subsequently be performed by simply irradiating the reaction mixture in the presence of the sol–gel catalyst for 3 h (85% yield).

Solvent-free ketone hydrogenations

Nearly 15 billion kilograms of organic solvents are used worldwide annually and a substantial amount serves simply as media for chemical reactions. Recyclable alternative solvents and reaction media are one of the mandatory conditions for current chemical research in order to minimize waste production. However, a solventless chemical reaction system also is an interesting alternative. Bullock *et al.* from the Brookhaven National Laboratory have developed a catalyst system for the hydrogenation of ketones which can be used with or without additional solvent (*Chem. Commun.*, 2004, 1014–1015). Their studies aim at the replacement of the expensive rhodium and ruthenium catalysts by the cheaper molybdenum systems. Relying on mechanistic insights in molybdenum hydride catalyst systems, they developed catalysts with the general formula $[HMo(CO)_2\{\eta^5:\eta^1\text{-}C_5H_4(CH_2)_2PR_2\}]$, which can be converted to cationic species using $Ph_3C^+BAr_4^-$.



In its cationic form the molybdenum compound serves as an efficient catalyst for the hydrogenation of $Et_2C{=}O$ (neat), yielding turnover numbers of up to 462 (10 days, counterion OTf^-, catalyst loading 0.086 mol%) without the need to employ additional solvents. Complete conversion is achieved within 8 days using 0.35 mol% catalyst at 50 °C and 55 atm H_2.

Modified binap ligands for highly enantioselective hydrogenations of *β*-aryl ketoesters in ionic liquids

Despite the impressive success of catalytic enantioselective hydrogenations of

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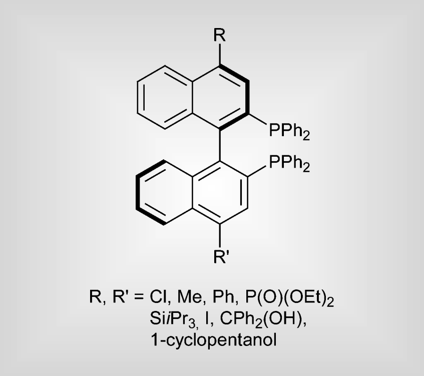
unsaturated compounds, there remains a large variety of prochiral olefins, ketones and imines which still cannot be hydrogenated with high enantioselectivities and turnover numbers. As an example, enantiomerically pure *β*-aryl *β*-hydroxy acids derived from *β*-aryl ketoesters are interesting precursors to *β*-amino acids and *β*-hydroxy-*α*-amino acids, which can be used as building blocks for novel peptides and peptidomimetic drugs. Lin *et al*. from the University of North Carolina have varied the binap ligand by introducing different substituents in the 4,4′ positions and subsequently obtained Ru catalysts for the highly enantioselective hydrogenation of *β*-aryl ketoesters (*Angew. Chem.*, 2004, **116**, 2555–2558). In a set of test experiments ethyl benzoylacetate was hydrogenated in methanol to explore the influence of different electron withdrawing and donating substituents as well as bulky groups on the 4,4′ positions of the parent binap ligand.

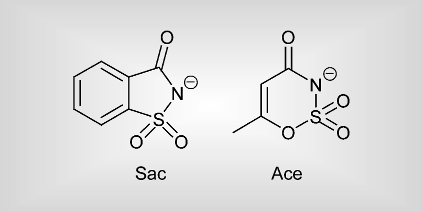


R, R' = Cl, Me, Ph, P(O)(OEt)$_2$
Si*i*Pr$_3$, I, CPh$_2$(OH),
1-cyclopentanol

Sterically demanding groups yielded the highest *ee* values (up to 94.2%), which was rationalized by molecular modeling studies on the corresponding transition states. Some of the catalysts were employed in IL–methanol systems. The *ee* values generally were very high (96–98%) and in some cases reached the 99% range, impressively demonstrating the performance of these catalysts in IL–MeOH solution. The ligand synthesis allows for easy tuning, which should lead to more interesting ligand developments in the future.

Novel non fluorous ionic liquids from non-nutritive sweeteners

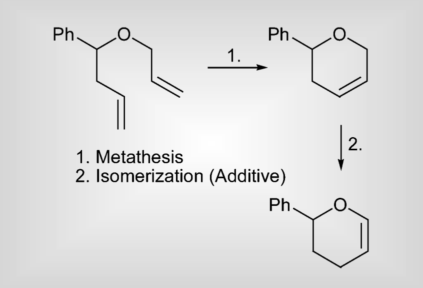
Ionic liquids have proven to be advantageous alternatives to commonly used organic solvents due to their non volatile nature, their good recyclability and their good "compatibility" with many catalytic reactions. However, the usage of the term "green" has been considered to be somewhat one-dimensional in cases where the anion of the IL contains fluorine. Even though environmental concerns might not play a significant role in using fluorinated ILs due to the small volume necessary for the application in question, toxicologically fluorine is always a problem. As a result research to develop alternative anions for ILs have concentrated on acetate and lactate derived compounds. Hoffman *et al*. from the University of South Alabama extended the search for novel anions to the sweeteners saccharin and acesulfame (*Chem. Commun.*, 2004, 630–631).



The reaction of the sodium, potassium or silver salts of the sweetener with imidazolium halides typically used for IL production furnishes the desired IL. The authors concentrated on the Sac and Ace anion and found ILs with C4-, C5-, C6- and C9MIM to melt between room temperature and 100 °C. By NMR investigations they showed that Sac and Ace anions have a weak capacity for H-bonding with the imidazolium cations in solution. The ability to coordinate transition metals was determined and compared with other typical anions to yield the following order of relative affinities for the *trans*-Rh(PPh$_3$)$_2$(CO)-fragment: Sac > TFA > Ace > ONO$_2$. The pairing of the non toxic sweetener anions with appropriate imidazolium cations shows that both environmentally benign and toxicologically harmless ILs can be generated, which should stimulate further research in this area.

Ruthenium catalyzed metathesis with subsequent isomerization

Reaction cascades provide interesting possibilities to use catalytic systems more efficiently. Subsequent ring-opening, ring-closing and cross-metathesis steps for instance are very useful for the directed synthesis of target molecules. Also it would be of interest to couple metathesis and non-metathesis steps, an approach which was employed recently for a metathesis–isomerization sequence by Schmidt from the University of Dortmund (*Chem. Commun.*, 2004, 742–743). It was shown that by a careful choice of catalyst and additive it is possible to synthesize a variety of cyclic enol ethers from allyl homoallyl ethers in *ca*. 2 h reaction time with yields of up to 82%.



1. Metathesis
2. Isomerization (Additive)

Interestingly the desired reaction with [Cl$_2$(PCy$_3$)$_2$Ru=CHOPh] as the catalyst proceeded satisfyingly only with isopropyl alcohol and NaOH as additives. Primary alcohols performed less well and an alternative catalyst–additive system consisting of [Cl$_2$(PCy$_3$)$_2$Ru=CHOEt]–ethyl vinyl ether showed an activity for isomerization that is too low for practical purposes.

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Life cycle analysis of cotton towels: impact of domestic laundering and recommendations for extending periods between washing†

Life cycle analysis of cotton towels by Richard Blackburn and John Payne has ascertained the impact of domestic laundering on the life cycle of cotton articles. It was found that any process or treatment that could reduce the washing frequency of that product would be likely to effect a significant reduction in energy, water and chemical consumption over a given time for that product, hence providing a greener life cycle for the product; one recommendation to achieve this, by reducing washing frequency, is through the use of anti-microbial finishes such as poly(hexamethylenebiguanide).

Introduction

The purpose of this life cycle analysis (LCA) of cotton towels is to ascertain the impact of domestic laundering on the life cycle of cotton articles and whether techniques to reduce washing frequency can provide an overall greener life cycle for the cotton product.

Laundering of textiles is one of the most commonly performed tasks throughout the world and is undertaken to restore the article to an acceptable condition by removing foreign soils and odour generating bacteria and separating this from the wash load; this is done with the application of laundry detergent formulations. In 1990 the estimated world consumption of household laundry products was 16 million tonnes per annum, with a market value of £15 billion.[1] The 1994 European and US markets were worth £6 billion and £10 billion respectively.[2] The principle of washing involves saturating fabric with water and then subjecting it to chemical, biological and physical breakdown of soils by the employment of laundry products and mechanical agitation, respectively. The fabric is then rinsed, sometimes with softeners or starch and finally dried.[2]

There is very little published information concerning the time intervals between launderings of towels. An Internet survey[3] gave the following wash frequencies for bath towels: 1 day, 10%; 3 days, 30%; 7 days, 57%; >7 days, 1%. The majority of users wash their towels once per week, but a significant minority wash them more frequently. Independent market research commissioned by Arch UK Biocides Ltd. reveals that Americans wash the towels in their homes an average of nine times per month.[4]

Life cycle analysis

Production

Data shown in Table 1 were collated for energy, extracted energy and water consumption at each stage of the processing of cotton to produce coloured 100% cotton towels. Extracted energy is the total energy consumption when traced back through all operations to extraction of raw materials from the earth. Extracted energy is associated with fuels consumed by machinery in operations, materials consumed, and transport modes (and associated fuel consumption). These extracted energy calculations were then used in collaboration with mass loss data to determine the total extracted energy and water consumption for the production of a towel as shown in Table 2. By extrapolation of the mass loss data (at the lowest value of the % loss range) it was calculated that 691.9 g of cotton fibre (lint) was required to make a 600 g towel, an overall associated minimum mass loss of 13.3%.

Product use and consumer care

Tables 3 and 4 summarise the extracted energy and water consumption for the towels during domestic laundering and drying, respectively. Based on the mass of the towel, totals were calculated for consumption over the lifetime of a towel (100 washes) based on previous literature and research on the subject: during the washing process a temperature of 40 °C[7] has been assigned as the typical domestic washing temperature for dyed towels. Again, this is consistent with the themes of this LCA, in that, it does not assume a ‘worst-case-scenario’ for energy, water or chemical consumption.

In addition, the typical load mass has been taken as 3 kg,[7] the detergent (standard powder) consumption taken as

Table 1 Energy, extracted energy and water consumption for processes in towel production[5]

Sector/process	Energy consumption/ MJ kg^{-1}	Extracted energy consumption/ kWh kg^{-1}	Water consumption/ dm^3 kg^{-1}
Preparation (total)	*8.6*	*10.23*	*0.0*
Opening and cleaning	2.1	2.50	0.0
Carding (cards)	2.6	3.09	0.0
Drawing (draw frame)	3.1	3.69	0.0
Roving	0.8	0.95	0.0
Spinning (total)	*24.5*	*29.16*	*0.0*
Spinning (ring frame)	18.7	22.25	0.0
Winding	5.8	6.90	0.0
Weaving (total)	*10.6*	*10.15*	*1.0*
Winding or pirning	1.0	1.19	0.0
Beaming and sizing	3.2	1.34	1.0
Weaving (rapier)	6.4	7.62	0.0
Textile dyeing and finishing (total)	*30.8*	*16.07*	*50.7*
Brushing/cropping	1.0	1.19	0.0
Singeing	0.2	0.08	0.0
Desizing and washing (jig, winch, kier)	5.1	2.14	1.4
Scouring (jig, winch, kier)	6.2	2.60	5.0
Bleaching	2.8	1.18	4.3
Mercerising	5.0	2.10	12.0
Dyeing (winch)	5.7	2.39	28.0
Dyeing chemicals (0.35 kg per kg fabric)[6]	—	2.36	0.0
Application of finish (padding)	3.0	1.26	0.0
Drying (stenter)	1.8	0.76	0.0
Making-up (total)	*2.0*	*2.38*	*0.0*
Making-up	2.0	2.38	0.0

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†The opinions expressed in the following article are entirely those of the authors and do not necessarily represent the views of either the Royal Society of Chemistry, the Editor or the Editorial Board of *Green Chemistry.*

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Table 2 Mass loss during production of 600 g 100% cotton towel and associated extracted energy and water consumption

Process stage	Typical % mass loss[11]	Mass (g) after process stage based on minimum % loss	Extracted energy consumption per towel/kWh[a]	Water consumption per towel/dm^3
Prior to treatment	—	*691.9*	—	—
Preparation/blending	2–10	678.1	6.94	0.00
Spinning natural fibres	1–20	671.3	19.57	0.00
Weaving	3–8	651.1	6.61	0.65
Dyeing and finishing	3–10	631.6	10.15	32.02
Making up	5–20	600.0	1.43	0.00
TOTAL			*44.70*	*32.67*

[a] Calculated from data in Table 1.

Table 3 Extracted energy and water consumption during laundering of towels

Matter consumed	Extracted energy per load/kWh[a]	Extracted energy per towel per load/kWh	Extracted energy per towel over life of 100 washes/kWh	Water consumption per towel per load/dm^3	Water consumption per towel life of 100 washes/dm^3
Energy for 40 °C wash[7]	2.62	0.52	52.40	—	—
Detergent[b]	1.00	0.20	20.00	—	—
Water[c]	0.34[d]	0.07	6.88	16.00	1600.00
TOTAL	*3.96*	*0.79*	*79.28*	*16.00*	*1600.00*

[a] Based on average 3 kg load.[7] [b] Standard powder 108 g per load (supplied by Unilever plc).[8] [c] 80 litres per wash.[7] [d] 533 kWh per 1000 dm^3 supply, 454 kWh per 1000 dm^3 sewerage treatment; supply & treatment 0.001 kWh electricity per dm^3 water; supply & treatment 0.0043 kWh extracted energy per dm^3 water; supply & treatment 0.344 kWh extracted energy per load.[9]

Table 4 Extracted energy consumption during drying of towels

Drying energy requirement	Extracted energy/kWh
Drying energy per kg[a]	3.60
Drying energy per towel (600 g)	2.16
Drying energy per towel over lifetime (50% line dried, 50% tumble dried)[10]	*108.00*

[a] Tumble drying; 0.74 kWh electricity per kg cotton; 3.6 kWh extracted energy per kg cotton.[7]

108 g per load,[8] and the typical water consumption taken as 80 dm^3 per wash.[7] Energy consumption data[9] for water supply and subsequent sewerage treatment has been used to calculate extracted energy consumption associated with domestic laundering (no allowance for evaporation). Energy associated with drying has been based on statistics that 35% of households own dryers and 15% own washer-dryers,[7,10] hence, 50% of all towels would be dried mechanically. This study does not take into account additional energy used to dry clothes inside households on radiators, *etc*.

Using these calculations, the extracted energy, water and chemical consumption for cotton towels over one year of use was calculated, based on average washing frequency. This data is given in Table 5.

The authors are aware that for their calculations that habits across the world differ and only in North America and part of Europe tumble-drying (which has the biggest energy impact) forms a major habit. Also the amount of water, chemical loading by detergent dosages differ strongly across the world. Nevertheless these trends observed are still applicable under alternative conditions, and increasing time between washing will still affect a life cycle benefit.

Disposal

There is no evidence that cotton towels are recycled after their useful life of 100 washes, hence, it has been assumed that all towels are disposed through landfill. The extracted energy associated with this process has been calculated using WISARD[13] waste management software.

Final life cycle assessment

Table 6 shows LCA for cotton towels with respect to extracted energy, water and chemical consumption. Fig. 1 details the representative proportion of extracted energy consumption over the lifetime of a towel. It can be clearly seen that the most important stage in the life cycle of such a towel is the consumer stage. Consequently, for this product, any change or operation that can cause a reduction in energy within the consumer stage of the product's life (domestic laundering), will subsequently affect a significant impact on the energy consumed within the life cycle of the product.

In light of these findings about the significant environmental effect of domestic laundering on the energy, water and chemical consumption of a laundered product, it is reasonable to predict that these observations would translate to any item that is subjected to domestic laundering. Furthermore, any process or treatment that can reduce the washing frequency of that product would be likely to effect a significant reduction in energy, water and chemical consumption over a given time for that product. Indeed, in industrial cleaning (hotel towels, sheeting, *etc*.) this is already recognised as in most hotels signs are posted in the bathrooms to make guests aware to avoid unnecessary laundering of towels; this now needs to be recognised for domestic applications.

Recommendations

One such method of reducing the washing frequency of any textile article, be it apparel or a functional item, is the application of an anti-microbial agent. Antimicrobial textiles are able to control fungi and bacteria that come into contact with the fibres, preventing odour generation, staining or degradation of the fibre, and the transfer of organisms between different areas, hence reducing the actual frequency of washing.

Table 5 Extracted energy, water and chemical consumption of treated and untreated towels over one year of consumer use

Matter consumed	Extracted energy/kWh	Water consumption/dm^3	Detergent consumption/kg
Untreated[a]			
Washing machine energy	47.82	0	0
Detergent	18.25	0	1.97
Water	6.28	1460.00	0
Drying	98.55	0	0
TOTAL	*170.89*	*1460.00*	*1.97*

[a] Washed every 4 days, washes per year = 91.25, life of towel (100 washes) = 1.10 years.

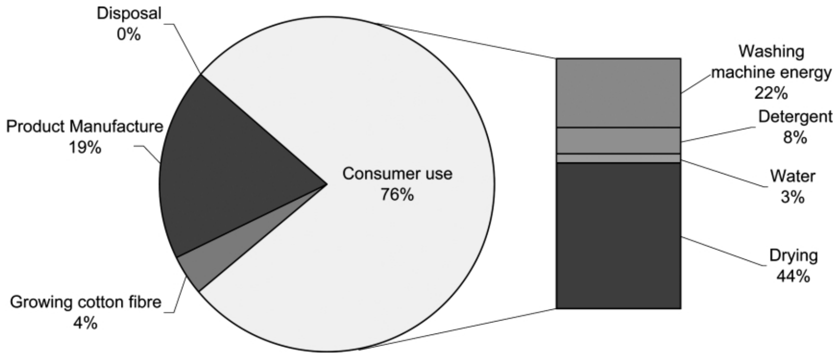


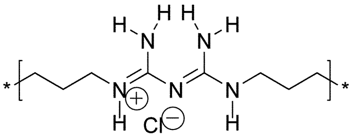
Fig. 1 Extracted energy consumption (kWh) of towels over lifetime.

Table 6 Extracted energy, water and chemical consumption of dyed 600 g 100% cotton towel over lifetime

Life cycle stage	Extracted energy consumption/ kWh	Water consumption/ dm^3	Chemical consumption/ kg
Growing cotton fibre[a]	9.35	[b]	[b]
Product manufacture[c]	44.70	32.67	0.22[d]
Washing machine energy	52.40	0	0
Detergent	20.00	0	2.16[e]
Water	6.88	1600.00	0
Drying	108.00	0	0
Consumer use total	*187.28*	*1600.00*	*2.16*
Disposal[f]	0.02	0	0
Overall total over lifetime	*241.35*	*1632.67*	*2.38*
TOTAL for untreated towels over 5 years	*1101.04*	*7448.33*	*10.86*

[a] 13.514 kWh per kg,[12] based on 691.9 g (see Table 2). [b] Water and chemical consumption for growing fibre not included. [c] No transportation consumption included. [d] 0.35 kg dyeing chemicals per kg fabric (see Table 1); based on 631.6 g (see Table 2). [e] 108 g detergent per load (see Table 4), 21.6 g detergent per towel per load, 2.16 kg detergent over 100 washes. [f] 0.0386 kWh per kg.[8]

The additional energy, water and chemicals associated with the application of an anti-microbial agent such as poly(hexamethylenebiguanide) (PHMB; **1**)[14] are essentially negligible, but the ability of such a treatment to reduce the number of washes required in any given time frame would cause a dramatic reduction in the extracted energy, water and chemical consumption in that same time frame. Hence, the application of PHMB to cotton towels (or any treated item) results in a product that is considerably more environmentally friendly than its untreated counterpart, when considered over its whole lifetime from raw materials to disposal.



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Any antimicrobial (or other) additive used on towels will have an environmental cost and to gain any real overall life cycle benefit, the advantages of antimicrobial treatment must be significantly higher than their disadvantages. This will be the case if the manufacture and application of the treatment do not use significant amounts of energy and generate waste, if the ultimate biodegradation of the towel is not adversely affected, and if there is no impact on wastewater. Any useful treatment must meet these criteria. Additionally, freshness, fragrance impact, handle (softness), shape and look of the towel after extended use must not be adversely affected by application of the antimicrobial agent, since that would not permit extended use periods.

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COMMUNICATION

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First semi-synthetic preparation of sex pheromones

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Here we describe the first construction of a genetically modified plant (GMP) with the ability to produce moth sex pheromone precursors. Previously prepared (Svatoš *et al.*, Czech Patent Appl. 2000/0125) *N. tabacum* GMP transformed with a plasmid encoding cabbage looper moth (*Trichoplusia ni*, Hübner, Lepidoptera, Noctuidae) acyl-CoA Δ^{11}-(Z)-desaturase (Knipple *et al.*, *Proc. Natl. Acad. Sci. USA*, 1998, 95, 15287) showed a substantial presence (*ca.* 6%) of the potential pheromone precursor, methyl (11Z)-hexadec-11-enoate (1). The ester 1 was isolated in bulk (6.5% of extracted lipids) from a greenhouse cultivated transgenic tobacco and the corresponding acetate, which are principal components of a large number of sex pheromones, was semi-synthetically prepared from the *in planta* produced pheromone precursor. The attractiveness of the prepared blends for moth, *Mamestra brassica* was proved in field trials.

Introduction

Sex pheromones are produced commercially in ton quantities worldwide to control the proliferation of numerous insect pests. The Wittig reaction and acetylene chemistry, bestowing *ca.* 95–97% of stereoisomeric purity, is preferentially used for the synthesis.[1] Exploitation of a pool of natural compounds suitable for the semi-synthetic preparation of the pheromone, *e.g.* fatty acids (FA) available from plants, is limited to a few examples, and the synthetic transformations employed are rather long.[2] The reason is that insects have developed unusual desaturases capable of forming carbon–carbon double bonds in the uncommon Δ11 position.[3] Further, the males' detection system is highly discriminatory for the position and geometry of double bonds.[1] Recently we were able to functionally express a Δ11Z desaturase from insects in a tobacco plant.[4] Plasmid pBI-DESTn bearing Pdest-Tn Δ^{11}Z encoding cabbage looper moth (*Trichoplusia ni*, Hübner, Lepidoptera, Noctuidae) acyl-CoA Δ^{11}-(Z)-desaturase[5] was transferred into *Agrobacterium tumefaciens* cells by electroporation and the obtained cells were used for transformation of the *Nicotiana tabacum*. The transgenic plant produces (Z11)-hexadec-11-en-1-olate derivatives at up to 6% of total fatty acids, which are very suitable precursors for semi-synthetic preparation of sex pheromones in a number of lepidopteran species.[6]

Here we report on the isolation of monoenic FA from transgenic tobacco[4] and their one-pot chemical transformation to an active sex pheromone, and the documentation of its effectiveness by field experiments.

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Results and discussion

A tobacco plant derived from the aseptic transgenic tobacco NtD15B line[7] was harvested after flowering and lipids were extracted with a chloroform–methanol mixture[4] providing 2.7 g (0.75% of the plant material) of crude lipids. A portion of the extracted lipids (1.3 g) was methanolyzed to form FA methyl esters (FAME), and filtered on a silica gel column, to afford 0.250 g of FAME (19% yield on starting lipids) containing methyl (Z11)-hexadec-11-en-1-oate [Z11–16:Me (**1**), 6.5%] (Fig. 1A). The target compound **1** was purified from this mixture, containing saturated, monoenic, dienic and trienic FAME using column chromatography on silica gel impregnated with 10% of $AgNO_3$. It afforded 23.3 mg (9.3%) of a mixture of monoenic FAME containing almost 50% of the required **1** (Fig. 1B and Table 1). While this mixture can be further purified by distillation to remove the methyl octadecenoates, we used this mixture for further experiments (see Scheme 1).

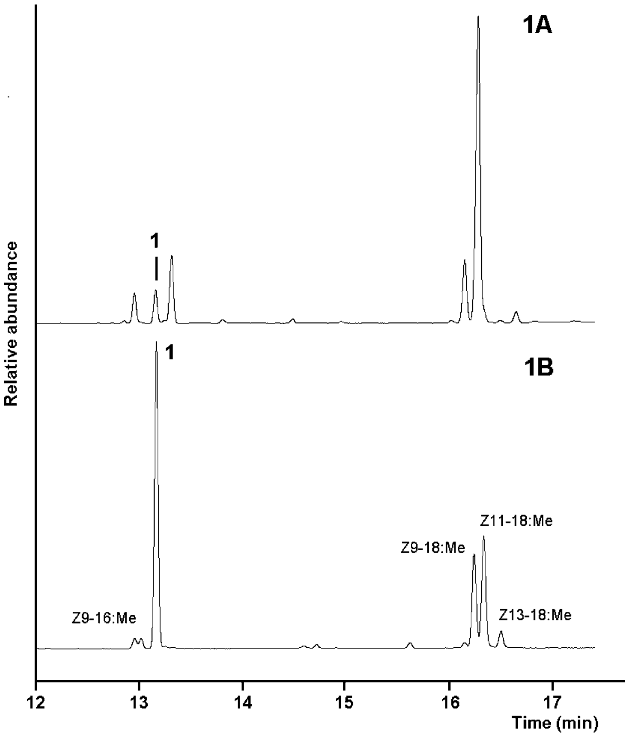

Fig. 1 A section of gas chromatograph traces obtained on an HP 5 phase for: **1A** FAME prepared from NtD15B a tobacco plant; **1B** monoenes isolated from this mixture using column chromatography on a silica gel impregnated with $AgNO_3$ (10%).

Table 1 Compositions of purified FAME and prepared acetates

Compound[a]	Z9–16	**2**	Z9–18	Z11–18	Z13–18	Others
:Me (%)	1.9	49.8[b]	17.9	21.1	3.4	5.9
:Ac (%)	1.9	48.6[b]	16.4	21.4	3.9	7.8

[a] Double bond positions were determined using acetonitrile chemical ionisation MS.[10] [b] E11 isomer was not detected (Carbowax 20M column).

In a one pot reaction we were able to prepare a mixture of monoenic acetates (containing 49% of (Z11)-hexadec-11-en-1-yl acetate **2**, Table 1) that was applied onto pheromone dispensers. By using alternative one-pot procedures, pheromonal aldehydes and alcohols can be easily produced as well.

The cabbage moth, *Mamestra brassicae* L. (Lepidoptera, Noctuidae), is an important pest found on vegetables in Europe. The efficacy of our semi-synthetic pheromone loaded dispensers to attract *M. brassicae* moth males was compared to those available commercially.[8] The field tests performed in the vicinity of two cabbage fields show the attractiveness of the semi-synthetic formulation for *M. brasiccae* males even at low population densities (Table 2).

Table 2 Catches of *M. brassicae* males in Delta traps baited with diverse lures

	Semice[a]	Mlékojedy[b]	
Lure	25.7.01–12.10.01	5.8.01–10.9.01	1.6.02–14.8.02
Semi-synthetic[c]	2/0[d]	3/0[d]	6/0[d]
MABR[9]	0/22[d]	4/7[d]	7/5[d]
Control	0/0[d]	0/0[d]	0/0[d]

[a] Central Bohemia, in the vicinity of Kostelec nad Labem. [b] Northern Bohemia, in the vicinity of Litomerice. [c] 2 mg of the acetate mixture in a PE vial. [d] *Ochropleura plecta* L. (Lepidoptera: Noctuidae, Noctuinae) male attracted (see ref. 12).

To our knowledge, this is the first synthesis of behaviourally active sex pheromone from fatty acids from a renewable plant material. It seems that "molecular farming" would have an economical advantage over the present synthetic procedures.[1] We are expecting that this strategy could be modified further to produce structurally more complex pheromones.

The advantage of the *N. tabacum* plant might be the availability of suitable cultivation, harvesting and processing technology. Then a slight modification of these processes might make our approach a viable alternative to normal chemical synthesis of pheromones.

The possibility that the transgenic plant will spontaneously produce sex pheromone components is now being tested. If a substantial production of sex pheromone *in planta* (in ng to μg amounts) can be realized, the potential use of such plants in an integrated pest management may be sought.

Experimental

Lipid extractions

The NtD15B plant, grown in a climatic chamber (Microclima 1000, Snijders, The Netherlands) operating at 10/14 L/D regimes, 24 °C, and 65% relative humidity, was harvested after flowering and the seeds capsules separated. The plant material (360 g, fresh weight) was homogenized, the slurry obtained extracted with chloroform–methanol mixture (2 : 1, 3 × 300 ml), and the resulting layers separated. The combined organic layers were concentrated at a reduced pressure (bath temperature max 35 °C) and the deep-green material (2.7 g) stored at −20 °C.

Basic methanolysis

Extracted lipids (1.3 g) were basically methanolyzed[9] using methanolic KOH solution (0.5 M, 15 ml) for 2 h, phosphate buffer was added (0.5 M, pH 7.1, 10 ml) and acidified with hydrochloric acid (1 : 3, *ca.* 25 ml) to pH 3. The opaque reaction mixture was extracted with hexane (for residual analysis, Merck, 3 × 15 ml) and the combined hexane extracts were passed thorough a pad consisting of Celite, magnesium sulfate and active carbon. Hexane was removed at reduced pressure providing crude mixture of fatty acids methyl esters (FAME, 0.60 g).

Preparation of monoenic FAME

Crude FAME mixture was purified on a column of silica gel impregnated with $AgNO_3$ (10 wt%) eluted with mixtures of ether in hexane with increased polarity (0–30%). The fraction containing monoenic FAME was separated yielding 21.3 mg of the material (for composition see Table 1).

Preparation of (Z11)-hexadec-11-en-1-yl acetate (2)

A solution of the fraction of monoenic FAME (21 mg, *ca.* 0.074 mmol) in dry ether (1 ml) was treated at 0 °C with lithium tetrahydridoaluminate (20 mg, 0.513 mmol) and the suspension obtained stirred at 20 °C for 1 h. The mixture was cooled in an ice bath, acetic anhydride was carefully added (2 × 50 μl) and the mixture was stirred at 20 °C for 40 min. The mixture was filtered and the solid residue extracted with ether (4 × 2 ml). The washes were combined with the filtrate and evaporated at reduced pressure to remove solvents and acetic anhydride. Chromatography on a short silica gel column provided a mixture of corresponding (Z11)-hexadec-11-en-1-yl acetate (18 mg, 86% yield). Spectral data for **2**: MS (70 eV): *m/z* (%): 282 (1) $[M^{+\cdot}]$, 222 (22) $[M^{+\cdot} - CH_3COOH]$, 166 (10), 152 (6), 138 (16), 124 (26) 110 (27), 96 (63), 82 (100) $[C_6H_{10}^+]$, 67 (90), 55 (50), 61 (7) $[CH_3COOH + H^+]$, 43 (51) $[CH_3CO^+]$. "In trap" acetonitrile CI-MS:[10] *m/z* (%): 336 (100) $[M^+ + 54]$, 294(5) $[M^+ + 54 - CH_3(CH_2)_3CH{=}CHCH_2]$), 152 (4) $[M^+ + 54 - CH_2CH{=}CH(CH_2)_{10}OCOCH_3]$. IR (gas phase):[11] ν (cm^{-1}): 3012 (Z H–C=C–H), 1761 (C=O), 1369 (CH_3–CO).

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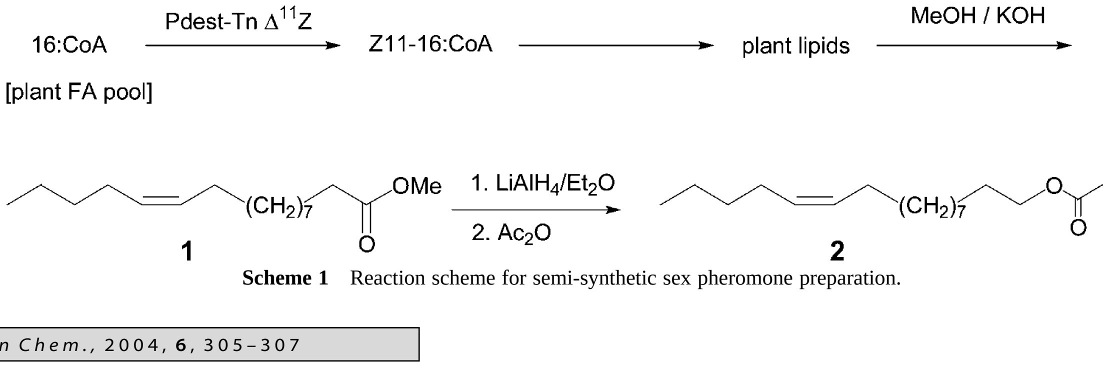

Scheme 1 Reaction scheme for semi-synthetic sex pheromone preparation.

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Sn-β molecular sieve catalysed Baeyer–Villiger oxidation in ionic liquid at room temperature

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Efficient oxidation of aryl ketones to esters at room temperature with 30% aqueous H_2O_2 and catalytic Sn-β-molecular sieve in ionic liquid was established.

Introduction

More than 100 years ago Baeyer and Villiger opened a new area to organic chemists by reporting the oxidation of ketone to ester, commonly known as Baeyer–Villiger oxidation.[1] Baeyer–Villiger oxidation is attractive for practical applications into building blocks for complex bioactive molecules. Traditionally this reaction is performed with peroxy acids as oxidant. This oxidation was made simpler by replacing traditionally used peroxyacids with hydrogen peroxide,[2] a cheaper and less polluting reagent. More benefits were expected from the catalytic version of this oxidation by minimizing reactant use and waste production. Efficient activation of ketone oxidation by hydrogen peroxide was achieved by employing dissolved platinum complexes,[3] zeolites,[4,5] and sulfonated resins.[6]

Recently Sn-β molecular sieve was reported as a potential heterogeneous catalyst for this oxidation in 1,4-dioxane at elevated temperature.[7] Excellent selectivity and yields of ester or lactones were described from saturated as well as unsaturated ketones. Corma and co-workers employed a concept that involves selective activation of a carbonyl group with a catalyst[7] which has been activated earlier by Lewis acids,[8,9] followed by reaction with hydrogen peroxide.

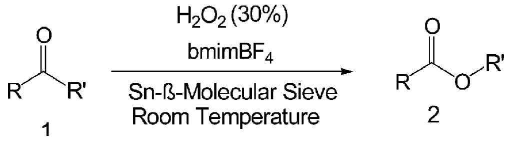
As a part of our ongoing programme to develop mild and efficient protocols for functional group transformation, we have undertaken a study on developing an efficient methodology for Baeyer–Villiger oxidation. Earlier we have communicated oxidation of 4-substituted 1,4-dihydropyridines to the corresponding pyridine at ambient temperature with hydrogen peroxide in ionic liquid.[10] In recent years the use of room temperature ionic liquids (ILs) as ‘green’ solvents in organic synthetic processes has gained considerable importance due to their solvating ability, negligible vapour pressure, easy recyclability and reusability.[11] Many reactions have been reported recently using ionic liquids as reaction media[12] and as rate enhancers.[13]

Recently Bernini[14] reported methyltrioxorenium catalysed Baeyer–Villiger oxidation in ionic liquid. In order to avoid the use of costlier methyltrioxorenium, we decided to develop an efficient and practical method for Baeyer–Villiger oxidation using Sn-β molecular sieve and hydrogen peroxide in ionic liquid.

Results and discussion

Herein, we wish to report an efficient oxidation method of ketones (**1**) to esters (**2**) with 30% aqueous hydrogen peroxide in 1-n-butyl-3-methyl-imidazolium tetrafluoroborate ([bmim][BF_4])[15] using catalytic Sn-β molecular sieve in excellent yields Scheme 1.

4-Methyl acetophenone (**1a**) on reaction with H_2O_2 (30%) in presence of a Sn-β molecular sieve[7] catalyst (20%) in ionic liquid [bmim][BF_4] at room temperature gave Baeyer–Villiger oxidation product (**2a**) in 88% yield in 10 hours. The workup procedure involved simple filtration of the catalyst and extraction of the product with ethyl acetate.



Scheme 1

4-Methyl acetophenone (**1a**) on reaction with H_2O_2 (30%) in presence of Sn-β molecular sieve catalyst (20%) in dioxane at room temperature remains unchanged. This “confirms” that the ionic liquid is essential for the transformation at room temperature. However, Corma reported the Baeyer–Villiger oxidation using Sn-β molecular sieve in dioxane at 80 °C.

Similarly it was also observed that 4-methyl acetophenone (**1a**) remains unchanged when treated with H_2O_2 (30%) at room temperature and 80 °C in presence of Ti-silicalite-1,[16] Sn-silicalite-1[17] and all-silica-β[18] in ionic liquid. This study “confirms” that the presence of the ionic liquid and Sn are critical for the Baeyer–Villiger oxidation (Table 1, entry 2–4).

Table 1 Feasibility of Baeyer–Villiger oxidation towards various catalysts, at room temperaure (rt) and 80 °C in ionic liquid

Entry	Ketone	Catalyst	Re-action time/h	Yield (%) at RT	Yield (%) at 80 °C
1.	**1a**	Sn-β molecular sieve	10	88	86
2.	**1a**	Sn-silicalite-1	10	—	—
3.	**1a**	Ti-silicalite-1	10	—	—
4.	**1a**	All-silica-β	10	—	—
5.	**1a**	All-silica-β-Sn impregnated	10	—	—

In order to examine whether the reaction occurs over the tetrahedral Sn-β framework or on the extra framework Sn in the form of SnO_2, Sn was impregnated on all-Si-β[19] and was used as a catalyst for the Baeyer–Villiger oxidation of 4-methyl acetophenone (**1a**) in ionic liquid at room temperature and 80 °C. It was observed that **1a** was unchanged. This observation confirms the presence of Sn in the β framework of the molecular sieve and not occluded as SnO_2 (Table 1, Entry 5)

Table 2 B-V oxidation of ketone (**1a–b**) to esters (**2a–b**) with recovered Sn-β molecular sieve and recovered ionic liquid [bmim][BF_4] at room temperature

				Yield (%)		
Entry	Ketone	Product	Time/h	Cycle I	Recycle I	Recycle II
1.	**1a**	**2a**	10	88	86	86
2.	**1b**	**2b**	10	83	81	80

Table 3 B-V oxidation of ketones (**1a–i**) with H_2O_2 (30%) and catalytic Sn-β molecular sieve to esters (**2a–i**) at room temperature in [bmim][BF_4]

	Compound **1**		Compound **2**			
Sr No	R	R′	R	R′	Yield (%)	Melting point/°C
a	CH_3	4-CH_3–C_6H_4	CH_3	4-CH_3–C_6H_4	88	Oil[21]
b	CH_3	4-OH–C_6H_4	CH_3	4-OH–C_6H_4	87	62[22]
c	CH_3	C_6H_5	CH_3	C_6H_5	72	Oil[21]
d	4-Cl–C_6H_4	CH_3	4-Cl–C_6H_4	CH_3	80	Oil[21]
e	2-Cl–C_6H_4	CH_3	2-Cl–C_6H_4	CH_3	77	Oil[21]
f	4-Cl–C_6H_4	C_6H_5	4-Cl–C_6H_4	C_6H_5	72	105[23]
g	4-Cl–C_6H_4	4-OH–C_6H_4	4-Cl–C_6H_4	4-OH–C_6H_4	76	117[24]
h	C_6H_5	4-OH–C_6H_4	C_6H_5	4-OH–C_6H_5	83	161[25]
i	CH_3	$PhCH_2$	CH_3	$PhCH_2$	81	Oil[21]

The catalyst as well as the ionic liquid which is responsible for bringing about the reaction, were recovered and reused for the reaction with identical results. Thus the recyclability of both was confirmed. (Table 2).

In order to prove the generality of the above protocol, a variety of aryl ketones (**1a–i**) were oxidized under identical conditions to esters (**2a–i**; Table 3) over 9–10 h. The results are in accordance with the reported migration trends of the R & R′ groups.[20]

Conclusion

In conclusion we have demonstrated an efficient and mild protocol for the oxidation of aryl ketones to esters at room temperature with 30% aqueous H_2O_2 and catalytic Sn-β molecular sieve in ionic liquid. Our protocol is in accordance with the ′atom economy′ and does not generate any by-products except water. The ionic liquid and catalyst are recyclable.

Experimental

Typical procedure for Baeyer–Villiger oxidation

Aqueous H_2O_2 (30%, 2.5 mL) was added to a mixture of 4-methyl acetophenone (**1a**, 0.500 g, 3.731 mmol), Sn-β molecular sieve (0.100 g, 20 wt%) and [bmim][BF_4] (1.0 g, 4.428 mmol) and stirred at room temperature for 10 hours. The progress of the reaction was monitored by TLC analysis. After the completion of the reaction, water (10 mL) was added. The catalyst Sn-β molecular sieve was recovered by a simple filtration on Whatman filter paper and dried at 120 °C for 2 h (0.087 g, 87%) and reused as such. The filtrate was extracted with ethyl acetate (3×10 mL). The organic layer was separated and washed with brine (2×4 mL), dried over anhydrous sodium sulfate, filtered and concentrated in a vacuum to obtain 4-methylphenyl acetate (**2a**, 0.492 g, 88%) as an oil. The aqueous layer was concentrated under reduced pressure to recover the ionic liquid (0.94 g, 94%) and reused as such.

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24 Melting point matches with the authentic **2g** prepared from *p*-chlorobenzoic acid and hydroquinone.
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COMMUNICATION

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Polymer-supported nitroxyl catalysts for selective oxidation of alcohols

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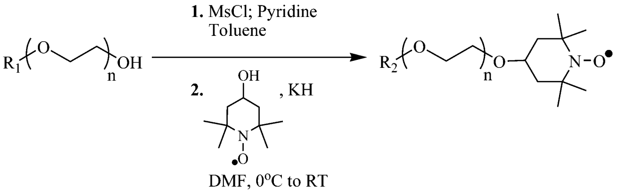
Novel non-toxic poly(ethylene glycol)-supported 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) moieties are demonstrated to give an excellent interfacial catalysis for the selective oxidation of alcohols to the corresponding carbonyl species in biphasic media and investigation for the recovery of these new macromolecular catalysts *via* precipitation with diethyl ether after catalysis has also been briefly studied.

The selective oxidation of primary and secondary alcohols into the corresponding aldehydes or carboxylic acids and ketones is undoubtedly one of the most important transformations in organic chemistry.[1] Reagents used normally for these oxidations such as chromium(VI) oxide salts are often toxic and their use thereby presents significant environmental issues. As a consequence, the development of catalytic systems of high atom efficiency based upon renewable clean oxidants such as oxygen, hydrogen peroxide or hypochlorite is preferred both in terms of environmental and economical perspectives.[2] Stable nitroxyl radicals of the 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) series are a class of interesting compounds[3] that present low toxicity[4] and an interesting reversible redox behaviour.[5] As a result of these properties, these reagents have received significant attention in recent years as selective catalysts for the metal free oxidation of alcohols.[2,5,6] For example, Anelli *et al.*[7] first described an oxidative catalyst system that was comprised of 4-methoxy-TEMPO (**catalyst A**) in combination with hypochlorite and bromide. This system has found a wide application in organic synthesis[8] as a consequence of its remarkable high activity (extremely large turnover number) and chemoselectivity that is not available with other catalytic systems. Although low catalyst concentrations are required (typically 1 mol%), product isolation and catalyst recovery remain key issues with this system.

Consequently, several solid supported TEMPO moieties have been described including silica-supported TEMPO,[9] MCM-41 supported TEMPO,[10] sol–gel entrapped TEMPO,[11] and polyamine immobilised piperidinyl oxyl (PIPO).[12] These catalysts were heterogeneous in nature and recovery consisted of simple filtration from the reaction medium.

Unlike heterogeneous supports, poly(ethylene glycol)s (PEGs) exhibit excellent solubility in a wide range of polar and non-polar solvents,[13] including dichloromethane and water – the solvents of choice in the biphasic oxidation protocol described by Anelli and co-workers.[7] In contrast to the heterogeneous catalysts (*vide supra*), the versatile solubility profile of PEGs can enhance greatly interfacial transport between the immiscible organic solvent and water. In addition, PEGs exhibit the propensity to form semi-crystalline phases leading to precipitation of the polymer. This induced precipitation can be achieved by either careful cooling of the solution or by dilution with an incompatible solvent, such as diethyl ether.[13] In addition to limited toxicity,[14] PEGs present varied end group chemistries[15] and interesting phase-transfer characteristics.[16] Furthermore, the commercial availability of PEGs possessing very narrow but defined polydispersity indices render these polymers interesting candidates as new supports for TEMPO catalysis in biphasic media (*i.e.* oxidation of water insoluble alcohols by NaClO/NaBr in water). Thus, we present an alternative approach to designing a recyclable TEMPO-type catalyst (see Scheme 1†). TEMPO species chemically tethered onto various PEG supports have therefore been carried out (see Table 1) and the investigation of the catalytic potential and recyclability is hereby described.‡



Scheme 1 Schematic representation of the synthesis of PEG-supported TEMPO catalysts.

Table 1 Resume of the polymer-supported catalysts prepared

Catalyst	M_w	R_1	R_2
B	164	CH_3^-	CH_3^-
C	2000	HO$^-$	TEMPO$^-$
D	5000	CH_3^-	CH_3^-
E	6000	HO$^-$	TEMPO$^-$
F	10000	HO$^-$	TEMPO$^-$

Fig. 1 shows a typical MALDI–TOF mass spectrum of the 6 kDa PEG-supported TEMPO (**E**) as compared to the untethered PEG. The mass shift of the spectrum corresponds to the gain of 308 amu (consistent with the addition of a TEMPO moiety per a reactive pendant group).

The selective oxidation of a range of model alcohols mediated by the polymer-supported catalysts **B–F** (see Table 1) compared to catalyst **A** (1 mol% nitroxyl content for all reactions) provided the activity profile for the proposed system and these results are summarised in Table 2. As anticipated, a slight decrease in activity was observed as the molecular weight of the polymeric support was increased. This observation can be explained by partial hindrance of the active site within the polymeric structure as a result of coiling of the PEG polymeric backbone. In contrast, in the case of unhindered alcohols (Table 2, entries 3 and 4) all of the catalysts

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† Catalyst synthesis: a series of linear PEG-supported TEMPO moieties have been prepared. Oligomeric and polymeric ethylene glycol supports with average molecular weights ranging from 164 Da to 10 kDa were converted to the corresponding mesylates, which were in turn displaced with the alkoxide of 4-hydroxy-TEMPO (Scheme 1) to afford a range of PEG-supported TEMPO catalysts (Table 1).

‡ During preparation of this manuscript a new paper was reported by Pozzi, Benaglia and co-workers that described a closely related approach to ours towards PEG-supported TEMPO catalyst. In their system a benzylic ether linker was used to chemically tether the TEMPO moieties to the polymeric backbone. (see ref. [17].)

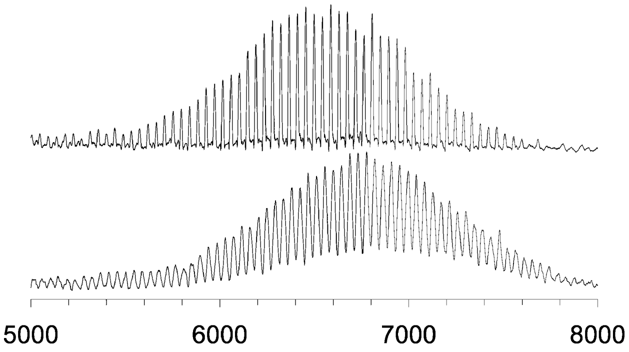

Fig. 1 MALDI–TOF mass spectra of untethered PEG_{6000} (top) and catalyst **E** (bottom).

Table 2 Oxidation of model alcohols by PEG-supported nitroxyl catalysts[a]

		Catalyst					
Entry	Substrate	A[b]	B	C	D	E	F
1	Cyclohexyl methanol	> 99	> 99	95	88	81	57
2	Benzyl alcohol	> 99	> 99	> 99	> 99	87	65
3	*trans*-Geraniol	> 99	> 99	> 99	> 99	96	97
4	1-Undecanol	> 99	> 99	> 99	97	99	> 99
5	2-Undecanol	86	80	49	66	53	51

[a] General oxidation procedure: to the alcohol (0.8 mmol in 1 mL of CH_2Cl_2), nitroxyl (0.008 mmol in 1 mL CH_2Cl_2) and NaBr (0.01 mmol in 0.16 mL of H_2O) were added at 0 °C, NaOCl (1.1 mmol in 2.0 mL of H_2O) and the reaction allowed to proceed under vigorous stirring for 5 min (primary alcohols) or 10 min (secondary alcohols). Crude mixtures were analysed by GC (*vs.* internal standard). Primary alcohols were found to yield aldehydes whereas secondary alcohols produced the corresponding ketones in > 99% selectivity. [b] 4-Methoxy-TEMPO.

afforded nearly complete conversion to the corresponding carbonyl compounds (*trans*-citral and undecanal, respectively) within 5 minutes. In the case of bulkier alcohols (Table 2, entries 1 and 2), the attenuation in activity was more pronounced but good yields of cyclohexanecarbaldehyde and benzaldehyde, respectively were obtained under the same experimental conditions. The slower rate associated with TEMPO mediated oxidation of secondary alcohols into ketones was also observed with these macromolecular catalyst systems (Table 2, entry 5).

Although there is a clear attenuation in activity of tethered catalysts towards the oxidation of activated alcohols (turnover frequency (TOF) of catalyst **F** = 0.218 s^{-1}) as compared to low molecular weight nitroxyls such as **A** (TOF = 0.333 s^{-1}), the polymer-supported catalysts, in general, retain most of the intrinsic high activity (Table 3). Thus, the polymer-supported TEMPO systems clearly demonstrate remarkably high oxidative activities (extremely large TOF) and more importantly high selectivities that are not generally available with other solid catalytic systems. It is also found that a slightly larger amount of catalyst can easily compensate for a moderate decrease in activity. This observation of the overall high activity was attributed to the efficient mixing of the organic soluble substrates (alcohols) and aqueous oxidants (NaOCl, NaBr) in presence of the macromolecular PEG catalysts at the interface, which thereby plays an active role in bringing the reagents into close proximity.

Table 3 Representative TOFs for a range of catalysts for the selective oxidation of alcohols[a]

Entry	Catalyst	Oxidant	Conv. (%)	Sel. (%)	in TOF ($\times 10^3$ s^{-1})
1	**A**	NaOCl	> 99	> 99	333[b]
2	**B**	NaOCl	> 99	> 99	333[b]
3	**C**	NaOCl	> 99	> 99	333[b]
4	**D**	NaOCl	> 99	> 99	333[b]
5	**E**	NaOCl	87	> 99	289[b]
6	**F**	NaOCl	65	> 99	218[b]

[a] All results were obtained for the oxidation of benzyl alcohol to benzaldehyde. [b] Initial TOFs obtained for the first 5 minutes of reaction.

The recyclability of the PEG-supported catalysts by means of precipitation was also briefly investigated. As predicted, low molecular weight PEGs afforded poor recovery yields by diethyl ether precipitation. However, careful control of the experimental conditions allowed for efficient recovery (in the case of PEGs with molecular weight in excess of 5 kDa *ca.* > 95%) of the catalyst. In particular, the high molecular weight catalyst **F** clearly facilitated efficient recoverability by solvent-induced precipitation. The oxidation of benzyl alcohol into benzaldehyde mediated by **F** was used to estimate the stability and recyclability of our system. The yield of benzaldehyde obtained in the first catalyst assay (70%) was in good agreement with results previously obtained in the activity studies (Table 3, entry 6). In the second assay (using the catalyst precipitate from the 1st assay), a pronounced reduction in catalytic activity was observed (Fig. 2) but no noticeable modification of catalyst structure (MALDI–TOF MS) was found post-catalysis. This phenomenon is not yet fully understood and is under further investigation. Nevertheless, factors such as the modification of the spatial orientation of the bulky PEG (affecting the accessibility to the TEMPO site) after its exposure to the catalyst mixture and/or precipitation conditions could account for the observed phenomena. However, after the initial drop in activity, subsequent cycles (2–5) provided consistent yields of benzaldehyde, which remained at 27 ± 5%. Thus, an average TOF of 0.1 s^{-1} was obtained for the runs 2–5 under recycling treatments. An average catalyst weight loss of ~ 2% was observed over the subsequent 4 cycles. This loss was attributed mainly to the mechanical loss of the catalyst during filtration, the extent of which may be further reduced through a careful filtration. Thus, the less active catalyst **F** appears to be stable under the reaction conditions by maintaining high selectivity and reasonable TOFs upon the repeated trials.

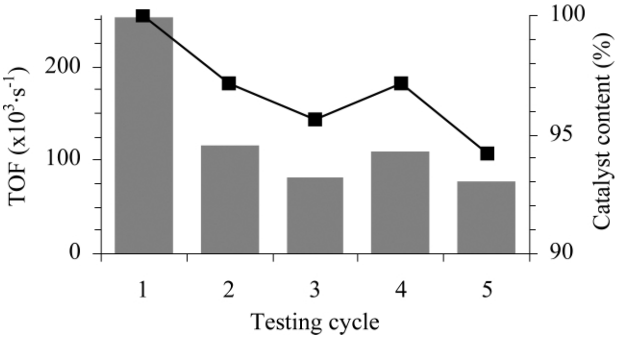

Fig. 2 Recyclability and catalytic activity studies of **F**.

In summary, a different approach to designing a recyclable TEMPO catalyst using non-toxic PEG macromolecular carriers for the selective oxidation of alcohols in biphasic solvent media is presently reported in this work. A brief study on the preparative methodology for the chemical tethering of TEMPO directly onto PEG molecules of different sizes, their characterisation, catalytic performance and recyclability has been initiated therein. Although the system at the present format (use of biphasic solvent system and chlorinated solvent, bromide salts, and solvent-induced precipitation) is not yet the cleanest approach regarding green synthesis it offers a new opportunity and a new concept for partial oxidation of organic molecules without the use of toxic metallic components. Replacement of cleaner reagents could be made possible in the future. Work is in progress to further address the recoverability and recyclability properties of these new catalysts.

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'Green' leaching: recyclable and selective leaching of gold-bearing ore in an ionic liquid

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The recovery of gold and silver from ore in an ionic liquid is reported for the first time. The 1-butyl-3-methyl-imidazolium hydrogen sulfate ionic liquid (bmim$^+$HSO$_4^-$) was employed, with iron(III) sulfate oxidant and thiourea added. Selective extraction of gold (≥85%) and silver (≥60%) from powdered ore (of dominantly chalcopyrite/pyrite/pyrrhotite/sphalerite mineralogy) was achieved at room temperature in 50 h, with other lower-value metals present in the ore (Cu, Zn, Pb, Fe) extracted to only low percentages. Gold extraction was similar to that achieved in aqueous H_2SO_4/thiourea/$Fe_2(SO_4)_3$, and silver extraction was significantly better. Moreover, the ionic liquid can be recycled following selective stripping of gold and silver on activated charcoal, with reuse in at least four successive treatments leading to neither ionic liquid degradation nor any loss in extraction efficiency.

Introduction

Ionic liquids have been identified as possible alternatives to traditional solvents in a wide variety of reaction processes, and in many cases ionic liquids have been shown to enhance the yield and selectivity of reactions.[1–3] Moreover, the non-flammability and negligible vapour pressure of ionic liquids are preferable to the high volatility and flammability associated with most organic solvents, and their stability at high temperatures is also of value. There has been recent interest in the electrodeposition of metals from ionic liquids but this has largely involved the air and moisture sensitive chloroaluminate ionic liquids.[4] Despite the interest in their application in organic reactions and in electrochemical processes, they do not appear to have been explored in any depth as mediums for leaching of ores.[5] This is in large part because ionic liquids are more expensive than traditional solvents, which is a major factor limiting their use in many commercial processes, particularly where large quantities of solvent are required. Seddon and co-workers have recently patented use of ionic liquids in the recovery of uranium and plutonium from spent nuclear fuel involving dissolution of the species into the ionic liquid and subsequent electrochemical recovery.[6] With more cost-effective ionic liquids under development, it is appropriate to examine their use in ore leaching, where there may be a potential role at least in recovery of high-value metals. Further, the ability of ionic liquids to be recycled in a process is of importance to their implementation in a commercial environment, and recyclability offers both cost and process benefits.

The effective extraction of metal ions from ore samples and the subsequent removal of these species from the leach liquor are of core importance in hydrometallurgy. The application of ionic liquids in solventometallurgical ore beneficiation may offer potential as environmentally sensitive media and alternatives to hydrometallurgical processes. In particular, the ionic liquid 1-butyl-3-methyl-imidazolium hydrogen sulfate (bmim$^+$HSO$_4^-$), formed in a facile reaction from the most prevalent and lowest cost inorganic acid,[7] is an attractive reagent. Currently, cyanide is used almost exclusively for the commercial hydrometallurgical extraction of gold and silver from ores and concentrates, but its toxicity and consequent environmental concerns are problematical. One solution to this issue has been to seek alternative leach chemicals. Thiourea has been recently examined as an alternative leaching agent, but only offers similar extraction capacity for gold and a lower capacity for silver.[8,9]

Here, we report the first study with an ionic liquid as the core of 'green' leach liquors, and the observation in the presence of bmim$^+$HSO$_4^-$ of significantly enhanced extraction of silver by thiourea and the same high yielding extraction of gold compared with an aqueous sulfuric acid liquor. Further, we demonstrate the ability of the bmim$^+$HSO$_4^-$ liquor to be recycled without decomposition or significant change in extraction outcome.

Experimental

The bmim$^+$HSO$_4^-$ was prepared as described.[7] The ionic liquid purity was gauged by ^{1}H NMR spectroscopy; samples employed were spectroscopically pure. Thiourea (reagent grade) was used without purification. All experiments were repeated in triplicate.

Leaching

A leach solution was prepared by dissolving thiourea (20 g kg^{-1} ore) in bmim$^+$HSO$_4^-$ (100 cm^3). This leach solution was stirred to dissolve the thiourea. The leach solution was added to the 45–106 μm fraction of powdered Perseverance Ore sample (25 g) and $Fe_2(SO_4)_3$ (0.5 g kg^{-1} ore) with a solid to liquid ratio of 1 : 4, capped and then tumbled end-over-end at 25 °C for 48 h. After leaching, the samples were then diluted 1 : 1 with milli-Q water and immediately centrifuged at 3000 rpm for several minutes. The leach liquor was then decanted and filtered using a 0.45 μm cellulose ester filter paper. A sample of the leach liquor was analysed by ICP-AES.

Recycling study

Leaching was carried out at 50 °C using the method described above. After filtration an aliquot of the leach liquor was analysed by ICP-AES. The remaining leach liquor was mixed with activated carbon and stirred overnight at ambient temperature. The activated carbon was removed by filtration and a sample of the ionic liquid was analysed by ICP-AES. The stripped leach solution was rotary evaporated at elevated temperature to remove the water and a sample was analysed by NMR.

The stripped leach solution was then reloaded with thiourea for use as the leach solution in the next cycle. The solution was cycled four times with volumes and masses reduced proportionally to allow for progressive diminution due to sampling for analyses. Transfer losses due to processing were very small, from monitoring mass in a cycle, and were not adjusted for.

Analysis

A Varian Liberty Series II Inductively Coupled Plasma Atomic Emission Spectrophotometer was used for the analysis. The leach solutions were analysed for the following elements: gold, silver, copper, iron, lead and zinc, after the leaching and stripping

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processes. The approach to ICP-AES analysis of solutions rich in ionic liquids has been described recently.[7]

Analysis of the ionic liquid by NMR was performed using a Bruker Avance DPX-300 spectrometer. ^{1}H and ^{13}C spectra were recorded for samples diluted in D_2O.

Results and discussion

There have been a number of non-aqueous solvent-based processes for the treatment of ores and concentrates reported,[10] but these processes centre on traditional organic solvents, with concomitant environmental concerns. The non-volatile and relatively benign ionic liquids offer a potentially more acceptable alternative to other solventometallurgical processes. Moreover, the observation of different chemistry in reactions performed in these solvents suggests that the formation and stability of metal complexes in ionic liquids may differ from those in aqueous solution. This may benefit the process of selective metal extraction. The observation that ionic liquids can exist with the common HSO_4^- ion, and a recognition that sulfuric acid and sulfates are commonly met in industrial processes, prompted us to pursue an examination of ionic liquids as media for metal ion extraction from ores. In this first study, we concentrated on examining a gold-bearing ore from the Perseverance mine of the Peak Gold Mine Pty Ltd in New South Wales, Australia. This is a complex ore with chalcopyrite, pyrite, pyrrhotite and sphalerite as the chief minerals. It contains Au (5.65 g t^{-1}) and Ag (18.72 g t^{-1}), in addition to Cu (1.52%), Zn (0.08%) and Pb (0.36%) as well as, of course, Fe (9.22%) and low levels of other metals. It presents a demanding task for both effective and selective extraction.

The effective extraction of gold and silver from the Perseverance ore is achieved using $bmim^+HSO_4^-$/thiourea/$Fe_2(SO_4)_3$ leaching in a high (1 : 4) solid to liquid ratio. As illustrated in Fig. 1, for the extraction of gold, an equivalent extraction is achieved for the $bmim^+HSO_4^-$ leaching system (86% extraction) compared with the aqueous system (85% extraction). This outcome is also achieved for the ionic liquid without the addition of sulfuric acid. However, the rate of extraction of gold into the $bmim^+HSO_4^-$ leach liquor is reduced somewhat, presumably due to reduced mixing of the sample as a result of the high viscosity of the ionic liquid at room temperature. For silver, the aqueous system gives a very poor result with a maximum extraction of less than 20%. The concentration of silver in the aqueous system reaches a maximum before slowly decreasing over time, as was also noted by Bruckard *et al*[8] and indicates the precipitation of an insoluble silver species. The $bmim^+HSO_4^-$ leaching system proved to be more promising for the recovery of silver from the Perseverance ore, with high selectivity for silver giving a 60% extraction at 50 hours. Also, no decrease in the concentration of silver was observed during the extraction time frame.

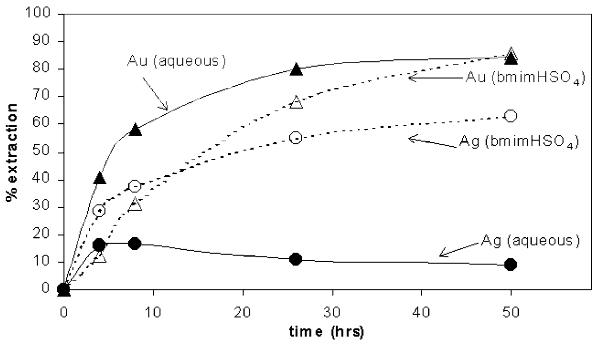

Fig. 1 Comparative leaching of gold and silver from ore using aqueous H_2SO_4 or $bmim^+HSO_4^-$ in the presence of Fe(III) and thiourea.

The uptake of copper, lead and zinc into the leach liquor is limited to a few percent of the total metal species present in the ore. A high concentration of iron (~ 5000 mg l^{-1}) is found in the leach liquor due to its initial addition as a soluble salt and some dissolution of pyrite and chalcopyrite; however, this is still limited to < 30% of the total iron present in the ore.

The ability of the $bmim^+HSO_4^-$ ionic liquid to be recycled was demonstrated by cycling the same leach solution four times and monitoring the concentration of metal species in the ionic liquid after the leaching and stripping stages of each cycle. Ideally, for $bmim^+HSO_4^-$ to be recyclable in the leaching process the metal must be effectively extracted from the ore and then removed without destruction of the ionic liquid. For the elements gold, silver and copper the concentration of each of the metals extracted during each leaching cycle remains relatively constant throughout the four cycles with minor variations attributed to the differences in ore composition. This is illustrated for gold in Fig. 2. The recyclable nature of the process for gold over four cycles is shown in Fig. 3, with an increase in metal concentration after the leaching stage and the effective removal of the metal in the stripping stage of the process starkly illustrated. The process of stripping the leach liquor with activated carbon was similar to that used by Ubaldini *et al.*[9] and was not optimised for this process. Subsequently, the concentration of metal ion remaining in the leach solution after the stripping process gradually increases after each cycle. However, the majority (> 75%) of the metal was successfully removed in each cycle.

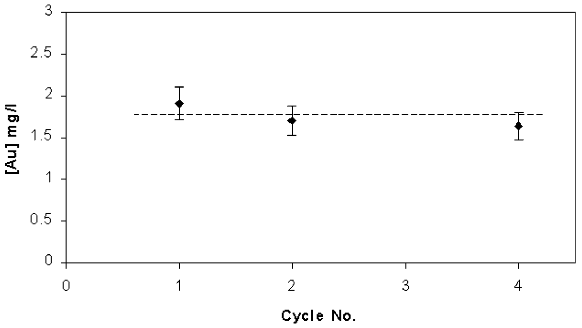

Fig. 2 Recovery of gold in successive cycles using recycled $bmim^+HSO_4^-$ ionic liquid.

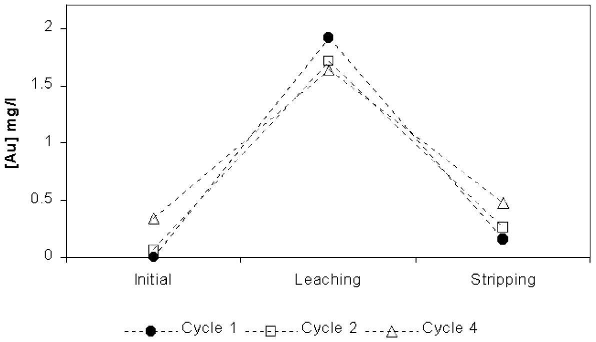

Fig. 3 Variation in gold concentration in the $bmim^+HSO_4^-$ ionic liquid determined prior to leaching (left), following leaching (centre) and following stripping with carbon (right), shown for several cycles.

Significant selectivity of the thiourea system for silver over base metals is observed even after four leach cycles. A comparison of the percentage extraction of silver compared with copper and lead, the two metals present in greatest amount after iron, is shown in Fig. 4. The latter metals are extracted to only small percentages. Whereas this may be anticipated for lead due to low solubility of its sulfate, this is not a restriction for copper. The presence of a range of metals in the complex ore does not impinge on both gold and silver uptake.

The concentration of iron in leach liquor was observed to increase during leaching and was not removed in the stripping process. An approximately linear increase in concentration is observed during the first two cycles. However, after four cycles the amount of iron being leached per cycle was lower, which can be

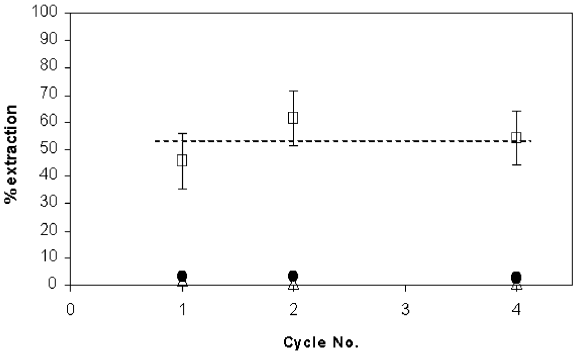

Fig. 4 % Extraction of silver (□), copper (●) and lead (Δ) in successive cycles using recycled bmim$^+$HSO$_4^-$ ionic liquid.

attributed to the concentration of iron in the leach liquor approaching its saturation limit. Notably, the high concentration of iron in the solution was not observed to hinder the extraction of the gold and silver from the ore.

The uptake of lead into the leach liquor, while minor, was observed to further decrease after each successive cycle, which is attributed to slow formation and precipitation of $PbSO_4$. The increase in sulfate concentration from pyrite oxidation in the leach liquor may assist in the precipitation of lead as lead sulfate. The concentration of zinc in the leach liquor is also limited by the solvent environment, reaching a maximum before decreasing in the fourth cycle. The carbon stripping of the low solvent loadings of lead and zinc from the leach liquor is not effective with $< 50\%$ of the lead and $< 60\%$ of the zinc being removed by this process. However, conditions required (*e.g.* carbon load, temperature) had not been optimised for their removal, nor is their optimised recovery a core issue.

Under the relatively mild conditions employed, reagent integrity is not severely compromised. The consumption of thiourea can be monitored by observation of the thiourea peak in the ^{13}C NMR spectrum. This peak was observed after every cycle, with no other soluble degradation products noted, indicating that all of the thiourea had not been consumed.

The thermal degradation of ionic liquids has recently been probed[11] with emphasis on the practical stability of the ionic liquids at elevated temperatures and for extended time periods. The stability of bmim$^+$HSO$_4^-$ was monitored by NMR spectrometry after each cycle. Even when the bmim$^+$HSO$_4^-$ was heated to 50 °C for 48 h in each cycle no decomposition products were observed in the ^{1}H or ^{13}C spectrum. No changes in the bmim$^+$HSO$_4^-$ spectrum were observed except for a slight broadening of peaks caused by the presence of small amounts of paramagnetic ions remaining in the sample. The bmim$^+$HSO$_4^-$ ionic liquid provides a robust anion that is not subject to decomposition as has been observed with the fluorinated anions[12] such as BF_4^- and PF_6^-, which undergo hydrolysis reactions to produce HF, a reaction that appears to be catalysed in the presence of an ore surface.

In conclusion, the bmim$^+$HSO$_4^-$/thiourea/$Fe_2(SO_4)_3$ leaching of a gold-bearing ore was observed to have both a high recovery and a high selectivity for the extraction of gold and silver, with the minimal uptake of other metallic species. Silver recovery was enhanced significantly compared with aqueous processing. The process is recyclable over at least four cycles, with no loss in the extraction efficiency of gold and silver and no degradation of the ionic liquid. The recyclable and selective nature of this process points to a potential 'green' role for the bmim$^+$HSO$_4^-$ ionic liquid in the recovery of precious metals.

Acknowledgements

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Deep desulfurization of oil refinery streams by extraction with ionic liquids

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Extraction of S- and N-compounds from gasoline and diesel oil by ionic liquids (ILs) indicates that such a process could be an alternative to common hydrodesulfurization (HDS) for deep desulfurization down to values of 10 ppm S or even lower. The results show the selective extraction properties of ILs, especially with regard to those S-compounds which are hard to remove by HDS, *e.g.* dibenzothiophene derivatives present in middle distillates like diesel oil. The application of mild process conditions (ambient pressure and temperature) and the fact that no hydrogen is needed, are additional advantages compared to HDS. Very promising ILs are [BMIM][$OcSO_4$] and [EMIM][$EtSO_4$], as they are halogen-free and available from relatively cheap starting materials. Extraction with ILs is not limited to diesel oil, but probably even more attractive for FCC-gasoline. Although HDS of S-species present in this gasoline constituent – mainly thiophenes – is relatively straightforward, a major drawback is the loss in octane number by olefin saturation, which favours extraction with ILs.

Introduction

During the last three decades much attention has been given to the desulfurization of fuels like diesel oil and gasoline since exhaust gases containing SO_x are a major cause of air pollution and acid rain. As a result the sulfur-limit for transportation fuels has been gradually decreased, *e.g.* in Germany for diesel fuel from 5000 ppm in 1975 to 350 ppm nowadays (ppm = mg kg^{-1}). Due to these restrictions, SO_2-emissions from transportation fuels contribute less than 5% to the total SO_2-emissions in many industrialized countries. Nevertheless, the S-limit will be tightened in 2005 in Europe, Japan and the USA for gasoline down to 30 ppm; in the case of diesel oil, the limit will then be 50 ppm (USA: 15 ppm in 2006). Due to tax incentives, in some countries (*e.g.* Sweden, Germany) the majority of fuels will then even be "S-free" (by definition < 10 ppm).

These additional restrictions mainly aim at the further reduction of CO, NO_x, and particulates: (1) Modern gasoline lean burn engines need $DeNO_x$-storage catalysts, which require ultra-low sulfur fuels. Any sulfur decreases the catalyst′s life-time, and the regeneration cycles are too frequent, which could nullify the better efficiency of such engines.[1] (2) In the case of diesel engines particulates need to be reduced further, which can be achieved with S-sensitive catalysts. (3) For fuel-cells (automotive and stationary systems) liquid fuels like gasoline or diesel oil will still be important as sources for fuel gas (H_2), at least for bringing such systems onto the market. Then fuels with less than 1 ppm S are needed.

So by 2010, the S-content both for gasoline and diesel oil will probably have reached an average value of about 10 ppm in many countries. This means that the degree of S-conversion needed to meet this limit is 99.9%, if a typical S-content of crude oil of 1 wt% is taken as basis.[2]

Current technology for desulfurization of fuels

State of the art in desulfurization technology is hydrodesulfurization (HDS). In this process the organic S-compounds are converted to H_2S and the corresponding hydrocarbons principally using catalysts based on CoMo or NiMo. Typical reaction conditions are 350 °C and 30 to 100 bar hydrogen pressure, requiring high pressure reactors and vessels *etc.*, and thus high investment costs. H_2S, which is separated from the desulfurized oil, is subsequently converted by catalytic oxidation with air into elemental sulfur. Hydrogen, which is fed into the HDS-reactor together with preheated oil is only consumed to a small extent in the trickle bed reactor, and is therefore recycled into the reactor after separation from the desulfurized oil. Recycle-rates of up to 50 are needed,[3] which results in high (re)compression costs.

The reactivity of sulfur compounds for HDS strongly depends on the molecular structure. Typical S-compounds that are found in transportation fuels are shown in Fig. 1. While paraffinic compounds like thiols (**1**), thioethers (**2**) and disulfides (**3**) are readily converted, cyclic and especially aromatic sulfur compounds like thiophene (**4**) or benzothiophene (BT, **5**) are less reactive for HDS.[4] Particularly refractory are dibenzothiophene (DBT) (**6**), methyldibenzothiophenes (MDBT) (**7**) and above all 4,6-dibenzothiophene (4,6-DMDBT) (**8**) (and similar multiple alkylated S-compounds). The rate of conversion of the DBT species (**6**)–(**8**) by HDS decreases in the named order by factors of about 2 and 10 respectively.[4] In other words, the rate of HDS superproportionally decreases with increasing degree of desulfurization because the remaining S-compounds, mostly sterically demanding DBT-derivatives, are much less reactive to HDS.

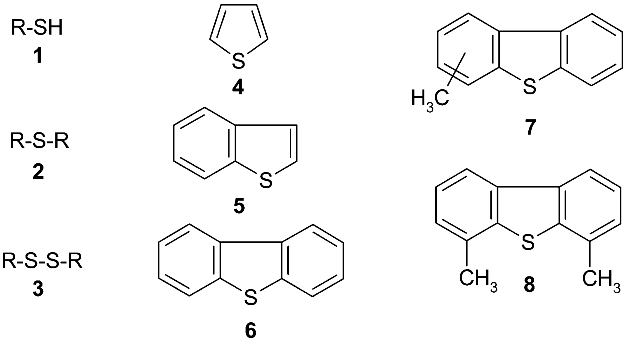

Fig. 1 Typical organosulfur compounds in transportation fuels.

So conventional HDS-technology is limited or at least expensive for deep desulfurization, and ultra-low sulfur specifications for diesel oil (and other middle distillates like fuel oil) can only be met

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by severe reaction conditions with respect to pressure and residence time.

In the case of gasoline, a S-limit of less than 10 ppm can only be reached by deep desulfurization of all gasoline streams including naphtha from fluid catalytic cracking (FCC), which is nowadays the main S-source in the gasoline pool. In principle, S-species in FCC-gasoline – mainly thiophene derivatives – are easy to convert by HDS, *e.g.* the rate to convert thiophene (**4** in Fig. 1) on CoMo is a factor of about 20 higher than the rate to convert DBT (**6**).[5] However, the simultaneous hydrogenation of olefinic compounds leads to an unwanted loss of octane number, which makes alternative (non-hydrotreating) technologies highly attractive.

Alternative processes for deep desulfurization

In order to improve the current HDS-technology, particularly with respect to the production of ultra-low sulfur fuels, the focus of research is a better reactor design and the development of better catalysts: (1) The efficiency of trickle bed reactors frequently used for HDS of diesel and heating oil or higher boiling oil fractions can be improved by an optimized gas–liquid distribution. (2) Trickle bed reactors are equipped with an expensive H_2-recycle, although the H_2-supply is far beyond the amount chemically consumed, at least for deep HDS of an already hydrotreated feed. (3) New catalysts based on noble metals have been developed, which are at least S-resistant for S-contents < 100 ppm and therefore applicable for deep desulfurization.[6]

Alternative desulfurization processes are therefore desirable, if possible without the need of hydrogen, high pressure and/or high temperature.

In addition to desulfurization, the denitrogenation of refinery streams is also of interest, as N-compounds (above all basic N-compounds like quinolines and acridines) strongly inhibit the HDS-reaction.[7] Alternative concepts discussed in the literature are adsorption[8] and (focus of this work) selective extraction[9–13] and even more unconventional methods like biodesulfurization.[14] Extractive desulfurization is another alternative concept that is carried out at or around ambient temperature and pressure and without the need for hydrogen.[9–13] In general, an ideal extracting agent should have the following properties: (1) The partition coefficient for S-compounds (ratio of S-concentration in the extracting agent to the one in the oil), above all for dibenzothiophene-derivatives, should be high (but not too high if the extracting agent has to be regenerated by reextraction with suitable hydrocarbons, see below). (2) The regeneration should be easy, *e.g.* by distillation, or at least the extraction should be reversible. (3) The agent should be absolutely insoluble in oil. (4) The (S-free) hydrocarbons of the oil matrix should not, or only to a small extent, be soluble in the extracting agent. (5) The agent should feature a high thermal and chemical stability, be non-toxic and environmentally benign.

Ideal candidates for this application are ionic liquids (ILs), which are low melting salts (< 100 °C) with no measurable vapour pressure, and represent a relatively new class of solvents and extracting agents. Research activities on ILs mostly center on the use of ILs in biphasic homogeneous catalysis, but the use of ILs for liquid–liquid extraction, *e.g.* of metals from aqueous systems[15] or of benzene derivatives from water,[16] is also described in the literature. As shown in this paper, ILs also have excellent extraction properties for organic S- and N-compounds and are – if chosen carefully – insoluble in oil. The basic concept of such an extraction process is outlined in Fig. 2.

As a contribution to a better general understanding of extraction of polar compounds by ILs as well as to determine the basic parameters of a technical extraction process for deep desulfurization, the following investigations – presented and discussed in this paper – were done: (1) Suitable ILs as extracting agents were identified by screening experiments with model diesel oil. (2) Selected ILs were then used to study the influence of different S-compounds, the IL to oil ratio, and of the level of S-concentration (multi-step extraction). The possible extension of extractive IL-desulfurization to other refinery streams was also tested by a model cracking gasoline. (3) During the course of these experiments the "cross-solubility" of hydrocarbons, and, *vice versa*, the absolute unwanted "contamination" of the desulfurized oil with IL were also investigated. (4) Extraction experiments were then also done with selected organic N-compounds. (5) In addition to the fundamental experiments with model oils, the desulfurization of real FCC-gasoline and diesel oil was also investigated with selected ILs. (6) With respect to a continuous extraction process (Fig. 2), the regeneration of S-loaded ILs was studied. (7) The continuous operation of the extraction was tested in a two-step mixer–settler miniplant. (8) Finally, strategies for integration of an IL-extraction process into the existing refinery structure are briefly discussed.

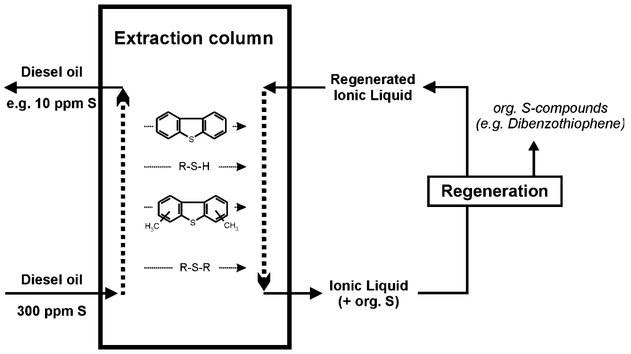

Fig. 2 Concept of deep desulfurization of refinery streams by extraction with ILs.

Results and discussion

Unless otherwise stated, the data were obtained by experiments in Schlenk tubes. Before and after extraction, the oil phases were analyzed with respect to the S- and N-content. The N-content of the oil (during the extraction experiments with S-compounds) is an important parameter to rule out a possible oil contamination by the (N-containing) imidazolium-based ILs used in this work. Details of the experimental procedure and data analysis are given at the end of this paper.

IL-screening: sulfur removal from model diesel oil

Early experiments on the selective extraction of S-compounds from model diesel oil (mixture of *n*-dodecane with DBT-derivatives) using chloroaluminate ILs like [BMIM][$AlCl_4$] showed promising results.[10–12] *i.e.* a high Nernst partition coefficient K_N (Table 1), which is defined in this work as the ratio of the concentration of sulfur in the IL ($mg_S\ kg_{IL}^{-1}$) to the S-concentration in the oil ($mg_S\ kg_{oil}^{-1}$). Nevertheless, the use of chlorometallate ILs is not desired for technical large scale applications due to their very limited hydrolysis stability and in some cases toxicity. Further screening experiments with alkylimidazolium tetrafluoroborate ([BMIM][BF_4]) and hexafluorophosphate ILs ([BMIM][PF_6]) were found to also have fairly high partition coefficients for model S-

Table 1 Sulfur partition coefficients K_N for extraction with ILs

IL	K_N in mg(S) kg(IL)$^{-1}$/ mg(S) kg(oil)$^{-1a}$
[BMIM]Cl/$AlCl_3$	4.0
[BMIM][BF_4]	0.7
[BMIM][PF_6]	0.9^b
[BMIM][$OcSO_4$]	1.9
[EMIM][$EtSO_4$]	0.8
[MMIM][Me_2PO_4]	0.7

^{a} Model oil: 500 ppm S as DBT in *n*-dodecane; mass ratio 1 : 1, mixing time 15 min, room temperature. ^{b} 60 °C.

compounds (see Table 1), which is consistent with data reported in the literature.[11,17,18] Although ILs of this type are significantly more stable to hydrolysis, their use as a large scale extracting agent is not optimal because of the relatively high price of the starting material. Additionally the formation of hydrolysis products – especially HF – is observed at elevated temperatures and in the presence of water.[19,20]

To avoid these stability and corrosion problems the present work concentrated on completely halogen-free ILs for the extraction of S- and N-compounds. Very promising ILs are 1-*n*-butyl-3-methylimidazolium octylsulfate ([BMIM][$OcSO_4$]), 1-ethyl-3-methyl-imidazolium ethylsulfate [EMIM][$EtSO_4$], and 1,3-dimethyl-imidazolium dimethylphosphate ([MMIM][Me_2PO_4]), Table 1. These ILs are not only halogen-free, but are also readily accessible from cheap starting materials, which are available on a large scale: sodium octylsulfate is used as a detergent, dialkylsulfates are already used as an alkylating agent on a larger scale. At first glance it might look inconsistent to use S-containing ILs for desulfurization. But any leaching of IL into the oil phase is unwanted anyway and a critical criterion for the selection of a suitable IL, which means the composition of the extracting agent is of no importance in this aspect.

Influence of S-species and S-concentration on extraction with halogen-free ILs

Table 2 shows the partition coefficients for selected S-compounds typically found in diesel oil and gasoline, thereby taking pure hydrocarbons and [BMIM][$OcSO_4$] as a model extraction system.

Table 2 Sulfur partition coefficients K_N for extraction of individual S-compounds with [BMIM][$OcSO_4$]

S-Compound	K_N in mg(S) kg(IL)$^{-1}$/ mg(S) kg(oil)$^{-1}$
Dodecanethiol[a]	0.1
Tetrahydrothiophene[a]	0.4
Thiophene[a]	0.7
BT[b]	1.6
DBT[b]	1.9
4-MDBT[b]	1.3
4,6-DMDBT[b]	0.9

[a] Model oil: individual S-compound in *i*-octane/*1*-octene, mass ratio oil : IL = 1 : 1, reaction time 15 min, room temperature. [b] Model oil: individual S-compound in *n*-dodecane, mass ratio oil : IL = 1 : 1, mixing time 15 min, room temperature.

The most likely mechanisms for the extraction of S-compounds with non-Lewis-acidic ILs are the formation of liquid-clathrates and π–π-interactions between aromatic structures of the extraction-target and the imidazolium ring system.[21] The relatively low distribution coefficients for thiols, sulfides and similar species are of no relevance in the case of the deep desulfurization of diesel oil and FCC-naphtha, as these compounds are virtually non existent in pre-desulfurized diesel oil and only in a very limited amount in FCC-gasoline.

The distribution coefficients for the extraction of DBT, 4-MDBT and 4,6-DMDBT (in *n*-dodecane) by [BMIM][$OcSO_4$] are given in Tables 2 and 3 for the extraction of the individual S-compounds and in addition for the simultaneous extraction of all three DBT-derivatives, respectively. Fortunately the K_N-values are in both cases virtually identical, which was proven in the case of the mixture of the three S-species by respective experiments using a gas chromatograph with a S-selective detector. So extraction is only to a small extent influenced by the degree of alkylation of the DBT-derivatives, which is a major advantage compared to HDS, where sterically demanding, alkylated DBTs have a much lower reactivity.[4]

Fig. 3 shows the influence of the IL to oil ratio on desulfurization in a multistage (cross-current) extraction (experimentally determined by stepwise extraction with fresh IL in Schlenk tubes). The logarithmic plot (straight line of log c_S *vs.* number of extraction steps) indicates that the extraction is controlled by a constant distribution coefficient according to Nernst's law. As expected in this case, the degree of desulfurization increases proportionally with increasing IL to oil ratio. The extraction is also reversible, as shown by reextraction experiments with pure *n*-dodecane, where the same distribution coefficients were found.

Table 3 Sulfur partition coefficients K_N for simultaneous extraction of DBT-derivatives with [BMIM][$OcSO_4$][a]

S-Compound	K_N in mg(S) kg(IL)$^{-1}$/ mg(S) kg(oil)$^{-1}$
DBT	1.9
4-MDBT	1.2
4,6-DMDBT	0.8

[a] Model oil: DBT, MDBT, and DMDBT (100 ppm S each) in *n*-dodecane, mass ratio oil : IL = 1 : 1, mixing time 15 min, room temperature.

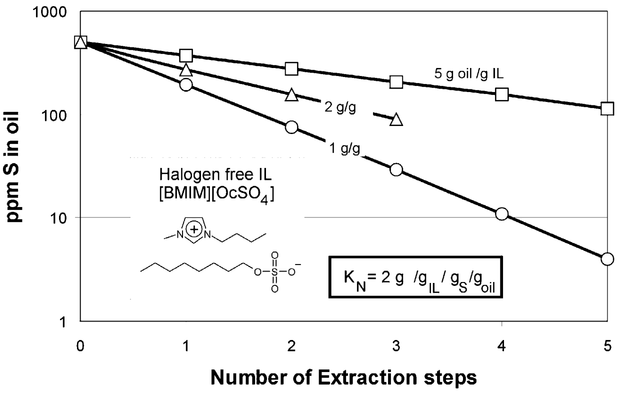

Fig. 3 Influence of the oil to IL mass ratio for cross-current extraction of a model oil (500 ppm S as DBT in *n*-dodecane; IL : [BMIM][$OcSO_4$], room temperature).

Cross-solubility of oil in the IL and *vice versa*

One drawback of [BMIM][$OcSO_4$] is the "cross-solubility" of hydrocarbons, *i.e.* in addition to the extraction target (S-compound) a small amount of the oil matrix is coextracted. Table 4 (left side) shows solubility data for typical hydrocarbons, determined by experiments with a one-to-one mixture (g/g) of the respective pure hydrocarbon and [BMIM][$OcSO_4$]. Pure aromatics like methylnaphthaline are completely miscible with [BMIM][$OcSO_4$], but only partly solved in [EMIM][$EtSO_4$], which probably reflects the influence of the longer hydrocarbon chain both in the anion and cation.

Table 4 Cross-solubility of pure hydrocarbons in ionic liquids (room temperature)

	Solubility in wt%	
Compound	[BMIM][$OcSO_4$]	[EMIM][$EtSO_4$]
n-Dodecane	4.0	1.0
Cyclohexane	40.0	2.5
i-Octane	13.0	1.9
1-Octene	22.0	2.8
1-Methylnaphthaline	∞ (monophasic)	22.0

So with respect to the extractive desulfurization of diesel oil with a content of up to 25% aromatics, the triangular diagram of the system "*n*-dodecane, methylnaphthaline and [BMIM][$OcSO_4$]" is instructive (Fig. 4): for a content of methylnaphthaline of less than about 50% (in the oil phase), a biphasic system is established by IL-addition, at least for an IL-content of less than about 90% in the mixture. Within the biphasic area, which is an absolute must for

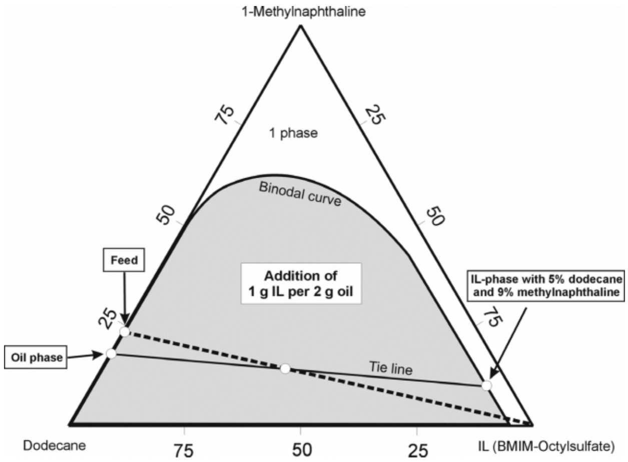

Fig. 4 Cross-solubility of hydrocarbons in [BMIM][$OcSO_4$].

extraction, an IL-rich phase and an IL-free oil phase are established. The IL-rich phase contains both the paraffinic and the aromatic hydrocarbon to a relatively small extent, whereby the extraction selectivity for the latter is higher.

Keeping this phase behaviour in mind, the triangular diagram of the S-containing system "oil–DBT–[BMIM][$OcSO_4$]" is now easy to understand, which is depicted in Fig. 5 for a representative diesel oil matrix (Fluka white spirit, 18% aromatics, rest paraffins, boiling range 180 to 220 °C). For clearness, only the relevant cut-out up to a S-content of 750 ppm is taken into account (lower part of Fig. 5). The result of a single step extraction, which is plotted in Fig. 5 based on an experiment with an IL to oil ratio of (only) 0.5, indicates the strong decrease of the S-content of the oil (P1 in Fig. 5). The cross-solubility of oil in the IL (P2 in Fig. 5) in this system is only 5% (compared to the model system shown in Fig. 4 with about 14%), and is practically independent of the oil to IL ratio used for the extraction. So in case of a high ratio of oil to IL, the portion of the oil transferred into the IL would be small, *e.g.* in the case shown in Fig. 5 only about 2.5%.

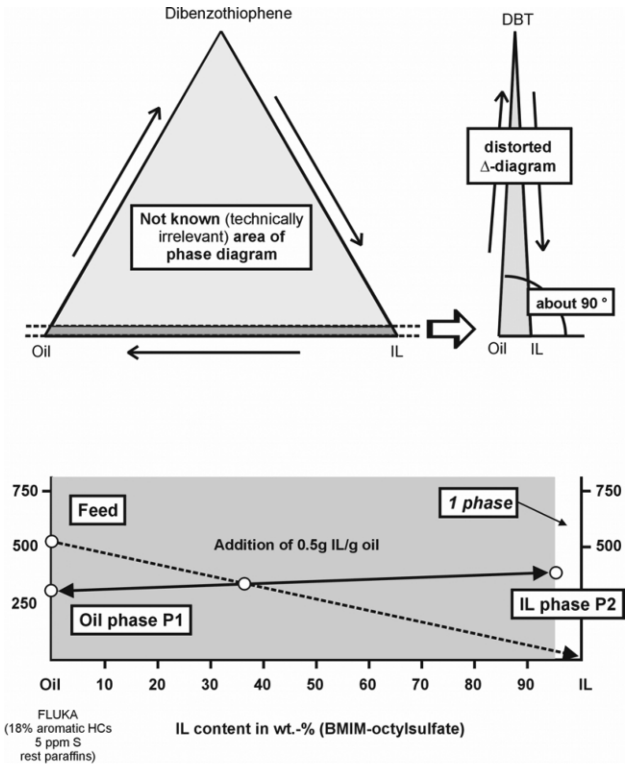

Fig. 5 Triangular diagram (cut-out) of the system oil–DBT–[BMIM][$OcSO_4$].

Nevertheless, the cross-solubility of hydrocarbons in the IL is an unwanted effect, as the coextracted hydrocarbons will have to be separated from the IL together with the S-compounds during IL-regeneration by distillation or reextraction. So a high cross-solubility will lead to a loss of oil or at least to an increase of process costs. For a technical application of extractive desulfurization no or only a small cross-solubility of oil in IL is desirable. As shown in Table 4, a promising IL with a significantly lower cross-solubility than [BMIM][$OcSO_4$] is [EMIM][$EtSO_4$], which is also available from relative cheap starting materials. The distribution coefficient for S-compounds is by a factor of about two lower than that for [BMIM][$OcSO_4$] (Table 1), but the cross-solubility is – depending on the hydrocarbon – by a factor of 4 to 16 lower (Table 4). So this extracting agent is therefore probably better for a technical extraction process.

It is important to state that the oil phase was never contaminated with IL, as proven by elemental N-analysis during all experiments: The N-content (respectively the IL-content) in the oil phase is at least less than 1 ppm. This important finding is supported by numerous experiments (about 1000). A leaching of IL into the oil is in any case not acceptable to maintain product quality. Additionally a leaching of ILs incorporating alkylsulfate (S-containing) anions as presented in this work would counteract the desulfurization efforts.

Extraction of N-compounds from model diesel oil

In addition to sulfur species, refinery streams also contain nitrogen compounds, which are in themselves not unwanted in many refinery products, *e.g.* in diesel oil they have a lubricating effect and are thus desired additives, but they strongly inhibit HDS.[7] Extraction experiments with a model oil with 1000 ppm N as indole in *n*-dodecane and [BMIM][$OcSO_4$] as extracting agent resulted in a partition coefficient K_N of 340 mg(N) kg(IL)$^{-1}$/mg(N) kg(oil)$^{-1}$. This amazingly high value – the K_N-value of the S-containing structural analogue BT is only 1.6 – is reproducible, but cannot be explained yet. To the contrary, the K_N-values of the N-species piperidine and pyridine are "only" 0.7 and 2.9, respectively, which is in the same order of magnitude as those of S-compounds. So in future other N-compounds – above all strong HDS-inhibitors like quinolines and acridines – will have to be investigated in order to prove whether a selective extraction of basic N-species is feasible. A competing absorption of N- and S-compounds was not detected, *i.e.* the partition coefficients (*e.g.* of DBT and indole in model oil) are not affected by simultaneous extraction.

Removal of sulfur from pre-desulfurized diesel

In addition to extraction experiments with model oils, "real" pre-desulfurized diesel oils (from MIRO refinery, Germany) were also used as feedstock. Due to the high number of different S-compounds present in the diesel oil, it was not possible to calculate substance-specific distribution coefficients. So an average partition coefficient based on the total S-content was calculated. Table 5 (and the comparison with the K_N-values already shown in Table 1) depicts that the S-removal from real diesel oil is harder than the desulfurization of model oils (lower K_N). In addition, the overall partition coefficient depends on the nature of the diesel oil, which can be explained by the variety of compounds present in diesel oil. Most likely the partition coefficient is not affected by the hydrocarbon matrix, and probably the distribution of the S-compounds in real fuels have a stronger impact on the extraction compared to the composition of the oil matrix: as shown in Table 5, the K_N-values found in *n*-dodecane as model base oil (see Tables 1 and 3) are virtually identical to those found in so-called white spirit oil (from Fluka).

So much more data are still needed with respect to the extraction of S-compounds from "real" diesel oils and gasoline (see below). This topic is currently under investigation.[13] However it was proven that the desulfurization of real diesel oil by extraction with

Table 5 S- and N-removal from pre-desulfurized diesel oil and white spirit model oil (partition coefficient K_N)

	K_N in mg(S) kg(IL)$^{-1}$/mg(S) kg(oil)$^{-1}$		K_N in mg(N) kg(IL)$^{-1}$/mg(N) kg(oil)$^{-1}$	
	Diesel oil[a]	White spirit[b]	Diesel oil[a]	White spirit[c]
[BMIM][BF$_4$]	0.2	0.7	1.5	> 50
[BMIM][OcSO$_4$]	0.3–0.8	1.6	0.7	> 50
[EMIM][EtSO$_4$]	0.1–0.4	0.7	1.2	> 50

[a] Different samples of pre-desulfurized diesel oil with 200–400 ppm S from MIRO refinery Karlsruhe, Germany; mass ratio oil : IL = 1 : 1, reaction time 15 min, room temperature (RT). [b] Model oil: DBT in Fluka white spirit, oil : IL = 1 : 1; mixing time 15 min, RT. [c] Model oil: indole in Fluka white spirit, oil : IL = 1 : 1; reaction time 15 min, RT.

ILs is in general possible, although the operating expenses (number of theoretical extraction steps) may vary and be higher than the one expected based on the experiments with model oils.

Sulfur removal from FCC-gasoline

The extractive desulfurization with ionic liquids is not only an interesting alternative for deep HDS of diesel oil, but probably even more attractive for FCC-gasoline with typically about 200 to 400 ppm S. (Note: in most refineries, the heavy oil feed of the FCC-unit up to now has not been desulfurized as the expenses needed are too high compared to a "post-desulfurization" of the product streams of the FCC-process.) This gasoline component has a high content of olefins – typically 30% – and is an important constituent of the gasoline pool.[22] S-compounds in FCC-gasoline are practically only thiophene and thiophene derivatives, which are relatively reactive for HDS.[5,23] So, in principle, FCC-gasoline is easy to desulfurize by classical HDS, but the major drawback is a loss in octane number of about 2 to 3 by undesired hydrogenation of the olefins.[22,24]

Extraction experiments with a model FCC gasoline containing thiophene or tetrahydrothiophene (500 ppm S in a one-to-one mixture of *i*-octane and 1-octene) resulted in a distribution coefficient K_N for thiophene of 0.7 ([BMIM][OcSO$_4$]), and for tetrahydrothiophene (THT) of 0.4 for [BMIM][OcSO$_4$] and 0.2 for [EMIM][EtSO$_4$]. The cross-solubility of the olefin in the IL is not much higher than for the paraffin, and above all the paraffin and the valuable olefin are only soluble in the latter IL to a small extent (Table 4). Subsequent to these promising tests with model oil, the desulfurization of a "real" FCC-gasoline (about 300 ppm S, from MIRO refinery, Germany) was investigated (Table 6). The distribution coefficients are still relatively high and the octane number will practically not be changed. This makes the desulfurization of FCC-gasoline a highly attractive application of the presented concept. Although more systematic investigations are still needed, the first results are very promising, also with respect to the regeneration of S-loaded IL, which is much easier in the case of gasoline than for diesel oil (see below "regeneration of S-loaded ILs").

Table 6 Sulfur removal from FCC-gasoline (partition coefficient K_N)

IL	K_N in mg(S) kg(IL)$^{-1}$/ mg(S) kg(oil)$^{-1}$ [a]
[BMIM][BF$_4$]	0.3
[EMIM][EtSO$_4$]	0.3
[BMIM][OcSO$_4$]	0.5

[a] FCC-gasoline with 300 ppm S from MIRO refinery Karlsruhe, Germany; mass ratio oil : IL = 1 : 1, reaction time 15 min, room temperature.

Continuous extraction in a mixer–settler system

To prove the feasibility of the extraction concept on a larger scale (30 kg IL) and above all in a continuous mode, experiments with a continuous working lab-scale mixer–settler unit (2 stages) were conducted at room temperature. Due to the high cost of pure dodecane for the large-scale experiments (50 l oil) in the mixer–settler unit cyclohexane was chosen as a model oil. As a model system [EMIM][EtSO$_4$] and DBT in cyclohexane (305 ppm S) were chosen. After a preliminery start-up period the system became stationary. The final S-concentration (130 ppm) was exactly the same as calculated for an ideal two stage counter-current extraction unit with the partition coefficient of 0.7, which was determined by the experiments with Schlenk tubes (Table 7). The average residence time in the mixing chamber(s) was about 2 min (mass ratio: 1.04 g oil per g IL, volume rates: 16 ml IL min— and 25 ml oil min^{-1}, volume of mixing chamber: 80 ml), which is obviously sufficient to reach 100% efficiency of separation. Additional measurements with a lower average residence time of 1.3 min show that the efficiency is then decreased down to about 50%, *i.e.* the partition coefficient apparently decreases to about 0.4, which reflects an influence of mass transfer (imperfect mixing). (Note: this characteristic mixing time of about 2 min was also detected by the experiments with Schlenk tubes; see Experimental below).

Table 7 Influence of the hydrocarbon (reextraction agent) on the partition coefficient K_N[a]

	K_N in mg(S) kg(IL)$^{-1}$/mg(S) kg(oil)$^{-1}$	
Hydrocarbon	[BMIM][OcSO$_4$]	[EMIM][EtSO$_4$]
Pentane	0.3	0.7
Cyclohexane	1.4	0.7
n-Dodecane	1.9	0.8
White spirit	1.6	0.7

[a] Model oil (500 ppm DBT in stated solvent), mass ratio oil : IL = 1 : 1, mixing time 15 min, room temperature.

So in a technical extraction unit, a residence time of about 2 min would be needed for each separation step – one tray in a column or one mixing vessel of a mixer–settler system – to ensure that the number of separation steps needed does not considerably exceed the number of theoretical plates calculated based on the K_N-value. Alternatively, an extraction temperature slightly higher than room temperature could be chosen: According to literature the viscosity of ILs strongly depends on temperature, *e.g.* in the case of [BMIM][OcSO$_4$] an increase from 20 to 60 °C leads to a decrease of the viscosity by a factor of 10.[25] So, in return, the diffusion coefficient (of S-compounds in ILs) will increase and the mixing time will decrease by this factor.

Regeneration of sulfur-loaded ILs

For the technical application of the IL-extraction the regeneration and subsequent recycling of the IL is of vital importance. There are several options for regeneration of the S-loaded IL: if the S- and N-compounds (and the coextracted hydrocarbons) have a low boiling point, the most elegant and cheapest option is the removal by distillation (either using thin-film-distillation, stripping columns or similar aggregates), as the IL has no measurable vapour pressure and will therefore remain in the liquid phase of the separator. It must be considered that the partial pressures of the S-compounds and the cosolved hydrocarbons are low and in addition will probably be affected (decreased) by the (reversible) interaction with the IL.

To prove this option for a simple regeneration of a S-loaded IL, an [EMIM][$EtSO_4$] sample containing tetrahydrothiophene (20 mg kg^{-1}) and a small amount of cyclohexane (2.5 wt%) was stripped with air at 100 °C for 30 minutes. By this means it was possible to remove the S-species and the hydrocarbon quantitatively, which was proven by subsequent reextraction experiments with the regenerated IL, whereby no sulfur could be detected within the limits of accuracy of the analysis (<1 ppm). The same was found for samples of [EMIM][$EtSO_4$], which were used previously for extractive desulfurization of "real" FCC-gasoline.

However, the regeneration of S-loaded ILs from diesel oil extraction is much harder: The removal of DBT or alkylated DBTs with a boiling point higher than 200 °C by this simple stripping is not possible (at least not economically feasible): Only about 20% of these S-compounds could be removed from a S-loaded IL (model system: 500 ppm S as DBT in [BMIM][$OcSO_4$]) by stripping with air at 120 °C for about three days. So, in the latter case, an additional reextraction step will be needed, followed by distillative separation of the reextraction medium and the high boiling S-compounds. The most promising reextraction medium are low boiling hydrocarbons like pentane or hexane. Table 7 shows the influence of the hydrocarbon used as reextraction agent on the partition coefficient of DBT. The K_N-value drops towards short-chain hydrocarbons, which is ideal for IL-regeneration by reextraction.

Other alternatives for regeneration of loaded ILs are discussed in the literature: if the IL is moisture insensitive (as is the case with alkylsulfate ILs), the dissolution of the spent IL in water enables the recovery of a nearly sulfur-free IL,[17] but this procedure is not economically feasible on a large scale with respect to the expenses of the subsequent separation of water by evaporation. The removal of various organic compounds by extraction with *sc*CO_2 is also reported in the literature,[26,27] but will probably also not be suitable for the regeneration on a multi-ton scale with respect to the energy expenses.

Integration into existing refinery network

Fig. 6 shows possible scenarios for the integration of IL-extraction into an existing refinery network for desulfurization of diesel oil. The extraction process may be installed downstream of a conventional hydrotreater in order to separate the unconverted DBT-derivatives from the pre-desulfurized product of HDS. Depending on the IL to oil ratio needed in the extraction unit (here a mass ratio of 1.5 was assumed), a certain portion of the oil is coextracted in the IL (*e.g.* here about 7%). For the example outlined in Fig. 6, an extraction column with (only) 6 theoretical plates would be needed.

The loaded IL is then fed to a regeneration unit, which is in the case of diesel oil probably a reextraction column followed by a distillation to separate the reextraction agent (*e.g.* a short-chain hydrocarbon) from the S-compounds and the coextracted hydrocarbons. The regenerated IL is then recycled into the extraction. The oil with the S-compounds from IL-regeneration can then be processed in other units of the refinery, *e.g.* in thermal cracking, coking, or can serve as co-feed in partial oxidation of heavy oils or in a power plant. Alternatively, this S-rich oil from IL-regeneration can also be recycled and added to the feed of the HDS reactor. By this means, the refractory S-compounds like 4,6-DMDBT are converted in the end to H_2S after several cycles (HDS and extraction) and a long total residence time in the HDS, respectively. By this means, the loss of product would be minimized.

As already addressed, ILs show amazingly high partition coefficients for certain N-compounds. Alternatively or in addition to an S-extraction, a small up-stream N-extraction unit can be installed for the selective separation of N-compounds. This would relieve the HDS unit because N-compounds strongly inhibit the HDS reactions. The partition coefficient for the extraction of N-compounds by ILs is so high that the IL to oil ratio needed for extraction would be very small. So, in return, practically all N- and only a very small amount of S-compounds and above all of hydrocarbons would be dissolved. Consequently the portion of the raw diesel oil dissolved in the IL would be so small that the N-rich oil from the regeneration of the loaded IL could easily be used as a co-feed in several units of the refinery.

In the case of desulfurization of FCC-gasoline the process scheme would be much simpler than for diesel: after extraction without any octane loss of the gasoline, the S-loaded IL is regenerated in one step by distillation, and the overhead product consisting of the S-species and a small amount of coextracted hydrocarbons would be used as co-feed for a gasoline HDS unit, where the thiophene derivatives are easily converted.

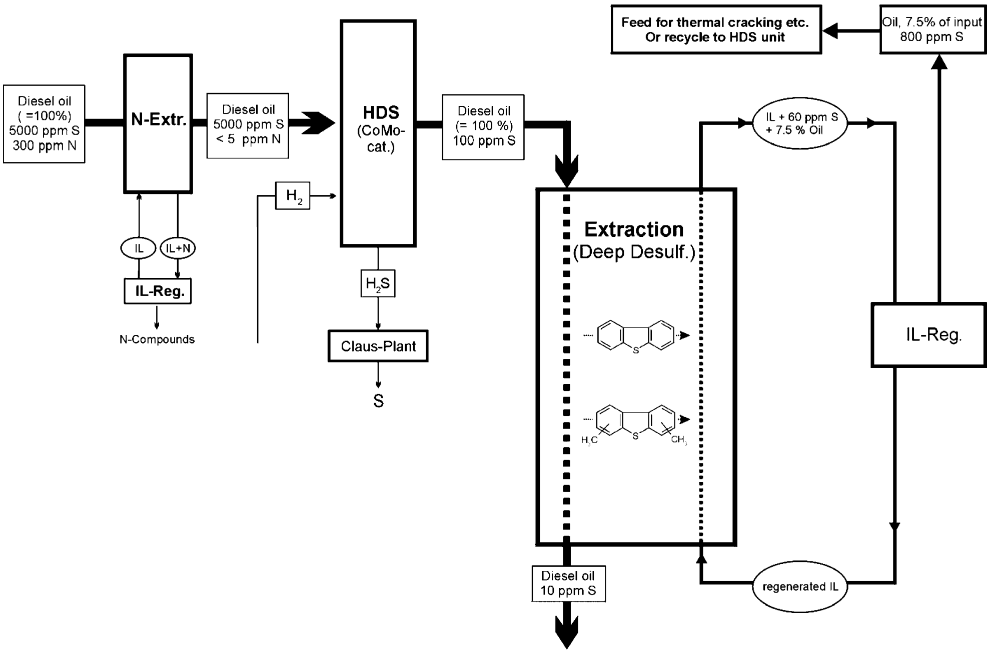

Fig. 6 Integration of extractive desulfurization of diesel oil into existing refinery network (data based on mass balance for [BMIM][$OcSO_4$] as extracting agent, cross-solubility of oil: 5%, mass ratio IL to oil: 1.5, $K_N = 0.8$, number of theoretical plates: 6).

Conclusions

Ionic liquids represent a novel class of solvents with interesting properties. This type of solvent can be used for the extractive desulfurization of refinery streams such as diesel oil and FCC-gasoline as a supplemental technology to conventional hydrodesulfurization (HDS). Especially for deep desulfurization and olefin-rich refinery streams, the presented concept has major advantages over HDS as it does not alter the oil matrix.

Another major advantage of the new concept is that hydrogen is not needed, which could be a bottle neck in some refineries; above all if practically all refinery streams will have to be desulfurized down to 10 ppm or even lower. The feasibility of the concept was proven in a continuous lab-scale mixer–settler unit. Further experiments *e.g.* concerning regeneration of ILs and selective extraction of N-compounds are still needed.

Experimental

Preparation of ionic liquids

[BMIM][BF_4] and [BMIM][PF_6] were prepared following standard procedures by metathesis of [BMIM]Cl with aqueous HPF_6 and $NaBF_4$ respectively. [EMIM][$EtSO_4$] was also prepared according to literature data,[28] [BMIM][$OcSO_4$] was prepared by metathesis of [BMIM]chloride and sodium octylsulfate.[25] [MMIM][Me_2PO_4] was synthesized by alkylation of 1-methylimidazole (from BASF) with trimethylphosphate (Fluka). A Bruker 250 MHz NMR was used to verify the structure of the ILs.

Determination of partition coefficients

For the determination of the Nernst partition coefficients, the IL sample was stirred with a model oil (or diesel oil) sample in a Schlenk tube for 15 min at a given temperature. The oil phase was then separated from eventual emulsified IL-droplets by centrifugation. The total S- and N- concentrations of the oil samples were determined by an ANTEK S/N 9000 elemental analyzer equipped with a pyrochemiluminescence N-detector and a pyrofluorescence S-detector with an average error of 1 ppm of S or N. Any leaching of IL into the oil (also never observed) was monitored by elemental N-analysis as, in contrast to the model oils (*e.g.* dodecane or cyclohexane), all investigated ILs contain imidazolium cations and therefore nitrogen.

It is interesting to note that a good mixing of the two immiscible phases (IL and oil) is essential to determine the Nernst coefficients (and thus also important for a technical process with respect to the number of practical separation steps needed). Experiments show that in the well-mixed Schlenk tubes about 2 min are needed (proven with the systems DBT/dodecane and [EMIM][$EtSO_4$] or [BMIM][$OcSO_4$]) to reach the thermodynamic equilibrium, and therefore in each case at least 15 min were used as a standard mixing time to be on the safe side.

The overall mass transfer of the S-species from the oil into the IL is extraordinarily slow in a static unmixed system. For example, the time needed to reach equilibrium in the unmixed system [BMIM][$OcSO_4$] and *n*-dodecane (with an initial S-content of 500 ppm as DBT) is more than three weeks (!) in a tube with 3 cm diameter (height of each phase: only about 1 cm). This reflects the very low diffusion coefficient of DBT in ILs, estimated based on these exchange experiments in this static system to be only about 2×10^{-11} m^2 s^{-1} in [BMIM][$OcSO_4$].

To determine the influence of aromatics in the oil, a white spirit (boiling range of 180–220 °C) with an aromatic content of 18 to 20 wt% was obtained from Fluka and used as model oil.

To identify S-compounds in more complex mixtures, oil samples were analyzed using a Varian GC 3800 gas chromatograph with S-selective pulsed flame photometric detector (PFPD)-detector with a CP-Sil 8CB column. The oil composition was analyzed by a Varian GC 3800 equipped with an FID-detector and CP-Sil Pona CB for ASTM D 5134-9 column.

Continuous extraction in a mixer–settler unit

The continuous experiments were carried out in a modular MEAB MSU-0,5 mixer–settler unit with 500 ml volume per unit, using two mixer–settler units to represent a two-stage counter-current extraction. Samples were taken from the outlet of the second stage and from the settler-area of both units.

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Anti-microbial activities of protic ionic liquids with lactate anion

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Minimum inhibitory concentrations (MIC) and minimum biocidal concentrations (MBC) were established for 1-alkylimidazolium and 1-alkoxymethylimidazolium lactates tested against rods, cocci and fungi. We found that anti-microbial activities of the protic ionic liquids are strongly related to the length of the substituent and to the DL- or L-type anion. Lactates with short substituents up to pentyl or pentyloxymethyl remain inactive toward microorganisms. In addition physical properties and thermal stability of protic ionic liquids have been described. We found them to readily undergo decomposition under the effect of ozone in aqueous solution.

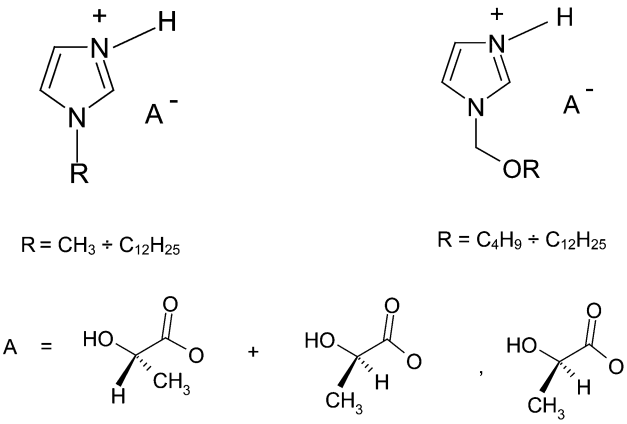
Introduction

Ionic liquids (ILs) represent a big success for industrial and engineering chemistry at the beginning of the 21st century. ILs are usually defined as thermally stable salts synthesized by combining bulky organic cations, *e.g.*, imidazolium or pyridinium, with a wide variety of anions, often with fluorine content, *e.g.*, tetrafluoroborate or hexafluorophosphate. Brønsted acid–base protic ionic liquids are an example of the varieties of ionic liquids. Their utility became more apparent with the implementation of the biphasic acid scavenging utilising ionic liquids (BASIL) procedure by BASF in the manufacture of alkoxyphenylphosphines. Here, the protic ILs involve N-methylimidazolium chloride, which has a melting point of 75 °C.[1] Even though the first protic ILs were obtained almost 100 years ago (in 1914[2]) as ethyl-, dimethyl-, and diethylammonium nitrates, more new compounds of this nature are emerging. Brønsted acid–base protic ILs were derived from the controlled combination of a monoprotic inorganic acid with an organic base under solvent-free conditions.[3,4] Recently, new studies have shown that it is possible to take ILs containing an inorganic anion and use them as both a catalyst and a solvent in the Mannich reaction,[5,6] esterification[7] and ether cleavage.[8]

The presence of fluorine in the anion of an IL jeopardizes the use of the liquids as 'green' solvents since their utilisation in combustion-requiring procedures is associated with the release of HF. At the same time, hexafluorophosphates have been shown to undergo hydrolysis in contact with moisture, resulting in the formation of volatile compounds, including HF, POF$_3$, *etc.*[9] Rogers, Holbrey and Swatloski[9] suggested that the concepts of non-toxic pharmaceutically acceptable ions and (generally regarded as safe) GRAS materials (taken from the pharmaceutical and food additive industries) should be used to provide guidelines for the development of new ILs for which the toxicological and environmental hazards of the individual ions are established and can be considered to be acceptably low. To that extent, lactates belong to a group of organic ions listed as non-toxic, pharmaceutically acceptable anions. The first aprotic ILs with lactate anion have been successfully used in Diels–Alder reactions.[10] Earlier, we have synthesized protic ILs in the form of 1-alkyl- and 1-alkoxymethylimidazolium lactates and salicylates.[11] In the present study, we examined protic ILs containing asymmetrical monosubstituted imidazolium cation and DL- or L-lactate anion.

Results and discussion

In the protonisation reaction of 1-alkyl- and 1-alkoxymethylimidazole lactic acid, DL-lactates (**1,2**) and L-lactates (**3,4**) were obtained, respectively, according to the earlier described technique.[11] Structures of all salts are shown in Scheme 1.



Scheme 1 Prepared protic ILs.

Anhydrous compounds were obtained by heating the samples at 70 °C under vacuum for 10 h. The synthesized salts are listed in Tables 1 and 2. For all the obtained salts physico-chemical parameters such as density, electrical conductivity and temperature of onset of decomposition were established. The density of the obtained DL-lactates (**1,2**) varied in the range of 1.1231–0.9591 g ml^{-1} while the density of L-lactates (**3,4**) fitted the range of 1.1281–0.9626 g ml $^{-1}$ (Tables 1 and 2). DL-Lactates exhibited lower density than L-lactates. Protic ILs were obtained with densities above or below the density of water. Here, the typical trait of ILs was preserved: increasing molecular weight was associated with a decrease in density.[12–16] For DL-lactates (**1,2**) the temperature of the onset of decomposition fitted the range of 188.0 to 244.5 °C (Table 1) while for L-lactates (**3,4**) the respective range was similar: 186.6 to 238.9 °C (Table 2). On the other hand, electrical conductivity was strongly related to the structure of the salts. The determined values are presented in Tables 1 and 2. Addition of CH$_2$ groups to the alkyl chain on the imidazolium cation decreased electrical conductivity. DL-Lactates (**1,2**) manifested higher conductivity than analogous L-lactates (**3,4**). The determined values corresponded to a range of 0.995 to 0.066 mS cm^{-1}. Testing of selected physical properties demonstrated differences in the values established for DL-lactates and L-lactates. Higher densities were manifested by L-lactates as compared to DL-lactates. A reciprocal relation was noted in the case of electrical conductivity.

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Table 1 1-Alkyl- and 1-alkoxymethylimidazolium DL-lactates (**1**, **2**)

Lactate	R	Mp/°C	$T_s{}^b$/°C	Yield (%)	Density[a] ρ/g ml^{-1}	Electrical conductivity[a] σ/mS cm^{-1}
	H	76–77	—	58	—	—
1a	CH_3	Liquid	196.5	92	1.1231	0.995
1b	C_2H_5	Liquid	207.5	95	1.1081	0.795
1c	C_3H_7	Liquid	211.0	98	1.0825	0.620
1d	C_4H_9	Liquid	244.5	96	1.0595	0.398
1e	C_5H_{11}	Liquid	228.5	93	1.0413	0.285
1f	C_6H_{13}	Liquid	226.0	95	1.0374	0.246
1g	C_7H_{15}	Liquid	224.5	97	1.0273	0.227
1h	C_8H_{17}	Liquid	223.0	95	1.0026	0.195
1i	C_9H_{19}	Liquid	209.0	91	0.9908	0.174
1j	$C_{10}H_{21}$	Liquid	206.5	99	0.9793	0.138
1k	$C_{11}H_{23}$	Liquid	197.5	93	0.9685	0.094
1l	$C_{12}H_{25}$	Liquid	194.0	94	0.9591	0.089
2a	OC_4H_9	Liquid	188.0	93	1.0640	0.281
2b	OC_5H_{11}	Liquid	197.0	99	1.0490	0.235
2c	OC_6H_{13}	Liquid	211.0	94	1.0252	0.215
2d	OC_7H_{15}	Liquid	224.5	94	1.0207	0.184
2e	OC_8H_{17}	Liquid	228.0	92	1.0105	0.148
2f	OC_9H_{19}	Liquid	238.0	95	0.9906	0.137
2g	$OC_{10}H_{21}$	Liquid	207.5	90	0.9861	0.105
2h	$OC_{11}H_{23}$	Liquid	222.0	97	0.9854	0.099
2i	$OC_{12}H_{25}$	Liquid	245.5	94	0.9804	0.091

[a] At 20 °C. [b] Safe temperatures = temperatures of onset of decomposition.

Table 2 1-Alkyl- and 1-alkoxymethylimidazolium L-lactates (**3**,**4**)

Lactate	R	Mp/°C	$T_s{}^b$/°C	Yield (%)	Density[a] ρ/g ml^{-1}	Electrical conductivity[a] σ/mS cm^{-1}
	H	76–78	—	56	—	—
3a	CH_3	Liquid	192.4	87	1.1281	0.978
3b	C_2H_5	Liquid	198.5	89	1.1098	0.744
3c	C_3H_7	Liquid	208.8	93	1.0900	0.545
3d	C_4H_9	Liquid	238.5	92	1.0625	0.362
3e	C_5H_{11}	Liquid	226.8	98	1.0451	0.232
3f	C_6H_{13}	Liquid	222.5	93	1.0383	0.206
3g	C_7H_{15}	Liquid	221.8	98	1.0313	0.192
3h	C_8H_{17}	Liquid	220.5	95	1.0055	0.178
3i	C_9H_{19}	Liquid	204.2	93	0.9996	0.155
3j	$C_{10}H_{21}$	Liquid	198.8	89	0.9879	0.121
3k	$C_{11}H_{23}$	Liquid	194.4	86	0.9714	0.071
3l	$C_{12}H_{25}$	Liquid	191.3	89	0.9626	0.066
4a	OC_4H_9	Liquid	186.6	93	1.0695	0.260
4b	OC_5H_{11}	Liquid	193.2	91	1.0530	0.212
4c	OC_6H_{13}	Liquid	207.8	93	1.0350	0.186
4d	OC_7H_{15}	Liquid	218.1	95	1.0254	0.162
4e	OC_8H_{17}	Liquid	223.3	95	1.0147	0.140
4f	OC_9H_{19}	Liquid	230.8	91	0.9992	0.128
4g	$OC_{10}H_{21}$	Liquid	201.8	94	0.9910	0.100
4h	$OC_{11}H_{23}$	Liquid	216.1	94	0.9875	0.095
4i	$OC_{12}H_{25}$	Liquid	238.9	97	0.9826	0.088

[a] At 20 °C. [b] Safe temperatures = temperatures onset of decomposition.

For lactates with 10 carbon atoms in the alkyl group (**1j, 2g, 3j, 4g**) viscosity, temperature of decomposition and glass transition temperature were determined. The viscosity of **1j, 2g, 3j** and **4g** proved to be much higher than that of water but did not show exceedingly high values as compared to described ILs of a similar molecular weight.[13,14] In the studied range of shear stress all the studied lactates were Newtonian fluids, as evident in Table 3. Results in Table 4 demonstrated that lactates **1j** and **3j** with decyl substituents as well as **2g** and **4g** with decyloxymethyl substituents exhibited a similar thermal stability. The DSC analysis confirmed the temperatures of the onset of decomposition determined in the automatic boiling point Büchi apparatus, model B-545, and presented in Tables 1 and 2. On the other hand the data presented in Table 5 document similar glass transition temperatures for all the four studied lactates (−71.0 to −66.8 °C). These protic ILs were good glass-formers, *i.e.*, they could be cooled down from the liquid state to low temperatures without crystalising, which was also observed in cases of aprotic ILs.[17,18]

Table 3 Dynamic viscosity of the lactates **1j**, **2g**, **3j**, **4g**[a]

Lactate	R	Shearing stress γ/s^{-1}	Viscosity cP
1j	$C_{10}H_{21}$	27.0–1312	218
2g	$OC_{10}H_{21}$	40.5–1312	161
3j	$C_{10}H_{21}$	27.0–1312	142
4g	$OC_{10}H_{21}$	40.5–1312	120

[a] Dried, at 20 °C.

Lactates containing 8 carbon atoms (**1h**, **2e**, **3h**, **4e**) or 11 carbon atoms (**1k**, **2h**, **3k**, **4h**) in the alkyl substituent were subjected to

Table 4 Thermal stability of the lactates **1j**, **2g**, **3j**, **4g**

Lactate	DSC signal	T_{onset}/°C	Thermal effect/J g^{-1}	T_{max}/°C
1j	endo	82.1	156.01	111.6
	exo	246.4	84.98	258.1
2g	endo	53.7	33.23	100.4
	exo	259.8	90.23	271.9
3j	endo	62.9	25.28	93.6
	exo	247.4	59.53	258.0
4g	endo	54.3	29.40	93.6
	exo	259.5	86.27	272.3

Table 5 Glass transition temperatures of the lactates**1j**, **2g**, **3j, 4g**

Lactate	T_{onset}/°C	Thermal effect/J g^{-1}	T_{max}/°C
1j	−71.0	0.384	−69.1
2g	−70.0	0.314	−68.6
3j	−68.1	0.217	−66.8
4g	−70.0	0.210	−68.6

oxidation with ozone in an aqueous solution. The obtained results are presented in Table 6. The extent of decomposition was calculated using the formula:

$$D = (1 - X/X_0)100\%$$

where X represented the content (%) of surfactant in the reaction mix following 10, 20, 30, 40 min of the process, X_0 was the original content (%) of surfactant. A direct two-phase back titration technique[19] allowed the determination of the percentage content of surfactant or the examined lactate. After 40 min of the process, 80 to 96% decomposition was reached. 1-Undecyloxymethylimidazolium L-lactate (**4h**) underwent the fastest and most effective decomposition. After 10 min the extent of decomposition exceeded 70% to reach 95% after 30 min, as illustrated in Fig. 1. Under the effect of ozone in water solution, 1-alkyl- and 1-alkoxymethylimidazolium lactates easily underwent oxidation with high efficiency.

Table 6 Degree of destruction D [%] of lactates

Time/min	**1h**	**1k**	**2e**	**2h**	**3h**	**3k**	**4e**	**4h**
10	34	34	42	58	35	35	60	71
20	45	67	53	73	50	73	79	86
30	66	80	73	81	73	85	91	95
40	85	89	87	93	88	92	94	96

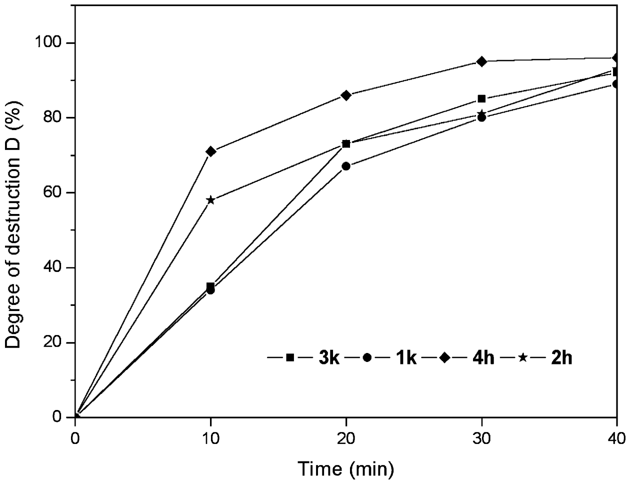

Fig. 1 Decay of 1-undecyloxymethylimidazolium lactates in the presence of ozone as a function of time.

For all the obtained salts their biological activity was estimated. The studies were conducted on five strains of rods, five strains of cocci and two strains of fungi. The minimum concentration required to inhibit growth of the microorganisms (MIC) and minimum biocidal concentration (MBC) were estimated. MIC and MBC values for DL-lactates **1a–1l** are shown in Table 7 and for **2a–2i** in Table 8. In turn, MIC and MBC concentrations obtained for L-lactates **3a–3l** and for **4a–4i** are presented in Tables 9 and 10. Moreover, in the Tables MIC and MBC values were presented for

Table 7 MIC and MBC values[a] of 1-alkylimidazolium DL-lactates (**1**)

		Salts								
Strain		**1a-1e**	**1f**	**1g**	**1h**	**1i**	**1j**	**1k**	**1l**	BAC
Gram-positive cocci										
M. luteus	MIC	> 5814	> 4132	> 3906	116	55	52	50	48	1.4
	MBC	> 5814	> 4132	> 3906	1852	880	419	200	96	11
S. epidermidis	MIC	> 5814	> 4132	> 3906	463	220	105	50	96	1.4
	MBC	> 5814	> 4132	> 3906	3704	440	419	400	96	5.6
S. aureus	MIC	> 5814	> 4132	> 3906	926	110	105	75	144	2.8
	MBC	> 5814	> 4132	> 3906	3704	880	419	200	192	23
S. aureus (MRSA)	MIC	> 5814	> 4132	> 3906	1852	220	209	100	96	5.6
	MBC	> 5814	> 4132	> 3906	3704	880	209	200	192	11
E. hirae	MIC	> 5814	> 4132	> 3906	1852	440	209	100	96	11
	MBC	> 5814	> 4132	> 3906	3704	880	419	200	192	88
Gram-negative rods										
E. coli	MIC	> 5814	2066	1953	463	220	209	200	192	2.8
	MBC	> 5814	> 4132	1953	231	440	419	300	287	2.8
P. vulgaris	MIC	> 5814	> 4132	3906	1852	880	209	400	383	88
	MBC	> 5814	> 4132	> 3906	1852	880	839	800	1304	88
K. pneumoniae	MIC	> 5814	2066	1953	463	220	209	200	192	11
	MBC	> 5814	> 4132	> 3906	1852	440	209	200	192	11
P. aeruginosa	MIC	> 5814	4132	> 3906	1852	1761	1678	3205	3067	175
	MBC	> 5814	> 4132	> 3906	1852	1761	1678	3205	3067	175
S. marcescens	MIC	> 5814	> 4132	1953	463	440	209	400	383	175
	MBC	> 5814	> 4132	> 3906	1852	880	419	800	959	175
Fungi										
C. albicans	MIC	> 5814	> 4132	> 3906	3704	880	419	200	383	11
	MBC	> 5814	> 4132	> 3906	3704	880	419	200	767	88
R. rubra	MIC	> 5814	2066	1953	463	440	105	200	192	23
	MBC	> 5814	> 4132	> 3906	1852	880	209	200	383	88

[a] In μM.

Table 8 MIC and MBC values^a 1-alkoxymethylimidazolium DL-lactates (**2**)

		Salts									
Strain		**2a**	**2b**	**2c**	**2d**	**2e**	**2f**	**2g**	**2h**	**2i**	BAC
Gram-positive cocci											
M. luteus	MIC	> 4098	3876	1838	1748	833	398	380	92	88	1.4
	MBC	> 4098	3876	1838	1748	1667	1592	1524	92	88	11
S. epidermidis	MIC	> 4098	3876	2757	1748	1667	1592	762	92	88	1.4
	MBC	> 4098	3876	3676	3497	3333	3185	1524	183	176	5.6
S. aureus	MIC	> 4098	3876	3676	1748	417	498	380	183	88	2.8
	MBC	> 4098	> 3876	> 3676	> 3497	833	498	706	183	88	23
S. aureus (MRSA)	MIC	> 4098	> 3876	> 3676	> 3497	1667	1592	1524	183	88	5.6
	MBC	> 4098	> 3876	> 3676	> 3497	> 3333	3185	3049	365	176	11
E. hirae	MIC	> 4098	> 3876	> 3676	> 3497	1667	1592	1524	183	176	11
	MBC	> 4098	> 3876	> 3676	> 3497	> 3333	3185	3049	365	176	88
Gram-negative rods											
E. coli	MIC	2049	969	459	219	104	49	95	92	350	2.8
	MBC	> 4098	> 3876	3676	1748	417	398	380	183	702	2.8
P. vulgaris	MIC	> 4098	3876	1838	437	208	99	190	365	350	88
	MBC	> 4098	> 3876	> 3676	3497	833	398	190	731	702	88
K. pneumoniae	MIC	> 4098	1938	229	219	208	199	190	183	176	11
	MBC	> 4098	> 3876	229	219	417	398	190	365	176	11
P. aeruginosa	MIC	> 4098	> 3876	3676	3497	3333	3185	3049	2924	2809	175
	MBC	> 4098	> 3876	> 3676	> 3497	> 3333	> 3185	3049	> 2924	> 2809	175
S. marcescens	MIC	> 4098	3876	3676	1748	833	398	762	1462	2809	175
	MBC	> 4098	> 3876	> 3676	3497	833	796	1524	2924	2809	175
Fungi											
C. albicans	MIC	> 4098	3876	3676	3497	833	199	190	92	350	11
	MBC	> 4098	> 3876	3676	3497	1667	796	380	183	702	88
R. rubra	MIC	> 4098	969	919	437	208	99	190	183	350	23
	MBC	> 4098	> 3876	> 3676	3497	417	199	380	365	702	88

^{a} In μM.

Table 9 MIC and MBC values^a of 1-alkylimidazolium L-lactates (**3**)

		Salts								
Strain		**3a–3e**	**3f**	**3g**	**3h**	**3i**	**3j**	**3k**	**3l**	BAC
Gram-positive cocci										
M. luteus	MIC	> 5814	2066	488	116	55	26	12	12	1.4
	MBC	> 5814	> 4132	1953	926	220	209	50	48	11
S. epidermidis	MIC	> 5814	4132	1953	463	110	52	25	12	1.4
	MBC	> 5814	> 4132	3906	1852	440	419	200	96	5.6
S. aureus	MIC	> 5814	4132	1953	926	110	52	25	24	2.8
	MBC	> 5814	> 4132	> 3906	926	440	419	200	192	23
S. aureus (MRSA)	MIC	> 5814	> 4132	3906	1852	440	105	50	96	5.6
	MBC	> 5814	> 4132	> 3906	3704	880	419	200	192	11
E. hirae	MIC	> 5814	> 4132	3906	1852	220	105	50	48	11
	MBC	> 5814	> 4132	> 3906	3704	880	419	200	383	88
Gram-negative rods										
E. coli	MIC	> 5814	2066	977	463	220	105	50	48	2.8
	MBC	> 5814	> 4132	> 3906	3704	880	209	200	192	2.8
P. vulgaris	MIC	> 5814	4132	1953	926	440	209	200	96	88
	MBC	> 5814	> 4132	3906	1852	880	419	400	383	88
K. neumoniae	MIC	> 5814	2066	1953	463	220	209	100	96	11
	MBC	> 5814	> 4132	3906	926	440	209	200	192	11
P. aeruginosa	MIC	> 5814	4132	3906	3704	880	839	802	1534	175
	MBC	> 5814	> 4132	3906	3704	880	1678	3205	3076	175
S. marcescens	MIC	> 5814	4132	1953	926	440	209	400	383	175
	MBC	> 5814	> 4132	3906	3704	1760	209	800	767	175
Fungi										
C. albicans	MIC	> 5814	4132	1953	1852	880	209	100	48	11
	MBC	> 5814	> 4132	3906	3704	1760	419	200	96	88
R. rubra	MIC	> 5814	4132	977	926	220	105	50	48	23
	MBC	> 5814	> 4132	3906	3704	1760	209	200	192	88

^{a} In μM.

benzalkonium chloride (BAC, an Aldrich Chemical Co. product, in which alkyl represents a mixture of alkyl from C_8H_{17} to $C_{18}H_{37}$). Relationships between mean MIC and MBC value for rods, cocci and fungi and the molecular weight of the agent are presented in Figs. 2–4. The examined salts exhibited biological activity against all of the microorganisms. The activity was related mainly to the length of alkyl and alkoxymethyl substituent and, thus, to molecular weight. The studied lactates manifested a more pronounced bacteriostatic activity, *i.e.* lower MIC values, than microbiocidal activity, measured by MBC values. An evident difference was also noted between MIC and MBC values obtained for DL-lactates and those obtained for L-lactates. Out of all the examined salts, the most pronounced microorganism growth-inhibiting effect (examined against cocci) was documented for L-lactates containing 11 or 12

Table 10 MIC and MBC values[a] 1-alkoxymethylimidazolium L-lactates (**4**)

		Salts									
Strain		**4a**	**4b**	**4c**	**4d**	**4e**	**4f**	**4g**	**4h**	**4i**	**BAC**
Gram-positive cocci											
M. luteus	MIC	4098	1938	1838	437	208	49	23.8	5.8	5.6	1.4
	MBC	> 4098	3876	3676	1748	833	199	96	92	44	11
S. epidermidis	MIC	4098	3876	1838	874	208	99	47.6	11.4	10.9	1.4
	MBC	> 4098	> 3876	3676	3497	1667	398	190	92	88	5.6
S. aureus	MIC	4098	> 3876	3676	874	417	199	47.6	11.4	10.9	2.8
	MBC	> 4098	> 3876	> 3676	3497	833	796	190	183	176	23
S. aureus (MRSA)	MIC	> 4098	> 3876	3676	3497	1667	796	95	45.6	88	5.6
	MBC	> 4098	> 3876	> 3676	> 3497	3333	1592	380	183	351	11
E. hirae	MIC	> 4098	> 3876	3676	1748	1667	398	95	45.6	44	11
	MBC	> 4098	> 3876	> 3676	> 3497	3333	796	380	183	176	88
Gram-negative rods											
E. coli	MIC	4098	1938	919	437	208	199	95	183	88	2.8
	MBC	> 4098	> 3876	3676	874	417	398	190	365	176	2.8
P. vulgaris	MIC	4098	3876	1838	874	417	398	190	183	176	88
	MBC	> 4098	> 3876	3676	3497	1667	796	380	365	350	88
K. pneumoniae	MIC	2049	1938	459	219	208	199	190	92	88	11
	MBC	> 4098	> 3876	3676	874	833	398	380	183	88	11
P. aeruginosa	MIC	> 4098	> 3876	> 3676	3497	1667	1592	3049	> 2924	> 2809	175
	MBC	> 4098	> 3876	> 3676	3497	1667	1592	> 3049	> 2924	> 2809	175
S. marcescens	MIC	> 4098	> 3876	3676	1748	833	398	762	2924	2809	175
	MBC	> 4098	> 3876	> 3676	3497	1667	796	1524	2924	> 2809	175
Fungi											
C. albicans	MIC	4098	3876	1838	437	208	96	96	92	175.5	11
	MBC	> 4098	> 3876	> 3676	1748	834	398	190	92	176	88
R. rubra	MIC	4098	3876	919	219	208	26	47.8	45.6	87.8	23
	MBC	> 4098	> 3876	3676	1748	834	199	190	183	176	88

[a] In μM.

carbon atoms in alkyl group (**3k, 3l, 4h, 4i**) and the most effective proved to be 1-undecyloxymethylimidazolium L-lactate (**4h**) (Fig. 2). The lowest MBC value against cocci was observed for DL-lactates containing 12 carbon atoms in the alkyl substituent (**1l, 2i**) and for L-lactates containing 11 carbon atoms (**3k, 4h**). However, it should be noted that decisively lower values of MIC were obtained for L-lactates than for DL-lactates (Fig. 2). On the other hand, in cases of biocidal activity, differences between the two groups of compounds were much less pronounced. Against rods, most effective proved to be 1-nonyloxymethylimidazolium DL-lactate (**2f**) and 1-decylimidazolium L-lactate (**3j**). In this case, DL-lactates exhibited much more pronounced microorganism growth-inhibiting properties than their biocidal properties (Fig. 3). The third group of examined microorganisms involved fungi. L-Lactates proved to be most biostatic including 1-dodecyl- (**3l**) and 1-nonyloxymethylimidazolium (**4f**) while the most biocidal agents included 1-dodecylimidazolium (**3l**) and 1-undecyloxymethylimidazolium (**4h**) L-lactates, as presented in Fig. 4. Although impressive, the biological activity spectrum of the studied salts was found to vary depending on the strain of microorganisms within the same group. Within the group of cocci it was poor against *Staphylococcus aureus (MRSA)* and within the rod group it was negligible against *Pseudomonas aeruginosa* and *Serratia marcescens*. As compared to the commercially available benzalkonium chloride (BAC), biological activity of the most effective lactates **3j, 3k, 3l, 4h** and **4i** was comparable against some microorganisms. However, BAC showed more effective action against all the tested microbes. Lactates with methyl, ethyl, propyl, butyl, pentyl, butoxymethyl and pentyloxymethyl substituent proved inactive.

Experimental

Melting points were measured using an electrothermal digital melting point apparatus, model JA 9100. Onset of decomposition temperatures were established using Büchi automatic apparatus, model B-545. A Mettler Toledo DA 110M scale was used for the mass/density measurements (temp. 20 ± 2 °C, sample volume = 2 ml). Viscosity of each salt was measured using a rotation viscosimeter, Rheotest 2. Electrical conductivity was measured using an impedance spectroscope ATLAS 9121 FRA and all tests were performed under an alternate voltage at 10 mHz to 99.9 kHz frequency range. Impedance spectra were interpreted using the IMP-91 software for impedance analysis. Values of electrical conductivity were determined as related to the conductivity of 0.01 mol l^{-1} aqueous KCl solution, amounting to 1.35 mS cm^{-1}. Glass transition temperatures were measured using differential scanning microcalorimetry (DSC) at a 10 °C min^{-1} scanning rate with power sensitivity of 16 mJ s^{-1} and with a recorder sensitivity of 5 mV. The instrument (Perkin-Elmer Pyris 1) was calibrated each time with a 99.9999 mole percent pure indium sample. The calorimetric accuracy was ±1% and the calorimetric precision was ±5%.

80% DL-lactic acid (Akwawit, Leszno, Poland) and 85% L-lactic acid (Aldrich) were used. Preparation of 1-alkyl- and 1-alkoxymethylimidazolium lactates followed the published method.[11]

1-Decylimidazolium DL-lactate (1j)

^{1}H NMR (DMSO-d_6) 0.88 (t, J = 6.7 Hz, CH_3, cation), 1.32 (m, 17H, CH_2 cation and CH_3 anion), 1.74 (qw, J = 7.2 Hz, CH_2), 3.98 (t, J = 7.1 Hz, N–CH_2), 4.08 (q, J = 6.9 Hz, CH, anion), 6.94 and 7.20 (2s, 2H, imid.), 7.62 (s, wide OH and N^+-H), 7.73 (s, 1H, imid.). ^{13}C NMR (DMSO-d_6) 13.9 (CH_3, cation), 20.5 (CH_3, anion), 22.1, 25,9, 28.5, 28.7, 28.95, 28.96, 30.6, 31.3 (CH_2), 46.1 (N–CH_2), 65.9 (CH, anion), 119.4, 127.7 and 137.1 (imid.), 176.7 (CO).

1-Decyloxymethylimidazolium DL-lactate (2g)

^{1}H NMR (DMSO-d_6) 0.88 (t, J = 6.7 Hz, CH_3, cation), 1.33 (m, 17H, CH_2 cation and CH_3 anion), 1.49 (m, CH_2), 3.37 (t, J = 6.5 Hz, O–CH_2), 4.10 (q, J = 6.9 Hz, CH, anion), 5.39 (s, N–CH_2–O), 6.96, 7.27 and 7.83 (3s, 3H, imid.), 8.27 (s, wide, OH and N^+–H).^{13}C NMR (DMSO-d_6) 13.9 (CH_3, cation), 20.5 (CH_3, anion), 22.2, 25,6, 28.8, 28.9, 29.07, 29.1, 31.4 (CH_2), 65.8 (CH, anion),

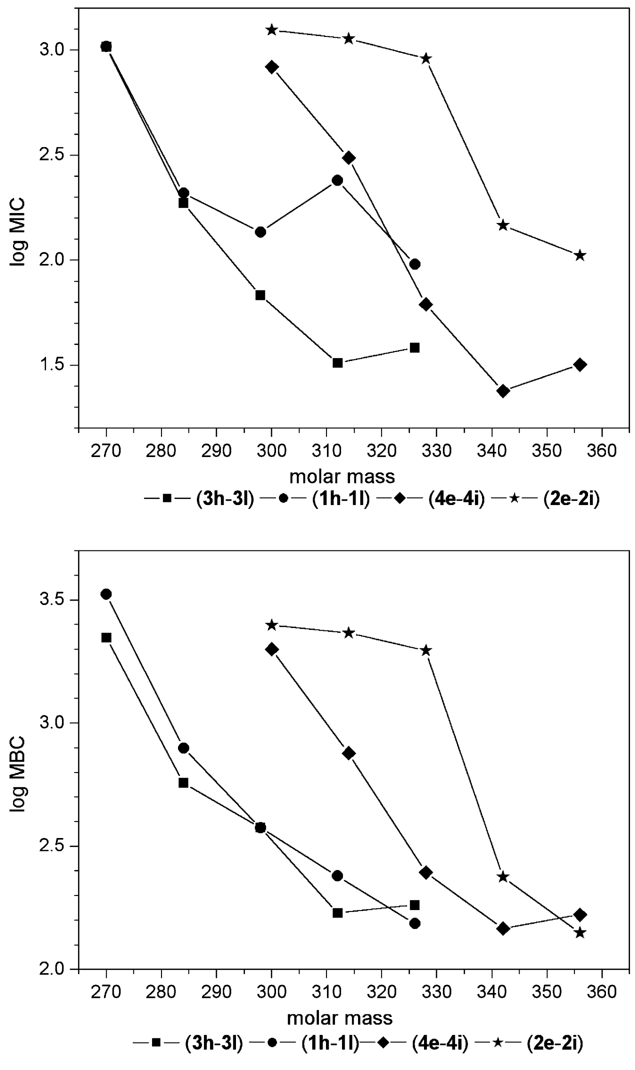

Fig. 2 Mean MIC and MBC values for cocci.

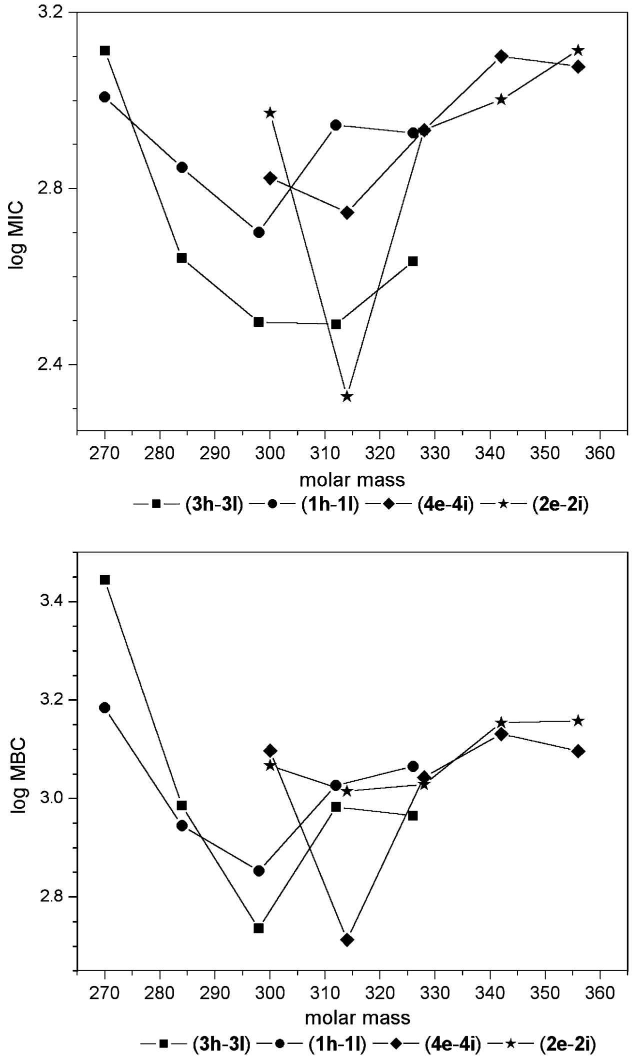

Fig. 3 Mean MIC and MBC values for rods.

67.9 (O–CH_2), 75.5 (N–CH_2–O) 119.4, 128.3 and 137.6 (imid.), 176.3 (CO).

1-Decylimidazolium L-lactate (3j)

^1H NMR (DMSO-d_6) 0.88 (t, J = 6.7 Hz, CH_3, cation), 1.34 (m, 17H, CH_2 cation and CH_3 anion), 1.74 (qw, J = 7.1 Hz, CH_2), 3.98 (t, J = 7.1 Hz, N–CH_2), 4.09 (q, J = 6.9 Hz, CH, anion), 6.95 and 7.19 and 7.74 (3s, 3H, imid.), 8.86 (s, wide, OH and N^+–H). ^{13}C NMR (DMSO-d_6) 13.9 (CH_3, cation), 20.4 (CH_3, anion), 22.6, 22.2, 26.0, 28.6, 28.8, 29.1, 30.6, 31.4 (CH_2), 46.2 (N–CH_2), 66.0 (CH, anion), 119.2, 127.5 and 136.9 (imid.), 176.7 (CO).

1-Decyloxymethylimidazolium L-lactate (4g)

^1H NMR (DMSO-d_6) 0.88 (t, J = 6.7 Hz, CH_3, cation), 1.35 (m, 17H, CH_2 cation and CH_3 anion), 1.49 (m, CH_2), 3.37 (t, J = 6.5 Hz, O–CH_2), 4.10 (q, J = 6.9 Hz, CH, anion), 5.34 (s, N–CH_2–O), 6.96, 7.27 (2s, 2H, imid.), 7.9 (s, wide, 1H imid., OH and N^+-H). ^{13}C NMR (DMSO-d_6) 13.9 (CH_3, cation), 20.5 (CH_3, anion), 22.2, 25,6, 28.8, 28.9, 29.06, 29.09, 29.3, 31.4 (CH_2), 65.9 (CH, anion), 67.9 (O–CH_2), 75.5 (N–CH_2–O) 119.4, 128.6 and 137.8 (imid.), 176.5 (CO).

Ozonation in aqueous solution. Aqueous ozone solution of approx. 5 mg ml^{-1} and of pH = 4.5 was prepared by bubbling ozone-oxygen gas through a 2 g l^{-1} aqueous solution of prepared lactates. The ozone reactor was kept at r.t. The concentration of lactates in the reaction mixture was determined by a direct two-phase back titration technique.[19]

Antimicrobial characteristics. The following microorganisms were used: *Micrococcus luteus* ATCC 9341, *Staphylococcus epidermidis* ATCC 12228, *Staphylococcus aureus* ATCC 6538, *Staphylococcus aureus (MRSA)* ATCC 43300, *Enterococcus hirae* ATCC 10541, *Escherichia coli* ATCC 25922, *Proteus vulgaris* NCTC 4635, *Klebsiella pneumoniae* ATCC 4352, *Pseudomonas aeruginosa* ATCC 27853, *Serratia marcescens* ATCC 8100, *Candida albicans* ATCC 10231 and *Rhodotorula rubra* PhB. The *Rhodotorula rubra* was obtained from Department of Pharmaceutical Bacteriology, University of Medicinal Sciences, Poznań. Antimicrobial activity was determined by the tube dilution method. Bacteria strains were cultured in Mueller–Hinton broth for 24 h and fungi on Sabouraud agar for 48 h. Suspensions of standard microorganisms at a concentration of 10^6 cfu ml^{-1} were prepared from each culture. Then to each dilution the broth medium inoculated with the suspension mentioned above was added in a 1 : 1 ratio. Growth of the microorganisms (or its lack) was determined visually after incubation for 24 h at 37 °C (bacteria) or 48 h at 28–30 °C (fungi). The lowest concentration at which there was no visible growth (turbidity) was taken as the minimal inhibitory concentration (MIC). Then, from each tube content 10 ml (calibrated loop) was smeared on an agar medium with inactivates (0.3% lecithin, 3% polysorbate 80 and 0.1% cysteine L) and incubated for 48 h at 37 °C (bacteria) or for 5 days at 22 °C (fungi). The lowest concentration of the lactates that kills 99.9% or more of the test

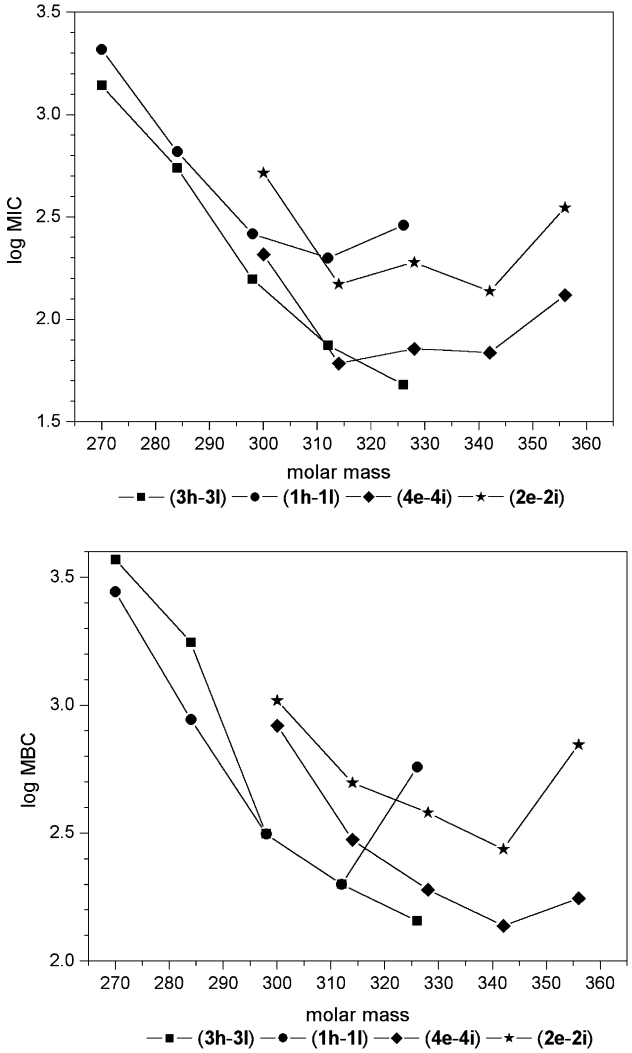

Fig. 4 Mean MIC and MBC values for fungi.

microorganism was defined as the minimum biocidal concentration (MBC).

Conclusion

In conclusion we found protic ILs, containing an organic anion such as lactate, to exhibit similar properties to widely studied aprotic ILs. The choice of an organic anion such as lactate was dictated by its non-toxic and pharmaceutically acceptable character, making the resulting ILs environmentally-friendly. These ILs are soluble in water and equipped with short substituents, they do not affect microbiological flora. In addition their decomposition by ozonation is very effective.

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Soybean oil epoxidation with hydrogen peroxide using an amorphous Ti/SiO_2 catalyst

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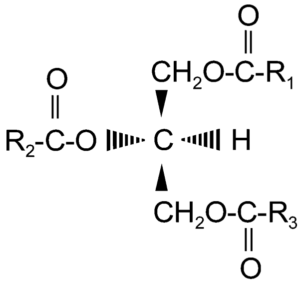
We report a study of the epoxidation of soybean oil and soybean methyl esters with hydrogen peroxide in dilute solution (6 wt%) using an amorphous heterogeneous Ti/SiO_2 catalyst in the presence of *tert*-butyl alcohol. The influence of some relevant process variables such as temperature and the hydrogen peroxide-to-double bond molar ratio on performance is examined. The highest yields of epoxidized olefins were obtained upon using a H_2O_2 : substrate molar ratio of 1.1 : 1. Higher ratios than this were not effective for speeding up the reaction. Under the experimental conditions employed in this work, no degradation of the oxirane ring was observed.

Introduction

Epoxidized vegetable oils (VO) and their derivatives (*e.g.*: fatty acid methyl esters, FAME) have been used for many commercial applications, *e.g.*, as plasticisers and stabilisers in chlorine-containing resins, as additives in lubricants, as components in thermosetting plastics, in cosmetics and pharmaceutical formulations, in urethane foams and as wood impregnants.[1–5] Epoxy fatty acid compounds are obtained at industrial scale mainly by the peracid process.[6–11] The peracid oxidant is obtained *in situ* when a carboxylic acid (usually acetic acid) reacts with hydrogen peroxide in the presence of mineral acids that act as catalysts. Several drawbacks must be improved in the peracid process, including: (i) the selectivity to epoxidized products is relatively low due to acid-catalysed oxirane ring-opening; (ii) the separation of acidic by-products, whose presence may be detrimental for further applications, is not easy; (iii) the handling of highly concentrated hydrogen peroxide and strong acids is dangerous and causes corrosion problems. Thus, in recent years several papers have dealt with the setting up of catalytic processes aimed at overcoming such disadvantages, using more sustainable compounds and technologies.[11–17]

Recently, it has been shown that the incorporation of Ti on an amorphous silica support produces oxidation catalysts that are highly effective in epoxidation reactions with hydrogen peroxide.[18–20] Deployment of this mesoporous support yields active catalysts for the selective oxidation of bulky substrates that are unable to diffuse inside microporous materials, such as the (expensive) titanium silicalites.

From the structural point of view, VOs can be considered to be formed by condensation of a glycerol molecule with three moles of fatty acids (FA), resulting in the formation of a triglyceride molecule and three water molecules.[21] Refined VOs contain a triglycerides percentage of 98%, the other 2% being phosphatides, sterols, tocopherols, free fatty acids, *etc.* Soybean oil (SBO) is a highly unsaturated oil (high iodine value), whose efficient processing affords compounds with a high oxirane index, even though according to its stereochemical structure (Scheme 1) the olefinic chains in triglyceride molecules contain more than 18 carbon atoms. Because of the oxidative properties of Ti/SiO_2 and the advantages related to the use of solid catalysts in industrial processes, the use of these amorphous catalysts could open new possibilities in the field of the utilisation of fatty acids and esters if their double bonds could be selectively and 'deeply' epoxidized, forming stable epoxides, employing only a green oxidant such as hydrogen peroxide (*i.e.*, avoiding the use of peracids).



Scheme 1 Triglyceride structure (R_1, R_2, R_3: alkyl groups).

Results and discussion

The amount of titanium incorporated into the silica support was 0.9 wt%. The nitrogen adsorption–desorption isotherms corresponded to type 4 of the IUPAC classification, which are characteristic of mesoporous materials. They also showed a type H1 hysteresis loop located at relatively high pressures of the adsorbate. This kind of loop is usually displayed by porous materials consisting of agglomerates or a compact packing of nearly uniform, regularly ordered microspheres. The surface area was 214 $m^2\ g^{-1}$, and the pore volume 1.5 mL g^{-1}.

The UV-Visible spectrum of the catalyst is shown in Fig. 1. This electronic spectrum consists of one peak located between 200 and 300 nm, which is characteristic of this kind of catalyst. Detailed line-profile analysis revealed the presence of a weak but sharp contribution close to 225 nm, typical of isolated titanium in tetrahedral coordination[22] and an additional, much more intense component at about 250 nm, characteristic of titanium species coordinated with water.[22] The absence of any signal somewhere around 330 nm precludes the formation of three-dimensional TiO_2 structures.

High-resolution photoelectron spectra of the Ti 2p core-levels of the catalyst outgassed *in situ* at 773 K were recorded. The spectra showed the characteristic spin–orbit splitting of Ti 2p levels (Ti $2p_{3/2}$ and Ti $2p_{1/2}$). Since chemical information can be derived from the analysis of binding energies of each level, attention will only be paid to the most intense Ti $2p_{3/2}$ component of the doublet. The

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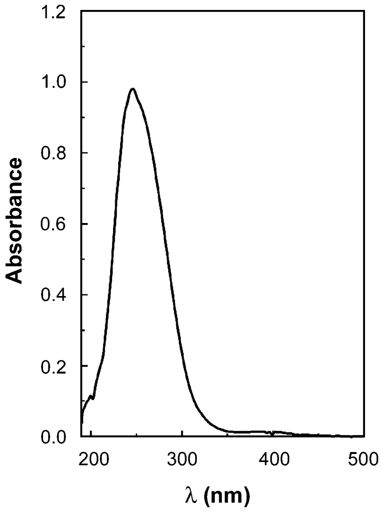

Fig. 1 UV-VIS spectra of the catalyst synthesized.

peak fitting of the experimental Ti $2p_{3/2}$ component revealed one contribution at 460.0 eV, (FWMH = 1.7 eV) typical of Ti(IV) coordinated tetrahedrally to oxide anions.[19,20]

These combined characterization results indicate that the titanium is in a tetrahedral environment, which is currently accepted to be the active site involved in these kinds of oxidation reactions of organic substrates.[22]

The Ti/SiO_2 catalyst was tested in the liquid phase epoxidation of SBO and soybean methyl ester substrates with dilute hydrogen peroxide solutions. Reaction conditions, double bond conversion, mass percent of epoxidized oil and percent yield are shown in Table 1.

First, the effect of temperature on the kinetics of soybean oil epoxidation was investigated. In these experiments, a H_2O_2 : double bond molar ratio of 0.6 : 1 was employed. This ratio was selected to minimize by-product formation through oxirane ring-opening, consecutive reactions. An increase in the reaction temperature from 353 to 368 K led to a remarkable increase in the reaction rate at all times (Fig. 2).

In the next step, the differences in reactivity of SBO and the corresponding methyl esters were investigated. Soybean methyl esters were prepared by derivatizing SBO with sodium methoxide. Under the same reaction conditions, the conversion curves of both substrates followed the same trace (Fig. 3). This finding is in agreement with the performance described in the literature for the epoxidation of these substrates with peracids.[23]

A blank experiment was conducted to check that no decomposition of the hydrogen peroxide had occurred during the epoxidation reaction. To this end, the catalyst was added to a solution of H_2O_2 (6 wt%) in the absence of soybean oil or its methyl ester and kept in a thermostatted bath at 368 K for 48 h, after which the concentration of H_2O_2 was measured. Since the concentration of H_2O_2 was the same as at the beginning, its decomposition into oxygen and water can be ruled out.

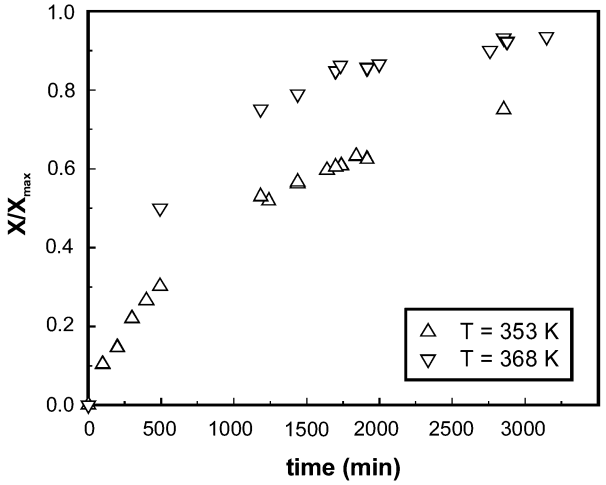

Fig. 2 Influence of temperature on double bond conversion in the epoxidation of soybean oil with hydrogen peroxide (molar ratio H_2O_2 : double bonds = 0.6 : 1, $X_{max} = [(IV_{initial} - IV_{min})/IV_{initial}] \times 100$, $IV_{initial} = 127.67$, IV_{min} (theoretical, molar-ratio based, minimum iodine value) = 51.11).

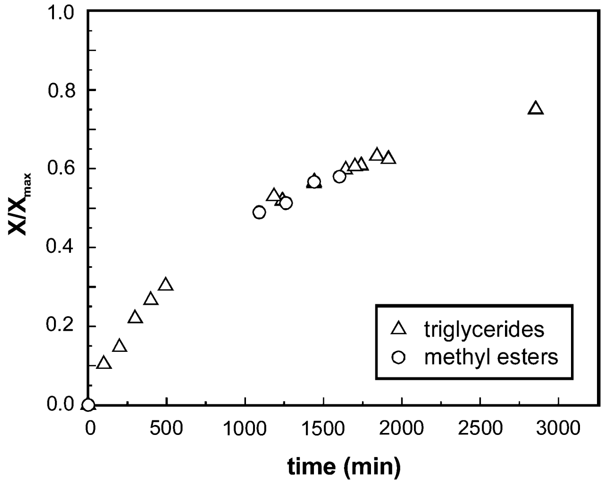

Fig. 3 Influence of the substrate nature on the conversion in the epoxidation of soybean oil with hydrogen peroxide (T = 353 K, molar ratio H_2O_2 : double bonds = 0.6 : 1, $IV_{initial} = 127.67$, IV_{min} (theoretical, molar-ratio based, minimum iodine value) = 51.11). $X_{max} = [(IV_{initial}-IV_{min})/IV_{initial}] \times 100$.

In previous experiments, the molar ratio between H_2O_2 and double bonds (C=C) was kept constant and equal to 1.1 : 1 because

Table 1 Reaction conditions, double bond conversion, mass percent of epoxidized oil and epoxide yield in the study of the epoxidation of soybean oil with hydrogen peroxide in dilute solution (6 wt%) using an amorphous heterogeneous Ti/SiO_2 catalyst in the presence of *tert*-butyl alcohol

Protocol	T/K	H_2O_2 : double bonds molar ratio	Duration/ min	Final IV[a]	Final % conversion[b]	Wt% epoxidized oil[c]	% Yield[d]
1	353	0.6 : 1	2855	70.23	44.99	40.19	43.12
2[e]	353	0.6 : 1	1602	83.27	34.78	32.43	34.80
3	368	0.6 : 1	3147	56.13	56.67	52.20	56.01
4	353	1.1 : 1	2873	37.20	72.03	66.97	71.85
5	353	5.5 : 1	1880	35.71	65.95	60.58	65.00
6	343	1.1 : 1	4320	36.54	71.38	67.09	71.98
7	363	1.1 : 1	3257	13.76	89.22	81.79	87.75

[a] IV stands for Iodine Value.[24] Initial iodine value ($IV_{initial}$) was 127.67. [b] Percent conversion of double bonds, calculated as $X = [(IV_{initial} - IV)/IV_{initial}] \times 100$. [c] Final weight percent of epoxidized oil (% Ep) in the organic phase. [d] Percent epoxide yield, calculated as $Y = [(\%Ep)/(\%Ep_t)] \times 100$, where $\%Ep_t$ stands for the theoretical maximum weight percent of %Ep ($\%Ep_t = 93.16$). [e] Soybean methyl esters ('methyl soyate').

this is the standard ratio used in the epoxidation of this kind of substrate with organic peracids, with only 10% H_2O_2 in excess with respect to the stoichiometric amount.[7] Thus, in order to further explore the influence of the molar ratio of H_2O_2 : C=C on the kinetics of epoxidation, two other levels of this ratio, corresponding to a large excess of the oxidant (5.5 : 1) and an excess of soybean oil (0.6 : 1), respectively, were also examined (Fig. 4). With the excess of soybean oil (molar ratio = 0.6 : 1), the kinetics of epoxidation was slower and led to a lower concentration of epoxides at the end of the reaction than for the 1.1 : 1 ratio, as expected (In this case, a maximum epoxidation of soybean oil of 60% could be achieved. Nevertheless, the kinetics found for the 5.5 : 1 ratio almost coincided with the one obtained with the 1.1 : 1 ratio. This indicates that an optimum in reactivity is obtained for the one-to-one molar ratio of H_2O_2 : double bonds, beyond which the active sites of the catalyst cannot activate the molecules of soybean oil any further. Additionally, the increase in the reaction rate when passing from a deficit of oxidant (0.6 : 1) to nearly the stoichiometric amount (1.1 : 1) or a large excess (5.5 : 1) suggests that the presence of the epoxide product in the reaction environment does not have an inhibitory effect on the kinetics of epoxidation. Notwithstanding, at 353 K the kinetics of epoxidation were rather slow, since a sizable amount of double bonds still remained intact at reaction times as long as about 50 h.

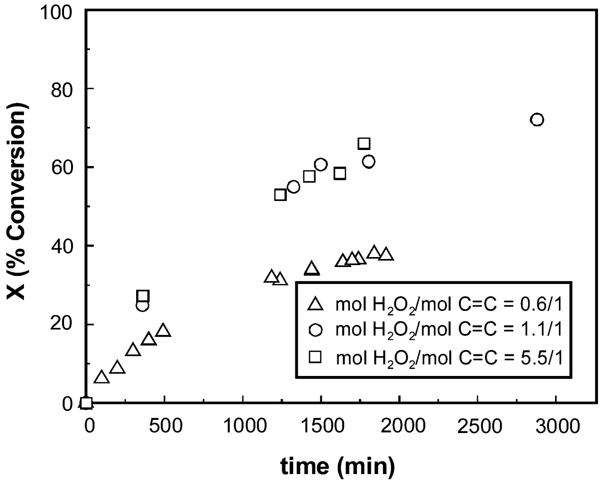

Fig. 4 Influence of the oxidant excess on the conversion in the epoxidation of soybean oil with hydrogen peroxide (T = 353 K).

In light of the above results, it appeared of interest to re-analyze the influence of the reaction temperature, always using the hydrogen peroxide oxidant in a slight excess (molar ratio of H_2O_2 to C=C of 1.1 : 1). As illustrated in Fig. 5, there was a remarkable impact of the reaction temperature on the epoxidation rate. At 363 K, under these experimental conditions double bond conversion levels above 90% were achieved, although such levels were obtained at still relatively long reaction times (> 54 h).

Gas-chromatography analysis is a powerful tool for identifying and quantifying reaction products, as it is able to simultaneously distinguish between the methyl esters of fatty acids and their epoxides and glycols as well.[24] Since the amounts of glycols in all GC analyses were negligible, no opening of the oxirane ring took place. Thus, it may be concluded that the epoxidation reaction using this amorphous Ti/SiO_2 is highly selective toward epoxide formation, even though long reaction times are required to achieve high conversion levels of soybean oil.

Despite this, if a comparison is made between the epoxidation reaction of SBO with the conventional peracid technology and the one described in this contribution, with a heterogeneous Ti/SiO_2 catalyst, an important advantage of the latter method is seen. The conventional peracid process is coupled with the *in situ* production of peracetic acid (usually at 333 K), by dropwise dosing H_2O_2(aq.) at *ca.* 30 wt% concentration, employing a C=C : H_2O_2 : acetic acid molar ratio of 1 : 1.1 : 0.5.[5,7] Under these conditions, low iodine values are obtained for reaction times close to 240 min, although the epoxide yields are deficient because one fraction of the epoxide produced is degraded through ring-opening reactions of the oxirane product. However, the amorphous heterogeneous Ti/SiO_2 catalyst does not degrade the oxirane ring, even though the reaction rate is slower than in the peracid route. Thus, this new heterogeneous process for epoxidizing vegetable oils with only aqueous H_2O_2 (*viz.*, no acids) in the presence of a Ti/SiO_2 catalyst has great potential for applications at industrial scale because corrosive or dangerous reactants are no longer necessary and the complex and costly separation steps after the reactor are also avoided.

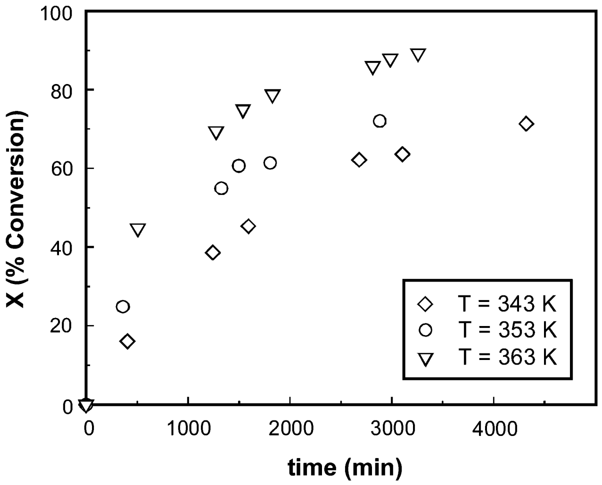

Fig. 5 Influence of temperature on the conversion in the epoxidation of soybean oil with hydrogen peroxide (molar ratio H_2O_2 : double bonds = 1.1 : 1).

However, to be green, the process outlined in the present paper requires an easy separation of products and recycling of solvents at the end of the reaction. The strategy to be implemented once the reaction is finished is the following: at the end of each batch run, after stopping stirring, there will be a (denser) aqueous phase at the bottom of the reactor, which can be simply removed (together with the heterogeneous catalyst) by means of a bifurcation and a three-way valve placed below the vessel and—after mechanical separation of the catalyst—subjected to distillation/rectification to recover *tert*-butanol and 1-phenylethanol from this polar phase. The mixture of epoxidized oil will be fractionated because the vapor pressures of the different compounds that constitute the non-polar organic mixture are very different. The solvents employed do not form azeotropic mixtures and have very different vapour pressures with respect to vegetable oils, which are known to have boiling points well above 613 K (Table 2).

Conclusions

The epoxidation of soybean oil with dilute solutions of hydrogen peroxide in a polar organic medium in the presence of an amorphous Ti/SiO_2 catalyst and *tert*-butanol as diluent of the reactants affords high reaction yields and selectivities to epoxide. The use of a H_2O_2 : C=C molar ratio of 1.1 : 1, slightly higher than the stoichiometric one, gives the highest reaction rate; no further enhancement is obtained by using hydrogen peroxide in a large excess. Even at the highest temperature explored (353 K), which is compatible with the stability of the reactants and products, the reaction time is prolonged if a small amount of catalyst is employed. Notwithstanding, the absence of unwanted side reactions and the negligible decomposition of H_2O_2 deserve further in-depth analyses of the process variables.

Table 2 Vapor pressure of the solvents employed in the epoxidation reaction

	Vapour pressure/Pa		
T/K	1-Phenylethanol	*tert*-Butanol	Water
283	25	1946	1228
293	45	3960	2333
303	80	7533	4240
313	139	13452	7373
323	233	22838	12332
333	388	37050	19918
343	632	57714	31157
353	1015	86845	47342
363	1604	126649	70086
368	2005		84512
373	2498		101323
383	3836		
393	5813		
403	8696		
413	12852		
423	18775		
433	27125		
443	38772		
453	54859		
463	76866		
473	106700		

Experimental

Catalyst synthesis and characterization

The supported titanium catalyst was prepared according to some reports in the literature.[18–20] Titanium isopropoxide (Aldrich, reagent grade; St. Louis, MO, USA) (0.75 g) was dispersed in cyclohexanol (150 mL). The solution was heated to 423 K under stirring and then silica (5.0 g) (Grace Davison G-952, BET surface area: 310 m^2 g^{-1}, pore volume: 1.5 mL g^{-1}) was added to the solution, which was kept under vigorous stirring at 423 K for 2 h. The solid thus obtained was filtered off and washed twice with 150 mL of hot solvent, dried at 383 K, and finally calcined at 773 K for 5 h.

The titanium content of the Ti/SiO_2 catalyst was determined using inductively-coupled plasma absorption spectrometry, with a Perkin-Elmer Optima 3300 DV instrument (MN, USA). The BET specific surface area and pore diameters were determined by N_2-adsorption at 77 K using a Micromeritics Tristar 3000 apparatus (Norcross, GA, USA). Ultraviolet-visible (UV-Vis) spectra were measured on an optic fiber Advantes AVS-2048 optic fiber spectrophotometer (Advantes, The Netherlands) equipped with a total reflection probe. A $BaSO_4$ disc was used as reference. All spectra were acquired under ambient conditions.

X-Ray photoelectron spectra were recorded on a VG Escalab 200R spectrometer (VG Generators, UK) equipped with a hemispherical electron analyzer and a magnesium X-ray source (12 kV and 10 mA) (Mg Kα = 1253.6 eV). The powdered samples were packed into small aluminium cylinders and mounted on a sample rod in the pre-treatment chamber and outgassed at 773 K for 1 h. The base pressure of the ion-pumped analysis chamber was maintained below 3×10^{-9} mbar during data acquisition. Peak intensities were estimated by calculating the integral of each peak after smoothing and subtraction of the "S-shaped" background. All binding energies (BE) were referenced to the adventitious C 1s line at 284.9 eV. This reference gave BE values with an accuracy of ± 0.1 eV.

Activity measurements

Throughout this study a soybean oil (Oleaginosa Humboldt, Santa Fe, Argentina) refined in the laboratory (degummed, neutralized, bleached and deodorized) was employed. Its FA composition was determined by GLC after derivatizing the triglycerides into FAME, following a standard procedure,[24] and was as follows (wt%): saturated FA: 6.8, oleic acid: 23.5, linoleic acid: 61.2; linolenic acid: 8.5. The iodine value (IV) was 127.67.[25]

Epoxidation reactions were carried out batch-wise in a mechanically stirred 250 mL thermostated glass-reactor equipped with a thermometer, a reflux condenser, and a septum for sample withdrawal. In a typical run, 20 g of oil (equivalent to 0.1 mol of double bond), *tert*-butanol (5.81 g) and 0.5 g of catalyst were mixed in the reactor and the suspension was heated to the reaction temperature. Then, 4 g of a 6 wt% organic solution of H_2O_2 (in 1-phenylethanol) was added dropwise to the reactor suspension while maintaining vigorous stirring over 20 min. Aliquots of 4 mL were periodically taken from the reactor. All reagents were purchased from Fisher Scientific (Pittsburg, PA, USA).

Two kind of analyses were performed with the extracted samples: (i) the iodine value, following the standard method of the American Oil Chemists' Society (AOCS)[25] to evaluate the conversion of unsaturated fatty acids; and (ii) GC analysis, to evaluate the selectivity of organic compounds. A Shimadzu GC-17ATF unit was used, furnished with a PE-5 (Perkin-Elmer, Norwalk, CT, USA) capillary column: 30 m × 0.53 mm ID × 1.5 μm film. Analytical conditions were as follows: split/splitless injector, injector port at 523 K, FID detector at 543 K, H_2 carrier gas (90 psig, 20 mL min^{-1}), and isothermal oven at 473 K. Response factors were obtained using capillary CG, 99% grade, heptadecanoic acid methyl ester (Sigma-Aldrich, St. Louis, MO, USA) as internal standard. Prior to injection, the dry samples were previously derivatized to fatty acid methyl esters with sodium methoxide (Sigma-Aldrich).[26]

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Li–CaO catalysed tri-glyceride transesterification for biodiesel applications

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A series of Li-promoted CaO catalysts with Li loadings in the range 0.26–4.0 wt% have been prepared which are effective in the transesterification of glyceryl tributyrate and methanol to methyl butanoate. A Li content of 1.23 wt% provides the optimum activity towards methyl butanoate formation. Li doping increases the base strength of CaO, and XPS and DRIFTS measurements reveal that the optimum loading correlates with the formation of an electron deficient surface Li^+ species and associated –OH species at defect sites on the support. High Li loadings result in bulk $LiNO_3$ formation and a drop in surface area and corresponding catalytic activity.

Introduction

Biodiesel is a biodegradable, nontoxic alternative fuel comprised of mono alkyl esters of long chain fatty acids, which are derived from vegetable oils or animal fats.[1] Biodiesel is oxygenated and essentially free of sulfur making it a cleaner burning fuel than petroleum diesel with reduced emissions of SO_x, CO, unburnt hydrocarbons and particulate matter.[2] Commercial biodiesel is produced from renewable resources including rapeseed, sunflower or soya bean oil which are composed of C_{14}–C_{20} fatty acid tri-glycerides.[3] These are converted to the respective alkyl ester and glycerol by transesterification with short chain alcohols, typically methanol or ethanol.[4] Methanol is generally preferred as it is cheap and readily available from syngas.[5] Transesterification can be performed using homogeneous basic catalysts including Na or K hydroxides, carbonates or alkoxides. Base catalysis is preferred to acid catalysed routes using sulfuric or sulfonic acids, which are more corrosive with lower activities.[1] However removal of the base after reaction is a major problem since aqueous quenching results in the formation of stable emulsions and saponification, making separation of the methyl ester difficult.[6] The use of a solid base catalyst offers several process advantages including the elimination of a quenching step (and associated contaminated water waste) to isolate the products, and the opportunity to operate in a continuous process.[7,8]

A variety of solid bases are known including alkali or alkali earth oxides, supported alkali metal ions, basic zeolites and clay minerals such as hydrotalcites.[9] Alkali earth oxides have potential as solid bases for use in tri-glyceride transesterification.[6] The origin of basic sites in alkali earth oxides has been the subject of review, and it is generally believed they are generated by the presence of M^{2+}–O^{2-} ion pairs in different coordination environments.[10] Basic low coordination sites thus exist at corners, edges or high Miller index surfaces. The basic strength of the group 2 oxides and hydroxides increase in the order $Mg < Ca < Sr < Ba$.[11] Of these Ca-derived bases are the most promising as they are inexpensive, exhibit low methanol solubilities and are the least toxic.[6] Additional promotion of basicity in alkali earth oxides can be achieved *via* doping with alkali metal. An increase in the number of basic sites is believed to occur *via* the exchange of lattice M^{2+} for M^+ upon calcination, leading to formation of O^- anion vacancies.[12] To date there are no systematic investigations into the application of alkali metal doped CaO in biodiesel synthesis.

Mechanistic studies of biodiesel synthesis from crude feedstock are complicated by the range of C_{14}–C_{20} fatty acid components, hence we chose glyceryl tributyrate as a simpler model substrate for screening catalytic activity. Here we report the detailed characterisation of a series of Li doped CaO catalysts and correlate their physicochemical properties with their activity in the transesterification of glyceryl tributyrate with methanol.

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Experimental

Catalyst preparation

A series of $LiNO_3$ impregnated CaO catalysts were prepared by wet impregnation with theoretical Li contents in the range 1–20 wt%. In a typical preparation 10 g of CaO (Aldrich 99.9%) was impregnated using 50 cm^3 of an aqueous $LiNO_3$ (Aldrich 99.9%) solution of appropriate concentration. The slurry was stirred for 2 hours, then evaporated to dryness and dried at 100 °C for 24 hours.

Catalyst characterisation

Li analysis was performed using a Perkin Elmer PU 9200 atomic absorption spectrometer. DRIFTS spectra were obtained using a Bruker Equinox 55 FTIR spectrometer. Samples were diluted with KBr powder (10 wt% in KBr), then loaded in an environmental cell and subjected to an additional drying under vacuum at 60 °C for 10 minutes prior to measurements to remove moisture physisorbed during air-exposure. Surface area measurements were performed by N_2 physisorption using a Micromeritics ASAP 2010 instrument. Surface areas were calculated using the BET equation over the pressure range $P/P_0 = 0.02$–0.2, where a linear relationship was maintained. XPS measurements were performed using a Kratos AXIS HSi instrument equipped with a charge neutraliser and Mg K_α X-ray source. Spectra were recorded at normal emission using an analyser pass energy of 20 eV, X-ray power of 144 W and were energy referenced to the valence band and adventitious carbon.

Base strength was determined by Hammett indicators; ~25 mg of sample were shaken with 1 cm^3 of a solution of Hammett indicator diluted in methanol and left to equilibrate for 2 hours. The colour on the catalyst was then noted. The following Hammett indicators were used: neutral red ($pK_{BH^+} = 6.8$), phenolphthalein ($pK_{BH^+} = 8.2$), Nile blue ($pK_{BH^+} = 10.1$), Tropaeolin-O ($pK_{BH^+} = 11$), 2,4-dinitroaniline ($pK_{BH^+} = 15$) and 4-chloro-2-nitroaniline ($pK_{BH^+} = 17.2$). While Hammett indicator measurements are conventionally performed using non-polar solvents,[13] it was deemed appropriate to use methanol in this instance, as a measure of the base strength of the catalyst under reaction conditions would thus be determined. The base strength is quoted as being stronger than the weakest indicator which exhibits a colour change, but weaker than the strongest indicator that produces no change.

Transesterification reaction

Reactions were performed in a stirred batch reactor with samples withdrawn periodically for analysis using a Shimadzu GC17A Gas

Chromatograph fitted with a DB1 capillary column (film thickness 0.25 μm, i.d. 0.32 mm, length 30 m), and AOC 20i autosampler. Transesterification reactions were performed at 60 °C using 0.36 g of glyceryl tributyrate (Aldrich 98%), 11.87 g of methanol (Fisher 98%), 0.1 g of catalyst, with 0.1 g of dihexyl ether (Aldrich 97%) added as internal standard. Reactions were run for 3 h with initial rates determined from the linear portion of the conversion profile. Catalyst selectivity and overall mass balances (closure was > 98%) were determined using reactant and product response factors (1.52 and 1.58 for glyceryl tributyrate and methyl butanoate respectively) derived from multi-point calibration curves. The systematic errors in the conversions and selectivities are ± 2% and ± 3% respectively.

Results and discussion

Successful impregnation of the CaO support was confirmed by elemental analysis shown in Fig. 1, which demonstrates a linear rise in Li content as the concentration of the impregnating solution increased. The deviation between the theoretical and actual Li loadings is attributable to the water of hydration of $LiNO_3$, determined to be 1.2 H_2O from the Li assay. Using this correction factor the theoretical values were in good agreement with those observed by elemental analysis.

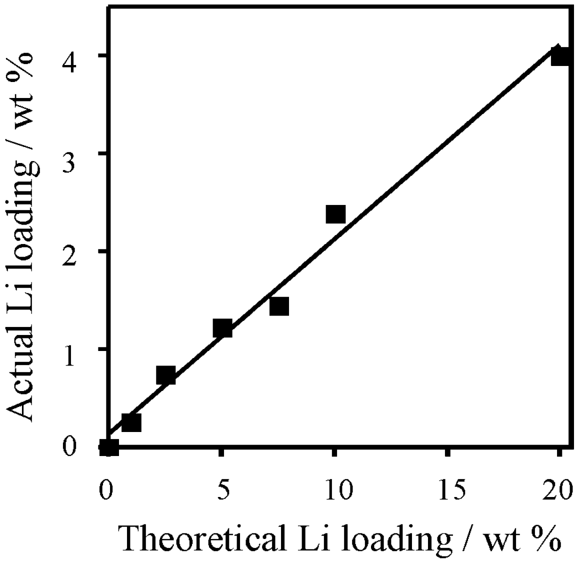


Fig. 1 Theoretical *versus* actual total Li content of $LiNO_3$ doped CaO.

BET surface areas of the resulting materials were determined by N_2 physisorption and the values are shown in Table 1. The parent CaO had a relatively low surface area of 20 $m^2\ g^{-1}$ in agreement with literature values.[14] $LiNO_3$ impregnation caused a slow continuous fall in surface area with rising Li content up to 2.4 wt% Li, above which the area dropped sharply to ~ 8 $m^2\ g^{-1}$ for the 4 wt% Li/CaO sample. This decrease may reflect micropore blockage followed by crystallization of a bulk $LiNO_3$ phase at the highest loading.

Table 1 Surface areas of $LiNO_3$ impregnated CaO samples

Sample	Surface area/$m^2\ g^{-1}$
CaO	20
0.26 wt% Li/CaO	18
0.76 wt% Li/CaO	17
1.23 wt% Li/CaO	16.5
1.45 wt% Li/CaO	16
2.40 wt% Li/CaO	15
4.00 wt% Li/CaO	8

Table 2 presents the results of base strength measurements on $LiNO_3$ impregnated CaO as a function of Li content using a series of basic indicators. The measurement of acid/base distributions of porous catalysts by such measurements remains controversial due to solvent-support interactions and the accessibility of the probe molecule within the micropores.[15] Consequently, for these measurements indicator solutions were prepared using methanol so that the surface basicity would be a truer reflection of that expected under reaction conditions, permitting semi-quantitative determination of the maximum strength of the solid base. From these measurements it can be seen that the pK_{BH+} of CaO is $10 > pK_{BH+} > 8$, whereas all the $LiNO_3$ impregnated samples have a $17.2 > pK_{BH+} > 15$.

Table 2 Basicity of $LiNO_3$ impregnated CaO samples

Sample	Base strength (pK_{BH+})
$LiNO_3$	—
CaO	$10 > pK_{BH+} > 8$
0.26 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$
0.76 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$
1.23 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$
1.45 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$
2.40 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$
4.00 wt% Li/CaO	$17.2 > pK_{BH+} > 15.0$

Fig. 2 shows the wide XPS scans for CaO and a 2.4 wt% $LiNO_3$ impregnated CaO sample. The CaO surface solely comprised Ca, O and trace C. Li and N signals emerged upon impregnation with $LiNO_3$, accompanied by an increased O signal. Figs. 3a–d present the high resolution O 1s, N 1s, Ca 2p and Li 1s regions for the series of impregnated samples. The O 1s spectra of CaO gave a single feature at 529.6 eV corresponding to lattice O^{2-} in agreement with literature values.[16] Following impregnation with $LiNO_3$ a new state appeared at 531.8 eV, its intensity increasing with Li loading, coincident with the O 1s reference spectrum from $LiNO_3$. Inorganic nitrates are reported to have O 1s binding energies over the range 531.4–532.8 eV hence this second state can be assigned to the presence of surface NO_3^- species.[16] Confirmation of this assignment is provided in Fig. 3b which shows the evolution of the corresponding N 1s state at 405.8 eV, which is consistent with the binding energy of the $LiNO_3$ reference and of literature values

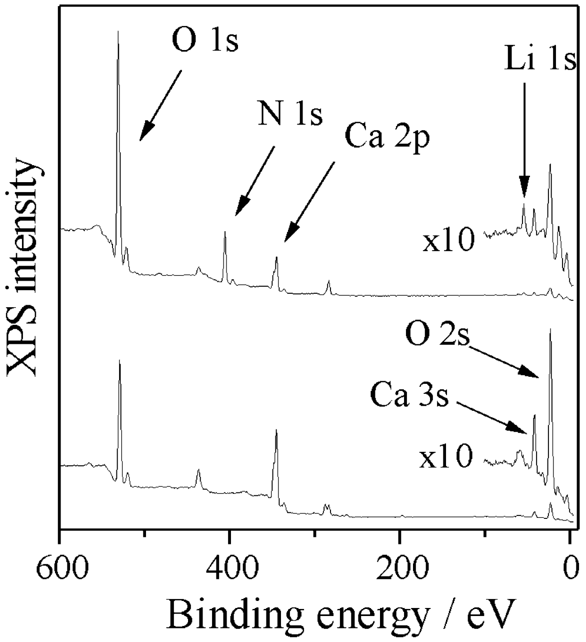


Fig. 2 Wide XP spectra of (bottom) CaO support and (top) 2.4 wt% $LiNO_3$ impregnated CaO.

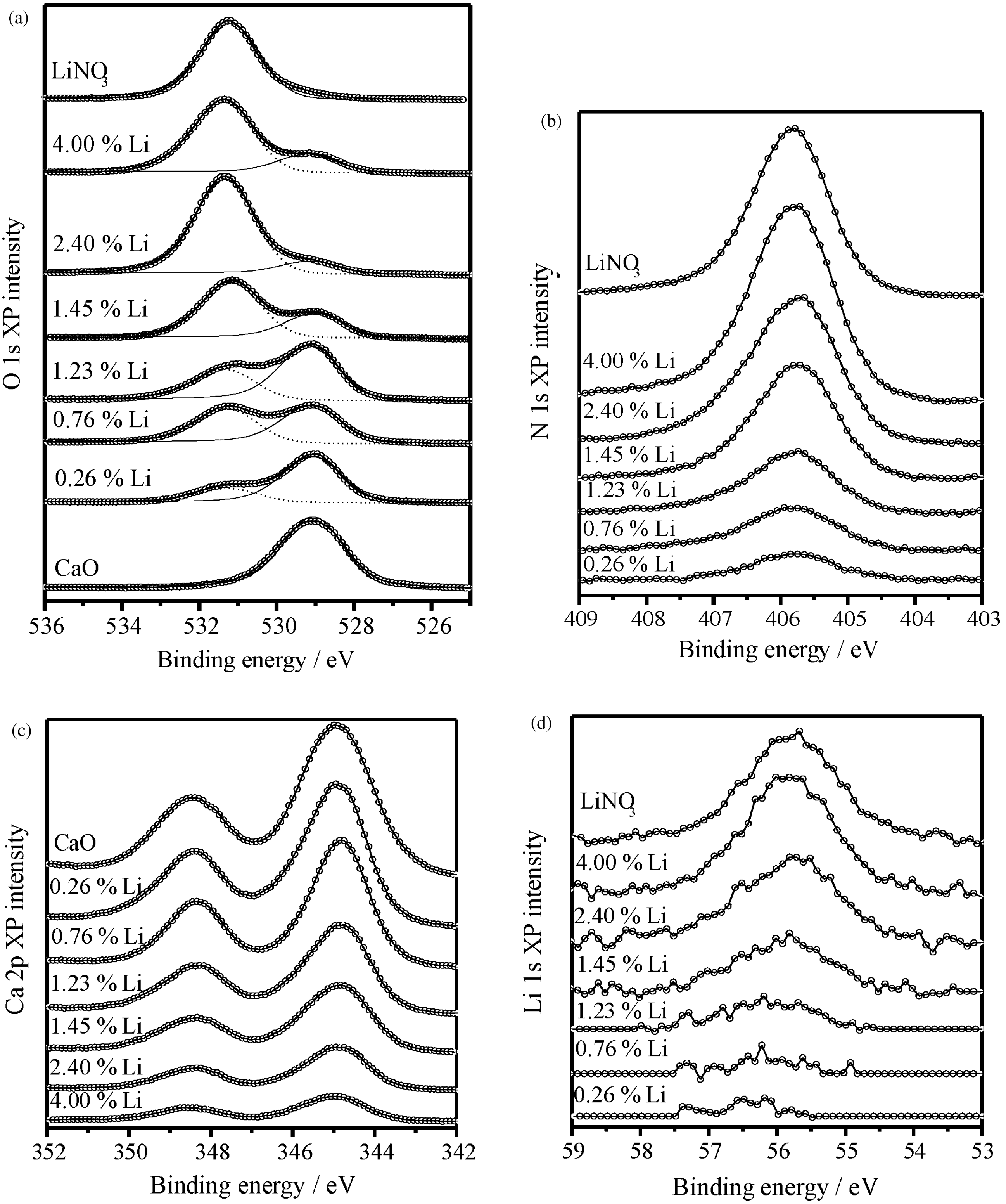


Fig. 3 (a) O 1s XP spectra of CaO and $LiNO_3$ impregnated CaO samples. (b) N 1s XP spectra of $LiNO_3$ impregnated CaO samples. (c) Ca 2p XP spectra of CaO and $LiNO_3$ impregnated CaO samples. (d) Li 1s XP spectra of $LiNO_3$ impregnated CaO samples.

which are reported up to 407.3 eV.[17] Only a single NO_3^- nitrogen environment was present for all samples indicating negligible decomposition of surface NO_3^- accompanied $LiNO_3$ impregnation.

Fig. 3c shows the associated Ca 2p spectra for the impregnated samples. Pure CaO exhibited a well-resolved spin orbit split 2p doublet (Δ = 3.45 eV) with the $2p_{3/2}$ at 345.3 eV.[18] Following impregnation with $LiNO_3$ the Ca signal was progressively attenuated in accordance with deposition of surface $LiNO_3$. Neither the Ca 2p binding energy nor peak shape changed following impregnation, suggesting a common Ca chemical environment and the absence of direct Ca–Li or Ca–NO_3 interactions.

In contrast the binding energy of the Li 1s spectra, shown in Fig. 3d, decreased with increasing Li content. The lowest loading 0.26 wt% Li sample exhibited a weak peak at ~ 56.3 eV which shifted to lower binding energy reaching a limiting value of 55.7 eV for the highest loading 2.4 and 4 wt% Li samples, matching that of the $LiNO_3$ reference.[17] The variation in Li 1s binding energy with loading is shown in Fig. 4, together with the corresponding integrated Li 1s and N 1s intensities. The latter were converted into surface atomic percentages using eqns. 1 and 2.

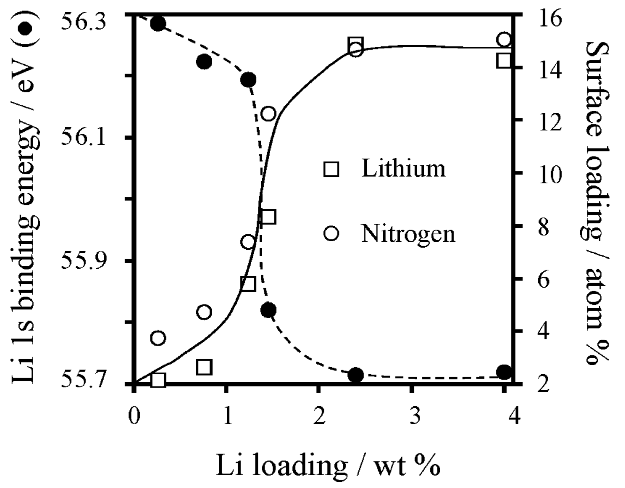


Fig. 4 Correlation between Li 1s binding energy and Li and N surface concentration as a function of $LiNO_3$ loading.

$$\text{Li (atomic \%)} = \frac{I^{\mathrm{Li}}/RF^{\mathrm{Li}}}{(I^{\mathrm{Li}}/RF^{\mathrm{Li}}) + (I^{\mathrm{O}}/RF^{\mathrm{O}}) + (I^{\mathrm{Ca}}/RF^{\mathrm{Ca}}) + (I^{\mathrm{N}}/RF^{\mathrm{N}})} \tag{1}$$

$$\text{N (atomic \%)} = \frac{I^{\mathrm{N}}/RF^{\mathrm{N}}}{(I^{\mathrm{Li}}/RF^{\mathrm{Li}}) + (I^{\mathrm{O}}/RF^{\mathrm{O}}) + (I^{\mathrm{Ca}}/RF^{\mathrm{Ca}}) + (I^{\mathrm{N}}/RF^{\mathrm{N}})} \tag{2}$$

where *RF* and *I* are the relative atomic sensitivity factor and signal intensity for the respective element.

A rise in the total Li loading was matched by increased Li and N surface concentrations, which both reached a plateau for 2.4 wt% total Li. A 1 : 1 atomic ratio of Li : N was maintained for all Li loadings.

The growth of surface Li and NO_3 species mirrored the decrease in Li 1s binding energy, which showed little change up to 1.23 wt% Li but dropped rapidly at higher loadings. Interpretation of core-level binding energy shifts is complex as they depend upon both initial- and final-state contributions.[18] However the correspondence between the limiting Li, O and N 1s spectra and the pure $LiNO_3$ reference, suggests a distinct switchover from highly electron-deficient surface Li in the low coverage regime, to a $LiNO_3$ environment above 1.45 wt% Li. This may reflect a transformation from dispersed free Li^+ ions trapped at defects in the submonolayer regime, to bulk (possibly crystalline) $LiNO_3$ multilayers.

Figs. 5a and b show the DRIFTS spectra recorded over the range 3600–3680 cm^{-1} and 725–750 cm^{-1}, corresponding to the ν(–OH)[19] and $\nu_4(NO_3)$[20] vibrational ranges respectively. CaO exhibited a weak mode at 3642 cm^{-1} which showed negligible increase upon treatment with H_2O and is attributed to the limited –OH functionality on the CaO surface. Hydrated CaO is reported to exhibit 2 types of hydroxyl modes at 3690 and 3640 cm^{-1} which are assigned respectively to $Ca(OH)_2$ and –OH bound at interstitial defects.[19] The mode at 3642 cm^{-1} in Fig. 5a therefore arises from hydroxyl groups formed by H_2O adsorption at defect sites in the CaO lattice. The intensity of this band increased following impregnation by $LiNO_3$, without a significant change in vibrational frequency. LiOH and $LiOH{\cdot}xH_2O$ are expected to exhibit respective vibrational modes at 3677 and 3565 cm^{-1}, and growth of the hydroxyl peak cannot therefore be associated with LiOH formation.[21] A possible explanation is that the adsorption of Li^+ ions promotes hydration of CaO defect sites. Fig. 5b shows the simultaneous evolution of a surface nitrate species, as evidenced by the ν_4 vibrational mode of NO_3^- at 736 cm^{-1}, which increases with Li loading, saturating above 2.4 wt% Li. Combined with the N 1s XP data these spectra provide strong evidence for both the non-dissociative adsorption of NO_3^- ions over the CaO surface, and the formation of $LiNO_3$ multilayers for high Li loadings.

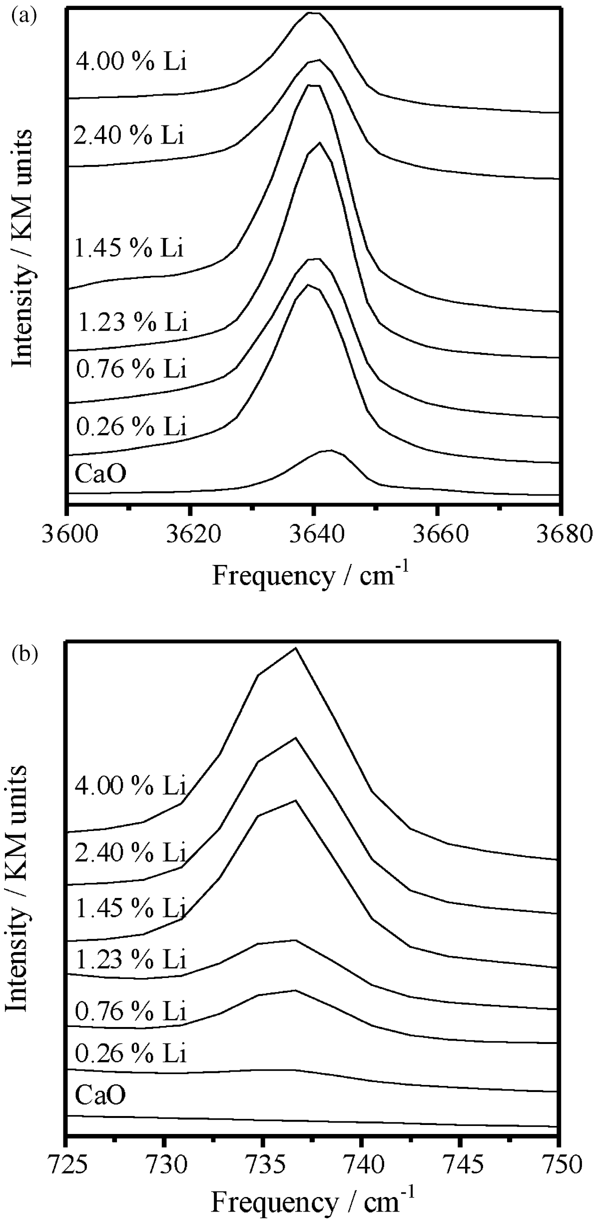


Fig. 5 (a) DRIFTS spectra of hydroxyl band intensity of CaO and $LiNO_3$ impregnated CaO samples. (b) DRIFTS of ν_4 (NO_3) mode as a function of Li loading.

The integrated intensities of the –OH and NO_3 vibrational modes are shown in Fig. 6. The intensities of both modes increase with Li content up to 1.45 wt% Li, at which point the intensity of the NO_3 mode saturates whereas that of the –OH mode decreases. These observations are consistent with earlier XPS measurements which indicate a transformation in the nature of the Li surface species above 1.23 wt% Li, and the attainment of characteristic bulk $LiNO_3$ structural and chemical properties for higher loadings.

The transesterification of glyceryl tributyrate was subsequently investigated using this series of $LiNO_3$/CaO catalysts. Fig. 7(a) shows a typical reaction profile obtained using the 2.4 wt% Li/CaO

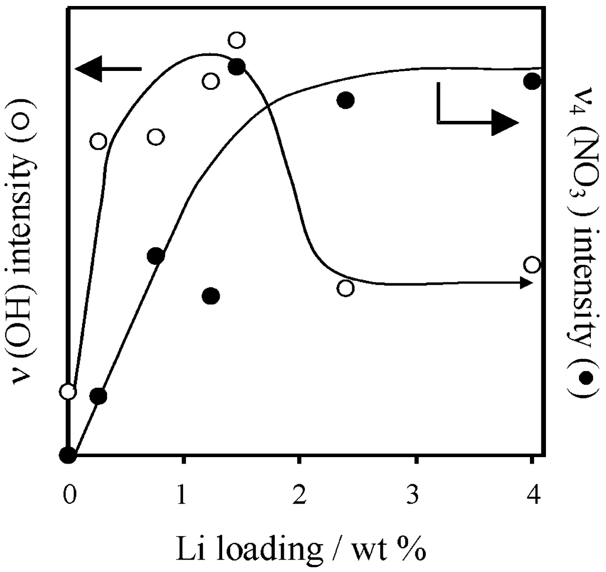
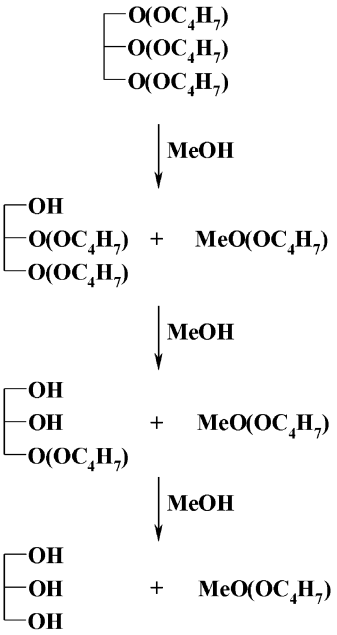


Fig. 6 Trend in ν(OH) and ν_4(NO_3) vibrational modes as a function of Li loading.

catalyst. Conversion of the tri-glyceride to the methyl ester was observed, while trace amounts of first di- and then mono-glycerides were formed and consumed as illustrated in the proposed reaction Scheme 1.

The conversion of glyceryl tributyrate is shown in Fig. 7(b) as a function of Li loading. CaO exhibited poor activity in transesterification, with only 2.5% conversion being observed after 20 minutes reaction. In contrast catalysts with as little as 0.23 and 1.23 wt% Li loadings showed greatly enhanced performances with 83 and 100% conversion observed respectively after the same reaction time. Further increases in Li content proved detrimental to catalyst activity with the 4 wt% Li sample giving only 37% conversion. Negligible leaching of $LiNO_3$ occurred during reaction; catalysts were successfully filtered and recycled with minimal (~ 10%) loss of activity. Pure $LiNO_3$ was inactive for transesterification, hence the influence of trace homogeneous Li^+ species can be discounted.

Fig. 8 shows that the initial rate of transesterification increased continuously with Li loading in the low surface coverage regime, passing through a maximum at 1.23 wt% Li. Higher loadings, associated with multilayer (bulk) $LiNO_3$, produced a dramatic decrease in activity.



Scheme 1 Transesterification of glyceryl tributyrate with methanol to glycerol and methyl butanoate.

XPS measurements showed the existence of a chemically distinct Li species in the low loading (high activity) regime, which we associate with dispersed Li^+ within the monolayer. These are an obvious candidate for the active phase promoting transesterification over CaO. Support for this postulate was sought by correlating the concentration of electronically perturbed surface Li, with the initial rates shown in Fig. 8. Since the Li 1s binding energy is sensitive to the Li electronic state, the product of the binding shift (ΔBE relative to $LiNO_3$), and the Li surface atom concentration, should provide such a measure of the number of "active" Li species.

Fig. 8 reveals a strong correlation between the concentration of perturbed surface Li species and the catalytic activity of Li doped CaO, both passing through a sharp maximum for 1.23 wt% Li and

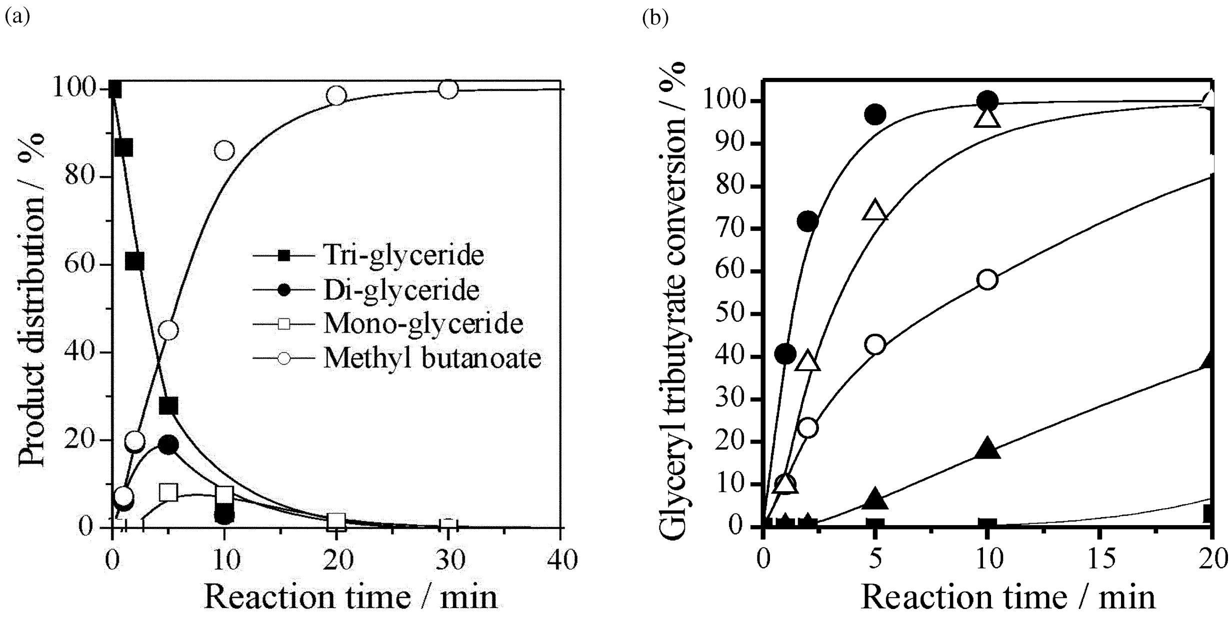


Fig. 7 (a) Reaction profile for the transesterification of glyceryl tributyrate with methanol using a 2.4 wt% Li/CaO catalyst. (b) Conversion of glyceryl tributyrate observed for the series of Li/CaO catalysts: ■ = CaO; ○ = 0.25 wt% Li/CaO; ● = 1.23 wt% Li/CaO; △ = 2.4 wt% Li/CaO; ▲ = 4.0 wt% Li/CaO.

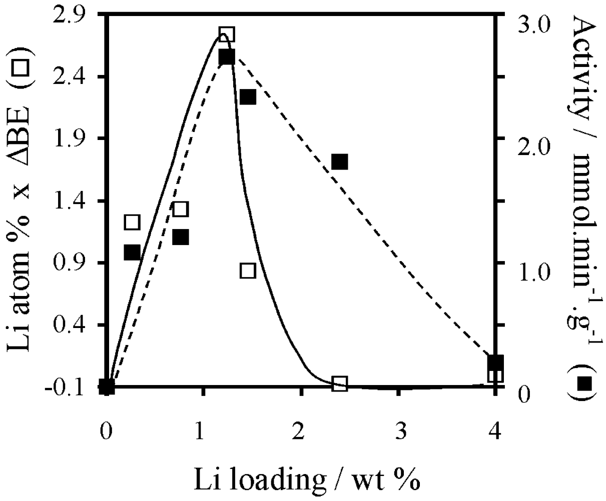


Fig. 8 Correlation between activity and number of electronically-perturbed Li sites in Li/CaO catalysts.

falling as bulk $LiNO_3$ overlayers are formed. The deviation at high Li loadings may be accounted for by the very short inelastic mean free path of Li 1s photoelectrons ($\lambda \sim 6$ Å).[18] Formation of $LiNO_3$ multilayers for loadings > 1.23 wt% Li, would strongly attenuate any contribution from catalytically-active Li species remaining at the CaO–$LiNO_3$ interface. This would produce a sharp decrease in ΔBE and thus the amount of active Li detectable by XPS, while substrate reaction at defects/cracks in the $LiNO_3$ overlayer may still continue at a relatively high rate. Clearly the electronic state of Li in the submonolayer regime is critical to maintaining high activity in transesterification.

We tentatively propose that in the low coverage regime, CaO acts as a surface for the adsorption of $LiNO_3$ as highly dispersed Li^+ and NO_3^- entities. Isolated Li^+ species react with CaO to generate defect sites which in the presence of H_2O form surface hydroxyl groups. As the surface density of Li^+ and NO_3^- increases XPS and DRIFTS show the formation of $LiNO_3$ becomes favoured.

Conclusions

A series of $LiNO_3$ impregnated CaO samples have been prepared which are effective catalysts in the transesterification of glyceryl tributyrate with methanol. An optimum Li content of 1.23 wt% gave maximum activity for methyl butanoate formation. Lithium incorporation is shown to increase the base strength of CaO. XPS and DRIFTS measurements show that this optimum loading correlates with the formation of an electron deficient Li^+ species and the evolution of –OH species at defect sites on the support.

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PAPER
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Quantification of chloride ion impurities in ionic liquids using ICP-MS analysis

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The residual chloride ion content in 1-butyl-3-methylimidazolium tetrafluoroborate, [bmim]BF_4, prepared *via* various methods, was analysed by ICP-MS. A preliminary analysis was also performed on 1-butyl-3-methylimidazolium hexafluorophosphate, [bmim]PF_6.

Room temperature ionic liquids have received substantial attention recently as neoteric solvents capable of facilitating a number of catalytic organic tranformations.[1] They are characterized by a unique series of properties including a lack of volatility, a polar non-coordinating nature and a broad liquid range. These properties have enabled catalysts used in ionic liquid systems to be recycled without loss of activity and have resulted in enhancements in yields, rates and selectivities. The physical properties of several ionic liquids such as those that are based on 1,3-dialkylimidazolium ions, have for the most part been reasonably well documented.[2] However, it has been noted that most authors do not yet report water content, drying procedures, if any, or impurity levels.[3] Lack of such data have resulted in inconsistently reported physical properties such as melting point.[4]

Several ionic liquids are generated from their halide salt precursors *via* a metathesis reaction. For example, 1-butyl-3-methylimidazolium chloride, [bmim]Cl, undergoes metathesis with sodium tetrafluoroborate, $NaBF_4$, in acetone or with hydrogen tetrafluoroborate, HBF_4(aq), to afford 1-butyl-3-methylimidazolium tetrafluoroborate, [bmim]BF_4. Quantitative analysis of residual chloride impurities in such preparations using Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) has not yet been reported in detail in the literature. It must be noted that ICP-Atomic Emission Spectroscopy has been applied in the case of determination of the amount of immobilized chloroaluminate ionic liquids on a solid support[5] which is different from the analysis undertaken here. Halide impurities, if present, account for discrepancies observed in literature melting points and viscosity measurements,[6] in addition to residual water or any other impurities. Also numerous catalytic ionic liquid systems[7] may be affected due to poisoning of transition metal catalysts.[8] Thus the importance of utilizing an ionic liquid which is free from impurities such as halide ions is self-evident.

The purity of 1-alkyl-3-methylimidazolium ionic liquid precursors with regards to organic impurities has been determined colorimetrically by Holbrey *et al.*[8] However, the method used to determine the chloride ion content was not discussed in this paper. Detection of residual chloride has been achieved by titration with $AgNO_3$ from an acidic solution.[9,10] The Vollhard method[11] has also been used to compare the results obtained from an analysis of chloride ion content by a chloride-selective electrode.[6] We report herein a detailed, yet simple method for the quantitative analysis of chloride ions in 1-butyl-3-methylimidazolium tetrafluoroborate, [bmim]BF_4, using Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS). The extension of this new method of analysis to other ionic liquids such as 1-butyl-3-methylimidazolium hexafluorophosphate, [bmim]PF_6, as well as to other halide impurities will be discussed.

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Experimental

Reagents

All organic solvents used were reagent grade. Celite '545' filteraid powder was used as supplied by Merck. Ultrapure water (resistivity of 18 MΩ) was used during all stages of synthesis and work-up. Ultrapure water was obtained by reverse osmosis (Milli-RO 12 Plus, Millipore water purification system) followed by water deionization (Sybron/Barnstead filtration unit). Sodium chloride (Fisher Scientific) had a purity of better than 99%.

Instrumentation

The Thermo Elemental VG PQ ExCell (Thermo Electron) ICP-MS was used for the chloride analysis. Samples were weighed using a TR-104 Balance (Denver Instrument Company), readability 0.1 mg, maximum weight capacity 110 g, linearity 0.2 mg, repeatability ±0.1 mg. Glassware used for the ICP-MS analysis was pre-rinsed 3 times with 10% HNO_3 (Trace Metal Grade, Fisher Scientific) followed by washing 3 times with ultrapure water. Sample vials used for the ICP-MS analysis were pre-rinsed with a small amount of the aqueous ionic liquid sample.

ICP-MS acquisition parameters

Instrument detector:	simultaneous
Dynamic range for chloride:	100–20,000 $\mu g\ L^{-1}$
Acquisition mode:	continuous, peak jumping
No. sweeps:	100
Dwell time:	30 ms
Channels per mass:	1
Acquisition duration:	3.00 s
Channel spacing:	0.02 amu
Main scan region:	^{35}Cl (34.96 amu)

Literature methods

Synthesis of [bmim]BF_4 from [bmim]Cl was accomplished using widely used methods from the literature.[11–16] Method A[11] and Method E[15] involved a metathesis reaction using $NaBF_4$ in dry acetone and water respectively whereas Method B,[12] C,[13] D,[14] and F;[16] made use of an acid–base reaction using aqueous HBF_4.

Sample collection

The [bmimBF$_4$] samples from Methods A–F were taken during various stages of the workup procedure in addition to the final isolated product.

Sample preparation

Approximately 100 mg of each [bmim]BF$_4$ sample were accurately weighed then pre-dried under high vacuum at 90 °C for 4 h then accurately re-weighed immediately. The samples were then prepared by dilution in ultrapure water in a 10-mL volumetric flask. Some samples required further dilution by a factor of 50 in order to avoid inaccurate measurements associated with saturation of the ICP-MS detector.

ICP-MS analysis

^{35}Chlorine isotope. The ^{35}Cl isotope was selected for analysis as the ^{37}Cl isotope is subject to interference from the polyatomic ion ^{36}Ar^{1}H. The natural abundance of ^{35}Cl is 75.53 percent.

ICP-MS optimization. The ICP-MS was tuned and optimised for maximum sensitivity and stability with a 1 μg L^{-1} ^{115}In tune solution. Two short term stability tests were performed to ensure that the ICP-MS measurements were repeatable on a short term basis. The first test used a standard solution containing 1μg L^{-1} each of ^{7}Li, ^{9}Be, ^{59}Co, ^{60}Ni, ^{115}In, ^{138}Ba, ^{140}Ce, ^{154}Ba, ^{156}Ce, ^{208}Pb, ^{209}Bi and ^{238}U. The second short term stability test used a 5 mg L^{-1} standard solution of [bmim]Cl. Each respective standard was acquired ten times for a duration of one minute per acquisition, hence each test lasted for 10 min. The percentage relative standard deviation (%RSD) for the multi-elemental standard in the range between ^{7}Li and ^{238}U was acceptable at less than two percent RSD. The percentage RSD obtained for the 5 mg L^{-1} [bmim]Cl standard was less than four percent. The tuning parameters were optimized to maintain the ratio of Ba^{++}/Ba^{+} and CeO^{+}/Ce^{+} to less than 5%.

Calibration. As the ICP-MS analysis was run over a period of time on different days a calibration curve of [bmim]Cl standards was generated on each occasion. Each calibration curve was generated from [bmim]Cl standards having the following concentrations; 0.1, 0.5, 1.0, 5.0, 10.0 and 20.0 mg L^{-1}. A typical equation for the curve is given by slope = 146.99[bmim]Cl + 30180. The calibration curve was forced through the blank. The ICP-MS software (PlasmaLab) automatically calculated the concentration of all samples using the calibration curve equation, taking into account any dilutions that may have been performed. The detection limit (DL) for chloride was determined to be 0.01 mg L^{-1} (3σ convention).

Sample analysis. Triplicate measurements were obtained for each sample. The validity of the calibration curve was verified by analysis of a 1 mg L^{-1} [bmim]Cl standard after every ten samples.

Results and discussion

ICP-MS was the technique of choice for this comparative study due to rapid sampling and analysis time in addition to low detection limits for chloride. A preliminary study using NaCl standards enabled accurate detection of 0.1 mg L^{-1} chloride (DL was 0.01 mg L^{-1}). In comparison, the majority of commercially available ion-selective electrodes have a detection limit of only 1.8 ppm (or 1.8 mg L^{-1}) chloride.

In order to ensure that the [bmim]$^{+}$ cation would not suppress the detection of chloride, a [bmim]Cl sample of known concentration (10 mg L^{-1}) was analyzed as an unknown against a set of NaCl standards ranging from 0.1 to 100.0 mg L^{-1} chloride. The result obtained indicated that the organic component of the ionic liquid did not influence the detection of chloride. Thus a set of [bmim]Cl standards were prepared having the following concentrations, 0.1, 0.5, 1.0, 5.0, 10.0 and 20.0 mg L^{-1}. Each of the methods A–F were performed in triplicate. The samples obtained were then analyzed by taking triplicate ICP-MS measurements of ^{35}Cl. PlasmaLab software used the calibration curve equation to convert each measurement into a concentration result. Thus for each method a total of nine individual measurements for chloride ion content were obtained. The averaged results for total chloride ion content of each [bmim]BF$_4$ sample appear in Table 1.

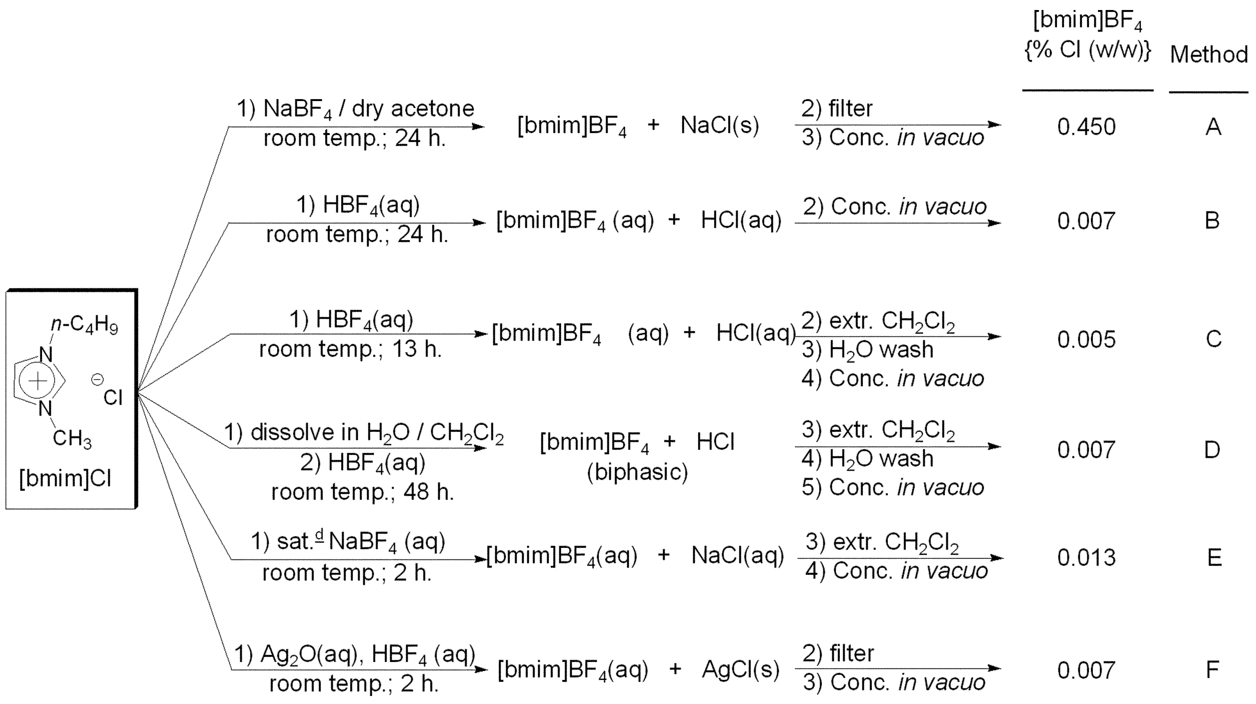
Table 1 Chloride content in [bmim]BF$_4$ prepared from [bmim]Cl by various methods

Entry	Total Cl/ mg L^{-1}	Dilution factor	Sample mass/mg	%Cl (w/w) $\{\bar{x} \pm \sigma\}$	Method
1	0.884	0.500	98.5	0.450 ± 0.164	A
2	0.728	0.010	97.7	0.007 ± 0.001	B
3	0.555	0.010	102.0	0.005 ± 0.003	C
4	0.658	0.010	100.3	0.007 ± 0.004	D
5	1.355	0.010	104.6	0.013 ± 0.011	E
6	0.667	0.010	94.8	0.007 ± 0.002	F

As can be seen in Table 1 and Scheme 1, Methods B, C, D and F gave very similar results. The residual chlorine content (%Cl (w/w)) in each of these methods is essentially the same when standard deviations are considered.[17] Methods B, C, and D share the feature of utilizing a metathesis reaction involving HBF$_4$(aq). These methods of preparing [bmim]BF$_4$ can be viewed as acid–base reactions in which HBF$_4$(aq) is the acid and [bmim]Cl is the base. Hence the conjugate acid in these cases would be HCl(aq) which can be easily removed to the levels observed through use of the application of high vacuum as a final step in their preparation. Chlorine is efficiently minimized in Method F through the formation of a highly insoluble AgCl(s) precipitate. It is apparent that this salt can be rather efficiently removed from the reaction mixture *via* straight forward filtration through a celite bed. Slightly lower residual levels of chlorine can be obtained from the metathesis of [bmim]Cl with HBF$_4$(aq) if the reaction mixture is dissolved in CH$_2$Cl$_2$ and washed with H$_2$O (see Methods C and D).

The use of NaBF$_4$ in the metathesis reaction resulted in consistently higher chlorine content in the [bmim]BF$_4$ ionic liquid. Regardless of whether the reaction was done in a heterogeneous fashion in acetone (Method A) or if it was conducted using a saturated solution of NaBF$_4$(aq) (Method E) in water the residual chlorine content was always higher than when the metathesis was conducted using HBF$_4$(aq).

During the course of our studies we noticed that the residual chlorine content in [bmim]BF$_4$ prepared using NaBF$_4$(s) in acetone (Method A) gave inconsistent results when replicate experiments were conducted to show reproducibility of our results. It soon became apparent to us that the cause of the inconsistent chlorine levels was a function of the acetone bottle used. We further surmised that when using “wet”, reagent grade acetone (*i.e.* acetone not freshly dried and distilled) resulted in some dissolution of chloride salts (*i.e.* NaCl or [bmim]Cl) that increased the residual chlorine content using Method A (see Table 2). Hence when dry, freshly distilled acetone was used in Method A the residual chlorine content was the lowest obtained for this method (See Table 1). The use of wet acetone in the metathesis reaction between [bmim]Cl



Scheme 1 Methods for the preparation of 1-butyl-3-methylimidazolium tetrafluoroborate, [bmim]BF$_4$.

Table 2 Variation of chloride content in [bmim]BF$_4$ prepared from [bmim]Cl using reagent grade acetone and Method A

Entry	Total Cl/ mg L^{-1}	Dilution factor	Sample mass/mg	%Cl (w/w)
1	14.482	0.500	113.6	6.372
2	0.5888	0.500	96.1	0.306
3	3.736	0.500	97.9	1.908
4	10.511	0.500	93.9	5.597
			$\bar{x} \pm \sigma$ =	3.546 ± 2.519

and NaBF$_4$ resulted in consistently high residual chlorine content. Indeed Method A afforded the highest residual chlorine content for all methods trialled for the preparation of [bmim]BF$_4$.

Since a number of popular methods commonly in use for the preparation of [bmim]BF$_4$ make use of a filtration step to remove precipitated salts (*i.e.* NaCl in Method A and AgCl in Method F) we investigated the effect of multiple filtrations on the final chlorine content for [bmim]BF$_4$ formed using Method A (Table 3). No decreased amounts of chlorine were detected upon multiple filtrations. Furthermore, the residual chlorine content remained high for this method as previously observed. These observations present the possibility that the solubility of NaCl(s) in [bmim]BF$_4$ itself may be responsible, at least in part, for the high residual chlorine content in those methods in which NaCl is a by-product.

Table 3 Variation of chloride content within a given preparation after successive filtrations through celite using Method A

Entry	Total Cl/ mg L^{-1}	Dilution factor	Sample mass/mg	% Cl (w/w)
1	0.485	0.500	99.5	0.244
2	0.455	0.500	103.2	0.220
3	0.472	0.500	102.8	0.229
4	0.401	0.500	94.4	0.212
5	0.446	0.500	99.2	0.225
6	0.422	0.500	96.6	0.218
			$\bar{x} \pm \sigma$ =	0.224 ± 0.009

In conclusion our findings indicate that the lowest residual chlorine content can be obtained *via* a metathesis reaction between [bmim]Cl and HBF$_4$(aq) in which chlorine becomes contained within the HCl by-product. Dissolution of the [bmim]BF$_4$ ionic liquid in CH$_2$Cl$_2$ followed by washing of the organic solution with water and concentration *in vacuo* removes any last artifacts of HCl (Method C). However, the use of any chlorinated solvents can be avoided and HCl removed by application of high vacuum only to obtain [bmim]BF$_4$ with essentially the same low residual chlorine content (Method B *vs.* D). Since any methods that produce NaCl as a by-product result in high residual chlorine content it is suggested that these methods be avoided if residual chlorine poses an issue with the specific application in which the [bmim]BF$_4$ is to be utilized.

The ICP-MS method of analysis performed in this study is easily applied to any water soluble ionic liquid. However, when we attempted this type of analysis on [bmim]PF$_6$ we encountered difficulties getting reliable results. These problems were due to the lack of solubility of [bmim]PF$_6$ in water. An attempt to overcome water solubility problems by addition of small amounts of methanol to aid dissolution met with limited success. We are presently studying halide and other impurities in this ionic liquid and several other water soluble and water insoluble ionic liquids of current interest in the literature using ICP-MS analysis.

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PAPER

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Recovery and recycle of fluoroalkyl-derivatised BINAP ligands using FRP silica gel

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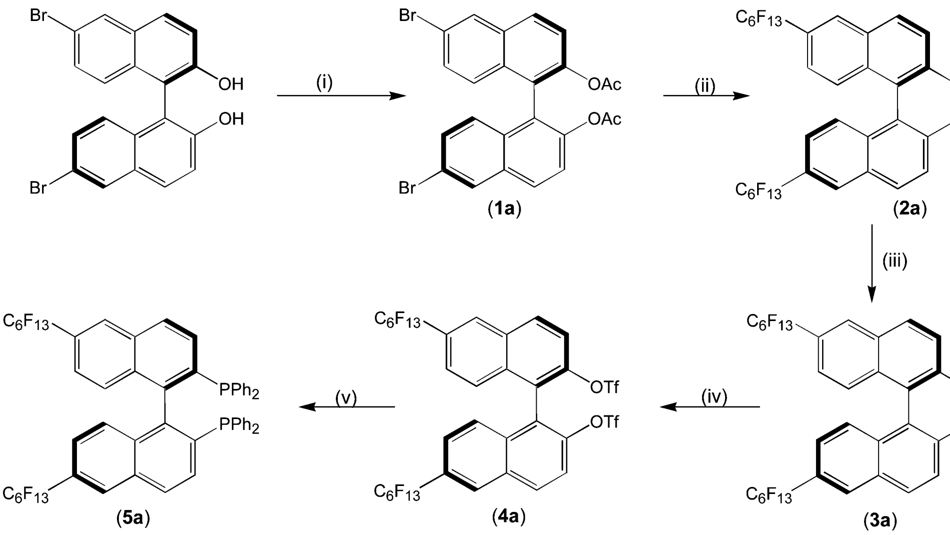
Three chiral perfluoroalkylated bidentate phosphorus(III) ligands have been prepared and characterised. These ligands have been evaluated in the asymmetric hydrogenation of methyl acetoacetate in dichloromethane and compared with the parent, non-fluorinated, ruthenium catalyst systems. After catalysis, recovery and reuse of the ligands has been achieved.

Introduction

We have probed the application of perfluoroalkylated phosphorus(III) ligands for catalysis in perfluorocarbon solvents,[1–3] under fluorous biphase conditions[4,5] and in $scCO_2$[6,7] as alternative reaction media to conventional organic solvents. More recently, we turned our attention to asymmetric catalysis,[8] including the synthesis of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (**5a**) and (*R*)-6,6′-bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (**11a**) and their application in the ruthenium-catalysed hydrogenation of dimethyl itaconate in methanol.[9] However, since > 60% fluorine by weight is normally required for preferential perfluorocarbon solubility[10] and perfluoroalkylated ligands give only modest activities/enantioselectivities in asymmetric hydrogenation reactions in $scCO_2$, even in the presence of the fluorinated BARF anion,[8] it is unlikely that viable fluorous biphase- or CO_2-compatible BINAP-based asymmetric hydrogenation catalyst systems could be prepared. However, Curran has recently developed fluorous reverse phase (FRP) silica gel[11] for the separation of "light fluorous" reagents, containing < 40% fluorine by weight, from products, as well as the removal of "light fluorous" products from non-fluorinated reagents.[12,13] We have recently described the first separation, recovery and reuse of a perfluoroalkylated metal catalyst, $[Ni\{F_{13}C_6C(O)CHC(O)C_6F_{13}\}_2]$, following catalysis in CH_2Cl_2, on an FRP silica column.[14] Here, we extend this work to the first attempts at the separation of asymmetric catalysts using the light fluorous approach. Preliminary results on the synthesis of two of the ligands have been reported previously.[9]

Results and discussion

The synthesis of fluorous-derivatised BINAP ligands with perfluoroalkyl chains directly attached to the binaphthyl backbone has been achieved *via* a copper-mediated cross-coupling reaction using perfluoro-*n*-hexyl iodide, following protection of the binaphtholic groups. After removal of the acetyl protecting groups, the perfluoroalkylated BINOL is converted to the bistriflate and a nickel-catalysed substitution using diphenylphosphine gave (*R*)- or (*S*)-6,6′-bis(tridecafluorohexyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl [(*R*)/(*S*)-R_{F6}-BINAP] **(5a/b)** in moderate overall yields (Scheme 1). The protection/deprotection sequence is not necessary in the synthesis of fluoroalkylated analogues of BINOL (**6a/b**), incorporating additional spacer units between the fluoroalkyl chains and the binaphthyl backbone, *via* palladium-catalysed Heck reactions. The resulting alkene can then either be hydrogenated using palladium on carbon or used directly in the subsequent reaction steps. Again, formation of the bistriflate followed by nickel-catalysed substitution reactions gave (*R*)- or (*S*)-6,6′-bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl [(*R*)/(*S*)-$R_{F6}C_2H_4$-BINAP] **(11a/b)** or (*R*)- or (*S*)-6,6′-bis(1*H*,2*H*-tridecafluoro-1-octenyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl [(*R*)/(*S*)-$R_{F6}C_2H_2$-BINAP] **(8a/b)** in moderate overall yields (Scheme 2). Each of the derivatised BINAP ligands show parent ions in their FAB mass spectra and are moisture-stable, but show signs of slow oxidation in the solid state after prolonged periods of time in air. The ^1H NMR spectroscopic data for these ligands are complicated in the aromatic region because of overlapping resonances associated with the binaphthyl



Scheme 1 (i) Ac_2O, Et_3N, DMAP, DCM, reflux; (ii) $C_6F_{13}I$, Cu, 2,2′-bipy, DMSO, C_6H_5F, 80 °C; (iii) NaOEt, MeOH, rt; (iv) $(CF_3SO_2)_2O$, pyridine, DCM, 0 °C; (v) $[NiCl_2(dppe)]$, Ph_2PH, DABCO, DMF, 110 °C.

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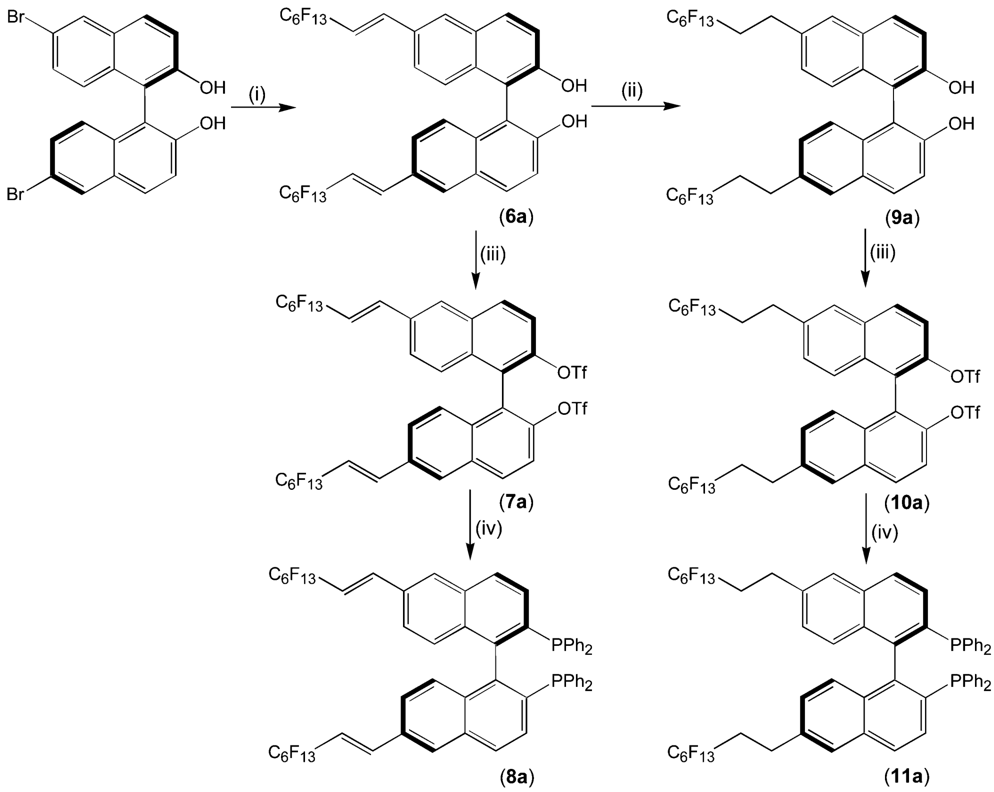
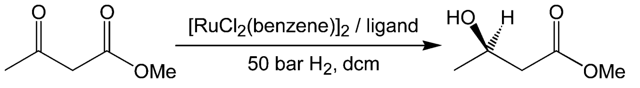


Scheme 2 (i) $CH_2=CHC_6F_{13}$, NaOAc, Hermann's catalyst, DMF, 125 °C; (ii) Pd/C, H_2, 80 bar, rt; (iii) $(CF_3SO_2)_2O$, pyridine, DCM, 0 °C; (iv) [NiCl$_2$(dppe)], Ph_2PH, DABCO, DMF, 110 °C.

and phenyl protons. The ligands exhibit five or six highly characteristic resonances in their $^{19}F\{^1H\}$ NMR spectra associated with the tridecafluorohexyl chains and diagnostic singlets in their $^{31}P\{^1H\}$ NMR spectra. The optical purities of the ligands were determined by CD, with all stereoisomeric ligands giving equal magnitude but opposite sign optical rotation values. As expected for bulky ligands with only two perfluoroalkyl substituents, these ligands partition almost exclusively (95 : 5) into the organic phase of a toluene : perfluoro-1,3-dimethylcyclohexane biphase.

We have evaluated the reactivity and enantioselectivity of these ligands in the ruthenium-catalysed hydrogenation of methyl acetoacetate in dichloromethane (Scheme 3) and compared the results directly to those obtained for the parent catalyst formed with BINAP (Table 1). In these unoptimised experiments, each repeated three times, it can be seen that inclusion of perfluoroalkyl groups in the BINAP ligands has no apparent effect on the reactivities or enantioselectivities of the ruthenium catalysts under the reaction conditions employed. The product *ee*'s are lower than those reported elsewhere,[15] but this can be attributed to the high pressure of H_2 gas used in this work, as substrate pressure has been shown to affect product *ee*'s.[16]



Scheme 3

Table 1 Asymmetric Ru-catalysed hydrogenation of methyl acetoacetate using fluoroalkyl derivatised BINAP ligands in CH_2Cl_2[a]

Ligand	Conversion (%)	ee (%)	Conversion (%)[b]	ee (%)[b]
(*R*)-BINAP	100	78	100	76
(*S*)-BINAP	100	76	100	72
(*R*)-R_{F6}-BINAP (**5a**)	100	76	100	74
(*S*)-R_{F6}-BINAP (**5b**)	100	72	100	70
(*R*)-$R_{F6}C_2H_2$-BINAP (**8a**)	100	76		
(*S*)-$R_{F6}C_2H_2$-BINAP (**8b**)	100	75		
(*R*)-$R_{F6}C_2H_4$-BINAP (**11a**)	100	80		
(*S*)-$R_{F6}C_2H_4$-BINAP (**11b**)	100	75		

[a] Ligand : Ru 1 : 1; 100 °C; substrate : catalyst = 1000 : 1; 1 h. [b] After first run and solid-phase recovery.

Having shown that the catalytic activity and enantioselectivity had not been compromised by the introduction of the tridecafluorohexyl units, the ability to separate and reuse the catalysts using solid supports was investigated. Initially, the separation and recovery of the fluorinated-BINAP ruthenium catalysts from the hydrogenation reaction mixtures using FRP silica gel was tested. The reaction mixture was concentrated by evaporation and passed down a short column of FRP silica gel. The ruthenium bound irreversibly to the surface of the silica and could not be removed with a wide range of solvents. However, using methanol as the mobile phase, the product could be eluted pure and free of the fluorinated BINAP ligands. Once the product had been washed from the column, the fluorous BINAP ligands could then be recovered by elution with dichloromethane, but subsequent analysis showed that the phosphorus centres had been oxidised. Using dry and degassed solvents, as well as degassed FRP silica gel under an inert atmosphere, it was possible to reduce the oxidation of the perfluoroalkylated BINAP ligands, although resonances due to a small amount of the phosphine oxide were still observed in the ^{31}P NMR spectrum of the recovered BINAP.

The separation and recovery of the non-fluorinated BINAP ruthenium catalyst from the hydrogenation reaction mixtures using conventional silica gel was also tested. Surprisingly, in view of the extensive literature on asymmetric hydrogenation using Ru-BINAP catalysts, this issue had not previously been addressed. The product could again be eluted free of the BINAP ligand with methanol and BINAP, itself, could then be recovered by elution with dichloromethane. However, similar to the fluorinated systems, the phosphorus centres had still been oxidised. When dry and degassed solvents and degassed silica were used under an inert atmosphere, predominately unoxidised BINAP ligand was recovered but it was still contaminated with small amounts of the phosphine oxide.

Recycle and reuse of the fluorous and non-fluorous BINAP ligands in further catalysis was established by addition of the recovered ligand to fresh aliquots of the ruthenium catalyst precursor and substrate. These experiments gave similar product yields and enantioselectivities to those obtained using fresh ligand, confirming that racemisation of the ligands had not occurred during their recovery. The recycling protocol for the perfluoroalkylated BINAP ligands should be applicable to a wide range of substrates in ruthenium-catalysed asymmetric hydrogenation, whereas there is no guarantee that this method for recycling the underivatised BINAP could be applied to all substrates without resorting to column chromatography.

Conclusions

The synthesis of chiral perfluorinated bidentate phosphorus(III) ligands has been achieved in moderate yield and the ligands successfully employed in the ruthenium-catalysed asymmetric hydrogenation of methyl acetoacetate. The addition of perfluoroalkyl ponytails to the BINAP ligands has no effect on the activity or enantioselectivity of the catalysts in this system. These ligands can be separated from the organic product(s) on FRP silica, selectively eluted and reused in the catalytic process without compromising activity or enantioselectivity. However, the catalytically active species cannot be recycled using the light fluorous approach, leaving residual metal on the solid support. Further work on more robust chiral catalyst systems is underway.

Experimental

Proton, ^{13}C, ^{19}F and ^{31}P NMR spectroscopies were carried out on a Bruker ARX250 spectrometer at 250.13, 62.90, 235.34 and 101.26 MHz or a Bruker DPX300 spectrometer at 300.14, 75.47, 282.41 and 121.50 MHz respectively and were referenced to external $SiMe_4$ (^1H), external $CFCl_3$ (^{19}F) and to external H_3PO_4 (^{31}P) using the high frequency positive convention. Elemental analyses were performed by the Elemental Analysis Service at the University of North London. Mass spectra were recorded on a Kratos Concept 1H mass spectrometer. Optical rotation measurements were obtained using a Perkin Elmer Polarimeter 341 at 589 nm using a Na/Hal lamp. Asymmetric hydrogenation reactions were carried out in a Parr high pressure reactor using a Brookes automatic pressure regulator. Percentage conversion was determined by ^1H NMR spectroscopic analysis. Percentage yield was determined gravimetrically and calculated to be greater that 90% in all cases.

(*R*)- and (*S*)-6,6′-Dibromo-1,1′-bi-2-naphthol[17] were prepared as described previously. DMAP is 4-dimethylaminopyridine. Dichloromethane and triethylamine were dried by refluxing over calcium hydride and distilled under dinitrogen, stored in closed ampoules over molecular sieves and freezed–pumped–thawed three times to remove all dissolved gases before use. Methanol was dried by distillation from magnesium sulfate under dinitrogen, stored in a closed ampoule and freezed–pumped–thawed three times before use. Dry dimethylformamide was purchased from Aldrich and freezed–pumped–thawed three times before use. H_2 (BOC) used in the hydrogenation experiments was used without purification. *Trans*-di-μ-acetatobis[2-(di-*o*-tolylphosphino)benzyl]dipalladium(II) (Herrmann's catalyst) was purchased from Lancaster Synthesis Ltd and used as supplied. Solid separations were performed using silica gel (60) or FRP silica gel, formed from silica gel (60) following the method developed by Curran.[11]

Preparation of (*R*)-6,6′-dibromo-2,2′-diacetoxy-1,1′-binaphthyl (1a)

Acetic anhydride (1.39 g, 13.6 mmol) was added dropwise to a stirring dichloromethane solution of 6,6′-dibromo-1,1′-binaphthol (3.04 g, 6.8 mmol in 50 ml solvent), triethylamine (4.19 g, 40.8 mmol) and DMAP (0.01 g, 0.08 mmol). The solution was refluxed for one hour. After cooling to room temperature, the solution was washed with 1 M hydrochloric acid (50 ml), 5% w/w sodium carbonate solution (50 ml) and water (50 ml), dried ($MgSO_4$) and the solvent evaporated under reduced pressure. The residue was washed with hexane to yield the title compound as an off-white solid, which was recrystallised from ethanol (2.52 g, 70%). (Found: C, 54.71; H, 2.89. $C_{24}H_{16}O_4Br_2$ requires C, 54.55; H, 3.03%). Mp 173–174 °C. MS (FAB): $m/z = 529$ [MH^+]. NMR ($CDCl_3$): δ_H 1.84 (6H, s, $COCH_3$), 7.05 (2H, d, $^3J_{HH} = 9.0$ Hz, 8-ArH), 7.49 (2H, dd, $^3J_{HH} = 9.0$ Hz, $^4J_{HH} = 1.8$ Hz, 7-ArH), 7.64 (2H, d, $^3J_{HH} = 9.0$ Hz, 4-ArH), 8.14 (2H, d, $^3J_{HH} = 9.0$ Hz, 3-ArH), 8.32 (2H, d, $^4J_{HH} = 1.8$ Hz, 5-ArH). δ_C 20.91, 120.48, 123.50, 123.62, 128.15, 129.24, 130.50, 130.69, 132.11, 133.01, 147.44, 169.53. $[\alpha]_D^{17}$ −33.7 (*c* 6.4, $CHCl_3$).

(*S*)-6,6′-Dibromo-2,2′-diacetoxy-1,1′-binaphthyl (1b). Compound **1b** was prepared similarly: (2.81 g, 77%). (Found: C, 54.62; H, 2.90. $C_{24}H_{16}O_4Br_2$ requires C, 54.55; H, 3.03%). Mp 171–172 °C. MS (FAB): $m/z = 529$ [MH^+]. NMR ($CDCl_3$): δ_H 1.83 (6H, s, $COCH_3$), 7.04 (2H, d, $^3J_{HH} = 9.2$ Hz, ArH), 7.49 (2H, dd, $^3J_{HH} = 9.0$ Hz, $^4J_{HH} = 2.1$ Hz, ArH), 7.64 (2H, d, $^3J_{HH} = 9.0$ Hz, ArH), 8.15 (2H, d, $^3J_{HH} = 8.7$ Hz, ArH), 8.30 (2H, d, $^4J_{HH} = 1.8$ Hz, ArH). δ_C 20.93, 120.45, 123.46, 123.59, 128.17, 129.26, 130.54, 130.66, 132.13, 133.04, 147.43, 169.53. $[\alpha]_D^{17}$ 69.2 (*c* 1.4, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-diacetoxy-1,1′-binaphthyl (2a)

A mixture of (*R*)-6,6′-dibromo-2,2′-diacetoxy-1,1′-binaphthyl (2.02 g, 3.83 mmol), perfluoro-*n*-hexyl iodide (5.02 g, 11.3 mmol), copper powder (2.52 g, 39.7 mmol), 2,2′-bipyridine (0.24 g, 1.5 mmol), fluorobenzene (50 ml) and DMSO (50 ml) was stirred for 72 h at 80 °C. After cooling to room temperature, the reaction mixture was diluted with water (150 ml) and diethyl ether (150 ml) and filtered. The organic layer was separated, washed with water (5×100 ml), dried ($MgSO_4$), filtered and the solvent removed under reduced pressure to yield a brown oil. The oil was purified by column chromatography (silica gel, ethyl acetate : hexane 1 : 9) (3.49 g, 68%). (Found: C, 42.84; H, 1.75. $C_{36}H_{16}F_{26}O_2$ requires C, 42.94; H, 1.59%). MS (FAB): $m/z = 1007$ [MH^+]. NMR ($CDCl_3$): δ_H 1.81 (6H, s, $COCH_3$), 6.93 (2H, d, $^3J_{HH} = 9.0$ Hz, 8-ArH), 7.24 (2H, d, $^3J_{HH} = 9.0$ Hz, 7-ArH), 7.41 (2H, d, $^3J_{HH} = 9.0$ Hz, 4-ArH), 7.85 (2H, d, $^3J_{HH} = 9.0$ Hz, 3-ArH), 8.08 (2H, s, 5-ArH). δ_F −81.31 (6F, t, $^4J_{FF} = 10.6$ Hz, CF_3), −110.70 (4F, m, α-CF_2), −121.89 (4F, m, CF_2), −121.95 (4F, m, CF_2), −123.17 (4F, m, CF_2), −126.52 (4F, m, CF_2). δ_C 20.85, 123.36, 123.92, 123.95 (t, $^3J_{CF} = 6.3$ Hz), 126.79 (t, $^2J_{CF} = 25.2$ Hz), 127.10, 128.43 (t, $^3J_{CF} = 7.1$ Hz), 130.79, 131.24, 135.03, 149.11, 169.39. $[\alpha]_D^{17}$ −44.7 (*c* 5.7, $CHCl_3$).

(*S*)-6,6′-Bis(tridecafluorohexyl)-2,2′-diacetoxy-1,1′-binaphthyl (2b). Compound **2b** was prepared similarly: (2.23 g, 58%). (Found: C, 42.72; H, 1.50. $C_{36}H_{16}F_{26}O_2$ requires C, 42.94; H, 1.59%). MS (FAB): $m/z = 1007$ [MH^+]. NMR ($CDCl_3$): δ_H 1.83 (6H, s, $COCH_3$), 7.45 (2H, d, $^3J_{HH} = 9.0$ Hz, 8-ArH), 7.74 (2H, d, $^3J_{HH} = 9.0$ Hz, 7-ArH), 7.89 (2H, d, $^3J_{HH} = 9.0$ Hz, 4-ArH), 8.51 (2H, d, $^3J_{HH} = 9.0$ Hz, 3-ArH), 8.61 (2H, s, 5-ArH). δ_F −81.17 (6F, t, $^4J_{FF} = 10.6$ Hz, CF_3), −110.70 (4F, m, α-CF_2), −121.86 (4F, m, CF_2), −121.86 (4F, m, CF_2), −123.17 (4F, m, CF_2), −126.52 (4F, m, CF_2). δ_C 20.82, 123.46, 123.92, 123.95 (t, $^3J_{CF} = 6.3$ Hz), 126.72 (t, $^2J_{CF} = 25.2$ Hz), 127.16, 128.47 (t, $^3J_{CF} = 7.1$ Hz), 130.76, 131.28, 135.08, 149.18, 169.49. $[\alpha]_D^{17}$ 52.1 (*c* 1.2, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(tridecafluorohexyl)-1,1′-binaphthol (3a)

Sodium ethoxide (0.50 g, 7.4 mmol) was added to a stirred solution of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-diacetoxy-1,1′-binaphthyl (2.00 g, 1.9 mmol) in methanol (25 ml). After five minutes, the reaction was quenched with 2 M hydrochloric acid (40 ml). The solution was extracted with dichloromethane (2 × 50 ml), the organic extracts dried over $MgSO_4$ and filtered. The solvent was removed under reduced pressure to obtain the product as an off-white solid. The pure product was obtained by recrystallisation from dichloromethane–hexane (1.79 g, 98%). (Found: C, 41.72; H, 1.27. $C_{32}H_{12}F_{26}O_2$ requires C, 41.65; H, 1.30%). Mp 77–79 °C. MS (FAB): m/z = 922 [M$^+$]. NMR ($CDCl_3$): δ_H 5.21 (2H, s, OH), 7.18 (2H, d, $^3J_{HH}$ = 9.0 Hz, 8-ArH), 7.37 (2H, d, $^3J_{HH}$ = 9.2 Hz, 7-ArH), 7.44 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 8.11 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.24 (2H, s, 5-ArH). δ_F −81.22 (6F, t, $^4J_{FF}$ = 10.7 Hz, CF_3), −110.98 (4F, m, α-CF_2), −121.88 (4F, m, CF_2), −121.88 (4F, m, CF_2), −123.21 (4F, m, CF_2), −126.59 (4F, m, CF_2). δ_C 110.96, 119.69, 124.72, 124.92, 125.15, 128.74, 128.74, 133.10, 135.41, 155.13. $[\alpha]_D^{17}$ −17.2 (c 1.2, $CHCl_3$).

(*S*)-6,6′-Bis(tridecafluorohexyl)-1,1′-binaphthol (3b). Compound **3b** was prepared similarly: (1.76 g, 98%). (Found: C, 41.73; H, 1.31. $C_{32}H_{12}F_{26}O_2$ requires C, 41.65; H, 1.30%). Mp 81–83 °C. MS (FAB): m/z = 922 [M$^+$]. NMR ($CDCl_3$): δ_H 5.21 (2H, s, OH), 7.18 (2H, d, $^3J_{HH}$ = 9.0 Hz, 8-ArH), 7.36 (2H, d, $^3J_{HH}$ = 9.2 Hz, 7-ArH), 7.46 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 8.12 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.23 (2H, s, 5-ArH). δ_F −81.22 (6F, t, $^4J_{FF}$ = 10.7 Hz, CF_3), −110.45 (4F, m, α-CF_2), −121.86 (4F, m, CF_2), −121.87 (4F, m, CF_2), −123.18 (4F, m, CF_2), −126.54 (4F, m, CF_2). δ_C 110.90, 119.66, 124.76, 124.94, 125.13, 128.59, 128.75, 133.11, 135.40, 155.12. $[\alpha]_D^{17}$ 17.4 (c 1.5, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(1*H*,2*H*-tridecafluoro-1-octenyl)-1,1′-binaphthol (6a)

A solution of (*R*)-6,6′-dibromo-1,1′-bi-2-naphthol (2 g, 4.5 mmol), 1*H*,1*H*,2*H*-perfluoro-*n*-1-octene (6.23 g, 18.0 mmol), Herrmann's catalyst (100 mg, 1×10^{-4} mol) and NaOAc (1.02 g, 0.013 mol) in DMF (40 ml) was stirred under nitrogen at 120 °C for 72 hours. After cooling, the solvent was removed under reduced pressure and the residue partitioned between ethyl acetate (40 ml) and water (40 ml). The organic layer was separated, washed with water (40 ml) and brine (40 ml), dried ($MgSO_4$), filtered and the solvent removed under reduced pressure to yield a yellow–brown solid, which was recrystallised from hexane (2.78 g, 63%). (Found: C, 44.49; H, 1.58. $C_{36}H_{16}F_{26}O_2$ requires C, 44.35; H, 1.64%). Mp 85–88 °C. MS (FAB): m/z = 974 [M$^+$]. NMR ($CDCl_3$): δ_H 5.40 (2H, bs, OH), 6.14 (2H, m, =CH), 6.91 (2H, d, $^3J_{HH}$ = 8.7 Hz, 8-ArH), 7.14 (2H, m, =CH), 7.32 (2H, m, 7-ArH), 7.35 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 7.86 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.04 (2H, s, 5-ArH). δ_F −81.20 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −111.24 (2F, m, α-CF_2), −121.95 (2F, m, CF_2), −123.24 (2F, m, CF_2), −123.55 (2F, m, CF_2), −126.53 (2F, m, CF_2). δ_C 113.10, 117.82, 118.00, 124.03, 128.41, 128.56, 129.42, 131.02, 131.53, 132.69, 138.35, 152.91. $[\alpha]_D^{17}$ −89.9 (c 1.2, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-1,1′-binaphthol (6b). Compound **6b** was prepared similarly: (2.98 g, 68%). (Found: C, 44.22; H, 1.58. $C_{36}H_{16}F_{26}O_2$ requires C, 44.35; H, 1.64%). Mp 83–86 °C. MS (FAB): m/z = 974 [M$^+$]. NMR ($CDCl_3$): δ_H 5.14 (2H, bs, OH), 6.14 (2H, m, =CH), 6.93 (2H, d, $^3J_{HH}$ = 8.7 Hz, 8-ArH), 7.14 (2H, m, =CH), 7.34 (2H, m, 7-ArH), 7.39 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 7.85 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.08 (2H, s, 5-ArH). δ_F −81.20 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −111.24 (2F, m, α-CF_2), −121.95 (2F, m, CF_2), −123.24 (2F, m, CF_2), −123.55 (2F, m, CF_2), −126.53 (2F, m, CF_2). δ_C 114.11, 118.82, 119.00, 125.08, 129.24, 129.44, 129.61, 132.16, 132.53, 132.69, 139.35, 153.91. $[\alpha]_D^{17}$ 78.4 (c 1.4, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-1,1′-bi- 2-naphthol (9a)

(*R*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-1,1′-bi-2-naphthol (3.12 g, 3.2 mmol) was dissolved in dichloromethane (15 ml) and 10% palladium on charcoal added (100% by weight, 3.08 g). The mixture was charged to an autoclave and placed under a dynamic atmosphere of hydrogen (80 bar) for 18 hours.

The gas was carefully vented and the reaction mixture removed from the autoclave. The solution was passed through celite and the solvent removed under reduced pressure to yield the product as a white solid (2.89 g, 92%). (Found: C, 44.12; H, 2.15. $C_{36}H_{20}F_{26}O_2$ requires C, 44.17; H, 2.05%). Mp 144–146 °C. MS (FAB): m/z = 978 [M$^+$]. NMR ($CDCl_3$): δ_H 2.37 (4H, m, CH_2), 2.98 (4H, m, CH_2), 4.98 (2H, bs, OH), 7.04 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 7.11 (2H, dd, $^3J_{HH}$ = 8.7 Hz, $^4J_{HH}$ = 1.38 Hz, 7-ArH), 7.33 (2H, d, $^3J_{HH}$ = 8.7 Hz, 4-ArH), 7.67 (2H, s, 5-ArH), 7.88 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH). δ_F −81.22 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −114.92 (2F, m, CF_2), −122.26 (2F, m, CF_2), −123.26 (2F, m, CF_2), −123.89 (2F, m, CF_2), −126.51 (2F, m, CF_2). δ_C 26.29, 32.93 (t, $^2J_{CF}$ = 21.1 Hz), 110.89, 118.22, 124.83, 127.27, 128.24, 129.60, 130.95, 132.25, 134.78, 152.62. $[\alpha]_D^{17}$ −14.9 (c 2.1, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-1,1′-bi-2-naphthol (9b). Compound **9b** was prepared similarly: (1.96 g, 98%). (Found: C, 44.16; H, 2.13. $C_{36}H_{20}F_{26}O_2$ requires C, 44.17; H, 2.05%). Mp 143–145 °C. MS (FAB): m/z = 978 [M$^+$]. NMR ($CDCl_3$): δ_H 2.35 (4H, m, CH_2), 2.97 (4H, m, CH_2), 4.95 (2H, bs, OH), 7.04 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 7.11 (2H, dd, $^3J_{HH}$ = 8.7 Hz, $^4J_{HH}$ = 1.38 Hz, 7-ArH), 7.33 (2H, d, $^3J_{HH}$ = 8.7 Hz, 4-ArH), 7.67 (2H, s, 5-ArH), 7.88 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH). δ_F −81.22 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −114.92 (2F, m, α-CF_2), −122.26 (2F, m, CF_2), −123.26 (2F, m, CF_2), −123.89 (2F, m, CF_2), −126.51 (2F, m, CF_2). δ_C 25.27, 31.90 (t, $^2J_{CF}$ = 21.9 Hz), 109.92, 117.21, 123.84, 126.25, 127.21, 128.58, 129.90, 131.26, 133.75, 151.61. $[\alpha]_D^{17}$ 19.8 (c 2.2, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (4a)

Triflic anhydride (0.73 g, 2.58 mmol) was added dropwise to a stirred dichloromethane solution of (*R*)-6,6′-bis(tridecafluorohexyl)-1,1′-bi-2-naphthol (1.0 g, 1.1 mmol in 50 ml solvent) and pyridine (0.15 g, 3.21 mmol) at 0 °C and the mixture stirred for four hours. The solvent was removed under reduced pressure and the product extracted into ethyl acetate (50 ml). This solution was then washed with 5% hydrochloric acid (100 ml), saturated $NaHCO_3$ (100 ml), 10% NaCl solution (100 ml) and water (100 ml). The organic phase was dried over sodium sulfate, filtered and the solvent removed under reduced pressure. The crude product was recrystallised from hexane (1.02 g, 83%). (Found: C, 34.39; H, 0.80. $C_{34}H_{10}F_{32}O_6S_2$ requires C, 34.40; H, 0.84%). Mp 120–122 °C. MS (FAB): m/z = 1186 [M$^+$]. NMR ($CDCl_3$): δ_H 7.29 (2H, d, $^3J_{HH}$ = 9.0 Hz, 8-ArH), 7.51 (2H, d, $^3J_{HH}$ = 9.2 Hz, 7-ArH), 7.70 (2H, d, $^3J_{HH}$ = 9.2 Hz, 4-ArH), 8.24 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.26 (2H, s, 5-ArH). δ_F − 74.92 (6F, s, OSO_2CF_3), −81.24 (6F, t, $^4J_{FF}$ = 10.7 Hz, CF_3), −111.00 (4F, m, α-CF_2), −121.88 (4F, m, CF_2), −121.93 (4F, m, CF_2), −123.18 (4F, m, CF_2), −126.54 (4F, m, CF_2). δ_C 114.58, 119.92, 122.03, 124.09, 126.29, 127.41, 130.35, 132.46, 133.68, 146.02. $[\alpha]_D^{17}$ − 48.4 (c 2.3, $CHCl_3$).

(*S*)-6,6′-Bis(tridecafluorohexyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (4b). Compound **4b** was prepared similarly: (1.16 g, 95%). (Found: C, 34.40; H, 0.80. $C_{34}H_{10}F_{32}O_6S_2$ requires C, 34.40; H, 0.84%). Mp 121–122 °C. MS (FAB): m/z = 1186 [M$^+$]. NMR ($CDCl_3$): δ_H 7.32 (2H, d, $^3J_{HH}$ = 9.0 Hz, 8-ArH), 7.51 (2H, d, $^3J_{HH}$ = 9.2 Hz, 7-ArH), 7.70 (2H, d, $^3J_{HH}$ = 9.2 Hz, 4-ArH), 8.23 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH), 8.25 (2H, s, 5-ArH). δ_F −74.86 (6F, s, OSO_2CF_3), −81.24 (6F, t, $^4J_{FF}$ = 10.7 Hz, CF_3), −111.00 (4F, m, α-CF_2), −121.88 (4F, m, CF_2), −121.93 (4F, m, CF_2), −123.18 (4F, m, CF_2), −126.54 (4F, m, CF_2). δ_C 114.67, 119.96, 122.08, 124.02, 126.31, 127.45, 130.29, 132.41, 133.41, 145.97. $[\alpha]_D^{17}$ 51.9 (c 2.6, $CHCl_3$).

(*R*)-6,6′-Bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (10a). Compound **10a** was prepared similarly: (1.64 g, 75%). (Found: C, 36.81; H, 1.36. $C_{38}H_{18}F_{32}O_6S_2$ requires C, 36.71; H, 1.45%). Mp 74–76 °C. MS (FAB): *m*/*z* = 1242 [M$^+$]. NMR ($CDCl_3$): δ_H 2.39 (4H, m, CH_2), 3.01 (4H, m, CH_2), 7.12 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 7.17 (2H, d, $^3J_{HH}$ = 8.7 Hz, 7-ArH), 7.53 (2H, d, $^3J_{HH}$ = 8.9 Hz, 4-ArH), 7.74 (2H, s, 5-ArH), 7.91 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH). δ_F −74.99 (3F, s, SO_2CF_3) −81.28 (3F, t, $^4J_{FF}$ = 10.1 Hz, CF_3), −114.90 (2F, m, α-CF_2), −122.29 (2F, m, CF_2), −123.30 (2F, m, CF_2), −123.85 (2F, m, CF_2), −126.58 (2F, m, CF_2). δ_C 25.42, 31.48, 118.83, 122.43, 126.13, 126.35, 127.83, 130.58, 131.03, 131.63, 137.36, 144.29. $[\alpha]_D^{17}$ −38.4 (*c* 0.6, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (10b). Compound **10b** was prepared similarly: (0.96 g, 77%). (Found: C, 36.82; H, 1.30. $C_{38}H_{18}F_{32}O_6S_2$ requires C, 36.71; H, 1.45%). Mp 73–75 °C. MS (FAB): *m*/*z* = 1242 [M$^+$]. NMR ($CDCl_3$): δ_H 2.37 (4H, m, CH_2), 3.01 (4H, m, CH_2), 7.06 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 7.15 (2H, dd, $^3J_{HH}$ = 8.7 Hz, $^4J_{HH}$ = 1.38 Hz, 7-ArH), 7.53 (2H, d, $^3J_{HH}$ = 8.7 Hz, 4-ArH), 7.69 (2H, s, 5-ArH), 7.86 (2H, d, $^3J_{HH}$ = 9.0 Hz, 3-ArH). δ_F −74.93 (3F, s, SO_2CF_3) −81.22 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −114.92 (2F, m, α-CF_2), −122.26 (2F, m, CF_2), −123.26 (2F, m, CF_2), −123.89 (2F, m, CF_2), −126.51 (2F, m, CF_2). δ_C 26.42, 32.45 (t, $^2J_{CF}$ = 22.6 Hz), 119.81, 123.39, 127.11, 127.32, 128.82, 131.56, 131.98, 132.58, 133.32, 145.24. $[\alpha]_D^{17}$ 49.51 (*c* 1.6, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(1*H*,2*H*-tridecafluoro-1-octenyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (7a)

(*R*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-1,1′-bi-2-naphthol (1.02 g, 1.0 mmol) was dissolved in dry dichloromethane (50 ml) and pyridine added (0.49 g, 6.2 mmol). The solution was cooled to 0 °C and trifluoromethanesulfonic anhydride (1.46 g, 5.16 mmol) added dropwise. The solution was then stirred over night.

Hydrochloric acid (5% solution, 50 ml) was added to quench the reaction and the organic layer separated. This was washed with saturated sodium carbonate solution (50 ml), brine (50 ml) and water (50 ml), dried ($MgSO_4$), filtered and the solvent removed to yield the crude product as a thick brown oil. This oil was washed with hexane and the solvent residues removed under vacuum to yield a yellow–brown solid. (0.88 g, 68%). (Found: C, 37.11; H, 1.17. $C_{38}H_{14}F_{32}O_6S_2$ requires C, 36.83; H, 1.13%). Mp 42–45 °C. MS (FAB): *m*/*z* = 1238 [M$^+$]. NMR ($CDCl_3$): δ_H 6.23 (2H, m, =CH), 7.18 (2H, d, $^3J_{HH}$ = 8.7 Hz, 8-ArH), 7.26 (2H, m, =CH), 7.47 (2H, dd, $^3J_{HH}$ = 9.0 Hz, $^4J_{HH}$ = 1.6 Hz, 7-ArH), 7.59 (2H, d, $^3J_{HH}$ = 9.1 Hz, 4-ArH), 7.98 (2H, s, 5-ArH), 8.10 (2H, d, $^3J_{HH}$ = 9.1, 3-ArH). δ_F −74.84 (m, 3F, SO_2CF_3), −81.27 (t, 3F, $^4J_{FF}$ = 10.2 Hz, CF_3), −111.69 (m, 2F, α-CF_2), −121.98 (m, 2F, CF_2), −123.28 (m, 2F, CF_2), −123.48 (m, 2F, CF_2), −126.58 (m, 2F, CF_2). δ_C 114.62, 119.52, 122.40, 124.57, 126.47, 128.22, 130.85, 131.34, 131.53, 132.69, 137.75, 145.11. $[\alpha]_D^{17}$ −100.8 (*c* 1.7, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (7b). Compound **7b** was prepared similarly: (0.83 g, 64%). (Found: C, 36.99; H, 1.22. $C_{38}H_{14}F_{32}O_6S_2$ requires C, 36.83; H, 1.13%). Mp 47–50 °C. MS (FAB): *m*/*z* = 1238 [M$^+$]. NMR ($CDCl_3$): δ_H 6.23 (2H, m, =CH), 7.18 (2H, d, $^3J_{HH}$ = 8.7 Hz, 8-ArH), 7.26 (2H, m, =CH), 7.47 (2H, dd, $^3J_{HH}$ = 9.0 Hz, $^4J_{HH}$ = 1.6 Hz, 7-ArH), 7.59 (2H, d, $^3J_{HH}$ = 9.1 Hz, 4-ArH), 7.98 (2H, s, 5-ArH), 8.10 (2H, d, $^3J_{HH}$ = 8.9, 3-ArH). δ_F −74.91 (m, 6F, CF_3), −81.22 (t, 3F, $^4J_{FF}$ = 10.1 Hz, CF_3), −111.67 (m, 2F, α-CF_2), −121.95 (m, 2F, CF_2), −123.26 (m, 2F, CF_2), −123.48 (m, 2F, CF_2), −126.55 (m, 2F, CF_2). δ_C 115.42, 119.57, 122.42, 124.60, 126.47, 128.22, 130.58, 131.35, 131.67, 132.71, 137.67, 145.13. $[\alpha]_D^{17}$ 110.9 (*c* 1.9, $CHCl_3$).

Preparation of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (5a)

To a DMF solution of $NiCl_2$(dppe) (0.044 g, 8.3 × 10^{-5} mol in 50 ml) was added diphenylphosphine (0.19 g, 1.05 mmol, 0.12 ml). The solution was then heated to 100 °C for thirty minutes. A DMF solution of (*R*)-6,6′-bis(tridecafluorohexyl)-2,2′-di(trifluoromethane-sulfonyloxy)-1,1′-binaphthyl (1.02 g, 8.6 × 10^{-4} mol) was then added. DABCO (0.38 g, 3.33 mmol) was also added at this stage. The resulting green solution was stirred at 110 °C for a further 2 h. An additional portion of diphenylphosphine (0.19 g, 1.05 mmol, 0.12 ml) was then added *via* a syringe. Heating and stirring was continued for 72 h.

The reaction was allowed to cool to room temperature and the DMF distilled from the reaction mixture. The resulting brown solid was stirred for thirty minutes in MeOH (50 ml) and filtered. The crude product was washed with methanol and dried *in vacuo*. A pure product was obtained by recrystallisation from dichloromethane–methanol. (0.32 g, 30%). (Found: C, 53.34; H, 2.29. $C_{56}H_{30}F_{26}P_2$ requires C, 53.42; H, 2.39%). Mp 249–253 °C (dec). MS (FAB): *m*/*z* = 1259 [MH$^+$]. NMR ($CDCl_3$): δ_H 6.84–7.36 (20H, m, Ph), 6.78 (2H, d, $^3J_{HH}$ = 9.4 Hz, 8-ArH), 7.38 (2H, d, $^3J_{HH}$ = 8.5 Hz, 7-ArH), 7.50 (2H, d, $^3J_{HH}$ = 8.0 Hz, 4-ArH), 7.93 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH), 8.06 (2H, s, 5-ArH). δ_F −81.21 (6F, t, $^4J_{FF}$ = 10.6 Hz, CF_3), −110.75 (4F, m, α-CF_2), −121.82 (4F, m, CF_2), −121.82 (4F, m, CF_2), −123.16 (4F, m, CF_2), −126.51 (4F, m, CF_2). δ_C 115.62, 122.81, 122.85, 127.83, 128.62, 128.82, 129.50, 131.80, 132.38, 133.19, 135.05, 135.22, 135.41, 137.52, 140.02, 144.89. δ_P −13.8 (s). $[\alpha]_D^{17}$ 104.2 (*c* 1.0, C_6H_6).

(*S*)-6,6′-Bis(tridecafluorohexyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (5b). Compound **5b** was prepared similarly: (0.46 g, 44%). (Found: C, 53.32; H, 2.29. $C_{56}H_{30}F_{26}P_2$ requires C, 53.42; H, 2.39%). Mp 257–260 °C (dec). MS (FAB): *m*/*z* = 1259 [MH$^+$]. NMR ($CDCl_3$): δ_H 6.84–7.36 (20H, m, Ph), 6.78 (2H, d, $^3J_{HH}$ = 9.4 Hz, 8-ArH), 7.38 (2H, d, $^3J_{HH}$ = 8.5 Hz, 7-ArH), 7.50 (2H, d, $^3J_{HH}$ = 8.0 Hz, 4-ArH), 7.93 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH), 8.06 (2H, s, 5-ArH). δ_F −81.23 (6F, t, $^4J_{FF}$ = 10.6 Hz, CF_3), −110.74 (4F, m, α-CF_2), −121.80 (4F, m, CF_2), −121.80 (4F, m, CF_2), −123.16 (4F, m, CF_2), −126.51 (4F, m, CF_2). δ_C 115.64, 122.81, 122.85, 127.84, 128.60, 128.85, 129.51, 131.83, 132.43, 133.17, 135.05, 135.23, 135.44, 137.54, 140.02, 144.81. δ_P −13.5 (s). $[\alpha]_D^{17}$ −96.4 (*c* 1.3, C_6H_6).

(*R*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (8a). Compound **8a** was prepared similarly: (0.31 g, 19%). (Found: C, 54.87; H, 2.52. $C_{60}H_{34}F_{26}P_2$ requires C, 54.96; H, 2.60%). Mp 165–167 °C. MS (FAB): *m*/*z* = 1310 [M$^+$]. NMR ($CDCl_3$): δ_H 6.05 (2H, m, =CH), 6.62 (2H, d, $^3J_{HH}$ = 8.7 Hz, 8-ArH), 6.81 (2H, m, =CH), 6.87–7.16 (22H, complex aromatic region, Ph and 7-ArH), 7.40 (2H, d, $^3J_{HH}$ = 8.1 Hz, 4-ArH), 7.79 (2H, s, 5-ArH), 7.84 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH). δ_F −81.22 (t, 3F, $^4J_{FF}$ = 10.0 Hz, CF_3), −111.43 (m, 2F, CF_2), −121.94 (m, 2F, CF_2), −123.26 (m, 2F, CF_2), −123.64 (m, 2F, CF_2), −126.52 (m, 2F, CF_2). δ_C 115.42, 119.57, 122.42, 124.60 125.35, 125.43, 126.47, 126.99, 127.11, 127.33, 128.22, 130.58, 131.35, 131.67, 131.99, 132.71, 137.67, 145.13. δ_P −14.5 (s). $[\alpha]_D^{17}$ 21.0 (*c* 1.7, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,2*H*-tridecafluoro-1-octenyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (8b). Compound **8b** was prepared similarly: (0.33 g, 20%). (Found: C, 54.83; H, 2.50. $C_{60}H_{34}F_{26}P_2$ requires C, 54.96; H, 2.60%). Mp 164–166 °C. MS (FAB): *m*/*z* = 1310 [M$^+$]. NMR ($CDCl_3$): δ_H 6.05 (2H, m, =CH), 6.60 (2H, d, $^3J_{HH}$ = 8.8 Hz, 8-ArH), 6.82 (2H, m, =CH), 6.86–7.17 (22H, complex aromatic region, Ph and 7-ArH), 7.40 (2H, d, $^3J_{HH}$

= 8.2 Hz, 4-ArH), 7.79 (2H, s, 5-ArH), 7.83 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH). δ_F −81.19 (t, 3F, $^4J_{FF}$ = 10.2 Hz, CF_3), −111.41 (m, 2F, CF_2), −121.92 (m, 2F, CF_2), −123.22 (m, 2F, CF_2), −123.58 (m, 2F, CF_2), −126.52 (m, 2F, CF_2). δ_C 115.52, 119.68, 122.46, 124.62, 125.37, 125.47, 126.48, 126.88, 127.19, 127.35, 128.27, 130.58, 131.38, 131.61, 132.07, 132.69, 137.72, 145.11. δ_P −14.5 (s). $[\alpha]_D^{17}$ −13.3 (*c* 1.5, $CHCl_3$).

(*R*)-6,6′-Bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (11a). Compound **11a** was prepared similarly: (1.22 g, 58%). (Found: C, 54.82; H, 2.89. $C_{60}H_{38}F_{26}P_2$ requires C, 54.79; H, 2.89%). Mp 205–207 °C. MS (FAB): *m*/*z* = 1314 [M$^+$]. NMR ($CDCl_3$): δ_H 2.26 (4H, m, CH_2–CF_2), 2.88 (4H, m, CH_2-Ar), 6.62 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 6.66 (2H, d, $^3J_{HH}$ = 8.8 Hz, 7-ArH), 6.90–7.24 (20H, m, PhH), 7.33 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 7.60 (2H, s, 5-ArH), 7.77 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH). δ_F −81.21 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −114.98 (2F, m, α-CF_2), −122.21 (2F, m, CF_2), −123.24 (2F, m, CF_2), −123.93 (2F, m, CF_2), −126.54 (2F, m, CF_2). δ_C 25.41, 31.80, 125.35, 125.43, 126.67, 126.99, 127.11, 127.33, 129.98, 131.17, 131.86, 131.99, 132.37, 133.17, 133.32, 133.46, 134.40, 136.19. δ_P −15.6 (s). $[\alpha]_D^{17}$ 64.64 (*c* 0.9, $CHCl_3$).

(*S*)-6,6′-Bis(1*H*,1*H*,2*H*,2*H*-tridecafluorooctyl)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (11b). Compound **11b** was prepared similarly: (0.25 g, 23%). (Found: C, 54.73; H, 2.82. $C_{60}H_{38}F_{26}P_2$ requires C, 54.79; H, 2.89%). Mp 203–205 °C. MS (FAB): *m*/*z* = 1315 [MH$^+$]. NMR ($CDCl_3$): δ_H 2.26 (4H, m, CH_2–CF_2), 2.88 (4H, m, CH_2-Ar), 6.60 (2H, d, $^3J_{HH}$ = 8.5 Hz, 8-ArH), 6.65 (2H, d, $^3J_{HH}$ = 8.8 Hz, 7-ArH), 6.90–7.21 (20H, m, PhH), 7.35 (2H, d, $^3J_{HH}$ = 9.0 Hz, 4-ArH), 7.57 (2H, s, 5-ArH), 7.76 (2H, d, $^3J_{HH}$ = 8.5 Hz, 3-ArH). δ_F −81.23 (3F, t, $^4J_{FF}$ = 10.2 Hz, CF_3), −114.94 (2F, m, CF_2), −122.22 (2F, m, CF_2), −123.24 (2F, m, CF_2), −123.91 (2F, m, CF_2), −126.53 (2F, m, CF_2). δ_C 25.43, 31.86, 125.32, 125.44, 126.69, 126.91, 127.12, 127.34, 130.01, 131.12, 131.88, 131.95, 132.39, 133.18, 133.32, 133.47, 134.42, 136.19. δ_P −15.6 (s). $[\alpha]_D^{17}$ −68.33 (*c* 1.2, $CHCl_3$).

Preparation of Mosher's acid ester diastereomers

Mosher's acid chloride (9.9×10^{-2} mol dm^{-3} solution in dichloromethane, 2 ml, 0.2 mmol) was added to a flame-dried 10 ml flask and pyridine (0.2 ml, 2.5 mmol) added. To this mixture, the product methyl-3-hydroxybutyrate (0.02 ml, 0.2 mmol) was added and the mixture stirred for 10 minutes. 1 M HCl (20 ml) and dichloromethane (10 ml) were added, the organic layer separated and the aqueous phase extracted with dichloromethane (10 ml). The organic layers were combined, washed with water (10 ml), dried, filtered and the solvent removed under reduced pressure to yield a colourless oil. The enantiomeric excess was determined by ^{1}H NMR spectroscopic analysis of the oil. δ_H 1.25 (d, (*S*)-enantiomer of product), 1.34 (d, (*R*)-enantiomer of product).

General procedure for asymmetric hydrogenation

$[RuCl_2(benzene)]_2$ (0.022 g, 44 μmol) and a BINAP ligand (88 μmol) were placed in an autoclave under nitrogen and methyl acetoacetate (10 g, 86 mmol) dissolved in dichloromethane (10 ml) added *via* syringe through the gas vent against a positive flow of dinitrogen. The autoclave was then sealed and heated to 100 °C for twenty minutes with constant stirring at 700 rpm before being placed under 50 atm of hydrogen gas for one hour with continued heating and stirring. After an hour, the reactor was allowed to cool for twenty minutes with external cooling using a desk fan before the gas was carefully vented and the product collected *via* syringe through the gas vent.

General method for determination of partition coefficients

The BINAP ligand (50 mg) was stirred in toluene (2 ml) and PP3 (2 ml) for twenty minutes. The mixture was allowed to settle for 20 minutes and then 1 ml of each layer separated and the solvent removed *in vacuo*. The amount of ligand in each phase was then determined gravimetrically.

General procedure for product separation and ligand recovery

Silica gel or FRP silica gel were dried and degassed under high vacuum at 150 °C for 24 hours. These solids were then added to a 1 cm diameter column and filled to 3 cm in length in a dry box under nitrogen. The reaction mixture to be separated was concentrated *in vacuo*, placed onto the column of silica and the product eluted with dry and degassed methanol under nitrogen. Recovery of non-oxidised ligand was then achieved by elution with dry and degassed dichloromethane, the solvent removed *in vacuo* and the recovered ligand used in subsequent catalysis without further purification.

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