

Supported catalysts and their applications in synthetic organic chemistry

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1 Introduction

This review covers the most significant publications during the period from April 2000 to March 2001 on supported catalysts with an emphasis on their applications in organic synthesis. Similarly to our previous review on this theme,¹ this article provides selected coverage on the key advances in the field, rather than a fully comprehensive review, and aims to address the most important issues arising from the recent literature. The scope of this review will be limited to well-defined immobilised catalysts or chiral ligands that have useful applications in organic synthesis.

Investigations on supported catalysts have been on-going for many decades now^{2–5} but wasn't until the explosion of interest in the field of Combinatorial Chemistry^{6–10} that the subject became an area of intense research activity. In particular, the immobilisation of a well-defined catalyst onto an insoluble support displays great advantages over the use of the homogeneous catalyst, such as simplified purification procedures which are key to the success of polymer-assisted solution-phase parallel synthesis.^{11–14}

Over the past year, there has been a dramatic rise in the number of reports dealing with the preparation, characterisation and use of supported catalysts. Several outstanding reviews on the subject have also appeared.^{15–19} The effect of the polymeric support on the catalytic activity and selectivity of chiral catalysts has been discussed in a recent review by Altava *et al.*²⁰

The development of supported catalysts for use in environmentally friendly or green solvents, as part of the drive towards developing more Green Chemistry, is also an idea that is becoming more widespread.²¹

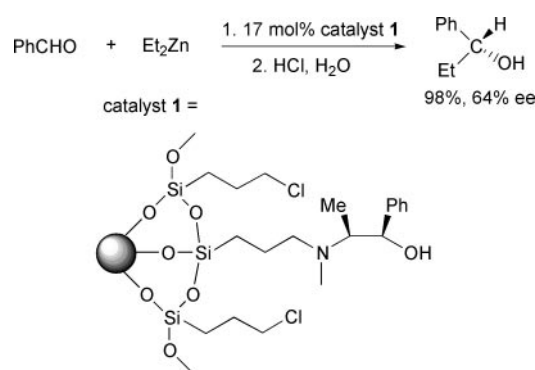
Finally, the application of combinatorial approaches to catalyst discovery^{22–24} is an area which is still in its infancy and has been the subject of some reviews. It will therefore remain outside the scope of this review.

Each supported catalyst will be discussed briefly and an example of its use in organic synthesis will be provided. The reader is encouraged to consult the literature source for more detailed information. Cross-linked polystyrene was the support of choice unless otherwise stated, as it was by far the most commonly used.

2 Enantioselective catalysts for C–C bond formation

2.1 Enantioselective additions to aldehydes and imines

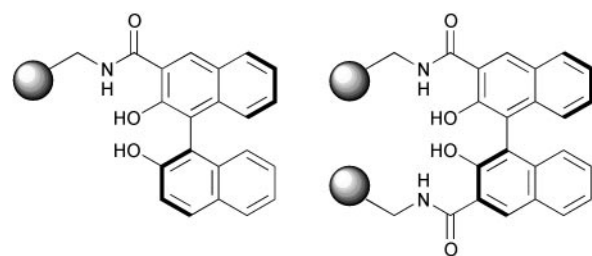
New asymmetric catalysts for the enantioselective addition of diethylzinc to aldehydes continue to be developed. Abramson *et al.*^{25,26} have reported the immobilisation of a chiral amino-alcohol onto the surface of various mesoporous aluminosilicate supports. The optimum heterogenised catalyst **1** (Scheme 1) was prepared by covalently linking (–)-ephedrine onto a support prepared by the sol–gel method. Its use in the addition of diethylzinc to benzaldehyde was investigated and it was found to result in moderate enantioselectivities, close to those obtained when homogeneous ephedrine was used as catalyst. However the use of silicate supports prepared by different methods or with smaller pore diameters gave poorer results. These catalysts could be reused three times without loss of enantioselectivity.



Scheme 1

Further studies on BINOL ligands anchored onto polystyrene resin and their homogeneous counterparts have been reported.²⁷ These supported species **2** (Scheme 2) were used as chiral ligands (20 mol%) to form titanium catalysts that displayed higher enantioselectivity than the homogeneous analogues. A similar approach was used by Seebach *et al.*²⁸ for the use of immobilised BINOL ligands in the Lewis acid-mediated diethylzinc and trimethylsilyl cyanide additions to

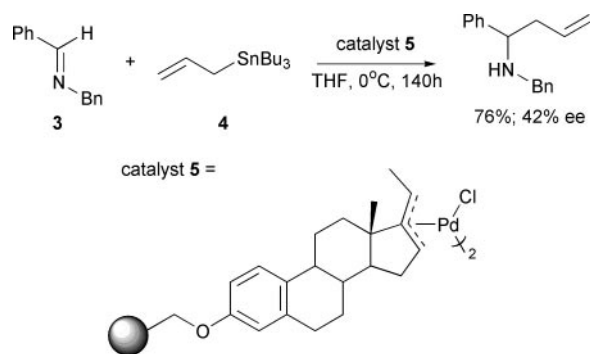
ligands **2** =



Scheme 2

aldehydes. In their strategy, BINOL ligands were incorporated into styrene monomers that were subjected to suspension polymerisation to give suitably functionalised beads. The corresponding catalysts had good activities over several cycles.

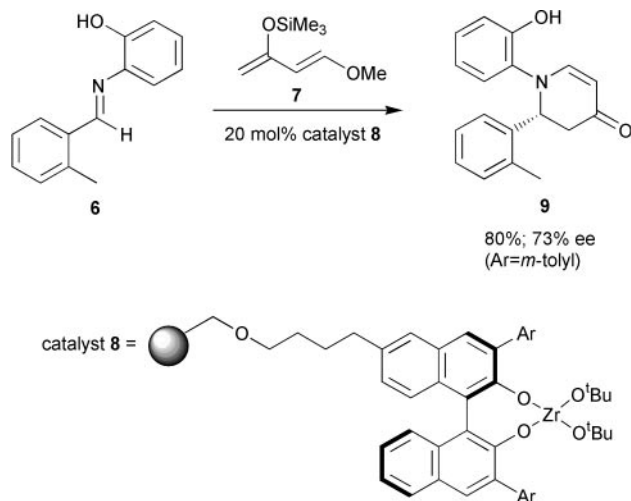
The asymmetric allylation of imines **3** with allyltributylstannane **4** (Scheme 3) has been achieved²⁹ with the use of a stable and recyclable polymer-bound chiral π -allylpalladium catalyst **5**. However the enantioselectivity of this catalyst was only moderate and the reaction times were long.



Scheme 3

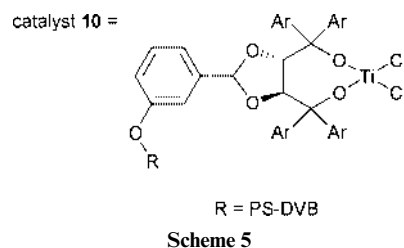
2.2 Diels–Alder reactions

The use of chiral supported catalysts in aza Diels–Alder reactions has been studied by Kobayashi *et al.*³⁰ In an elegant approach to catalyst optimisation, several supported BINOL ligands were prepared and employed in the generation of a small library of chiral zirconium complexes **8**. Their catalytic activity was investigated in the reaction of aldimines **6** with Danishefsky's diene **7** (Scheme 4) to give piperidine adducts **9** in good to high yields with moderate to high enantioselectivities. Furthermore, the results obtained did not vary over three runs.



Scheme 4

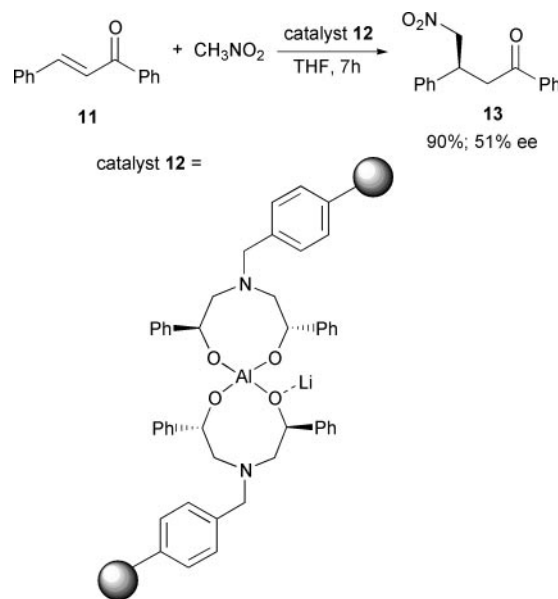
Altava *et al.*³¹ have also developed a supported chiral catalyst **10** (Scheme 5) for use in the Diels–Alder reaction. The titanium-TADDOLate complex[†] attached to a (highly cross-linked) polystyrene monolithic column **10** showed very high stability and led to reversed selectivity when compared to the non-monolithic polystyrene-grafted catalyst. This highlights the importance of the nature of the polymer backbone in supported enantioselective catalysis.



Scheme 5

2.3 Michael addition reactions

In the search for chiral catalysts for asymmetric Michael addition reactions, Sundararajan's team³² have reported a novel polymeric asymmetric aminodiol ligand (prepared by free radical copolymerisation) and used it to generate a chiral aluminium-containing catalyst **12** (Scheme 6). Its use has been demonstrated in the Michael addition reactions of thiols, amines and nitromethane. In the latter case, addition to chalcone **11** led to the formation of the desired product **13** in high yield and with higher enantioselectivities than in the case of the homogeneous catalyst.



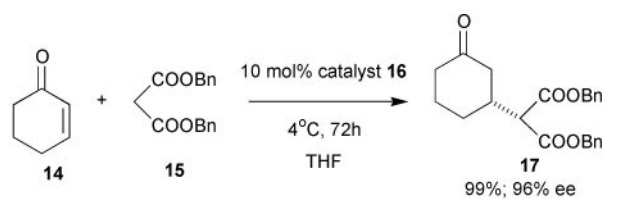
Scheme 6

The use of a polymer-supported BINOL ligand has also been exploited³³ in the development of a novel La and Zn-containing catalyst **16** (Scheme 7). The Michael addition reaction between **14** and **15** (for example) in the presence of this catalyst resulted in the formation of the adduct **17** in high yield and enantioselectivity. However, while the ligand could be easily regenerated and recycled, the recovery of the supported catalyst could not be achieved.

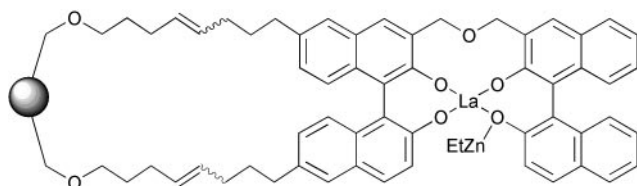
2.4 Other enantioselective C–C bond forming reactions

A C–C bond forming (Strecker-type) reaction involving the enantioselective addition of cyanide to an unsaturated imine **18**

[†] TADDOL = $\alpha,\alpha,\alpha',\alpha'$ -tetraaryl-1,3-dioxolane-4,5-dimethanol.

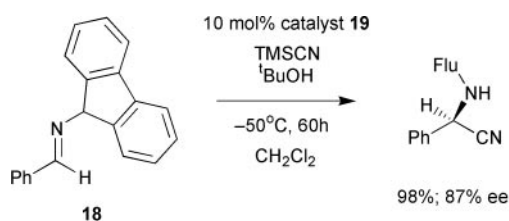


catalyst 16 =

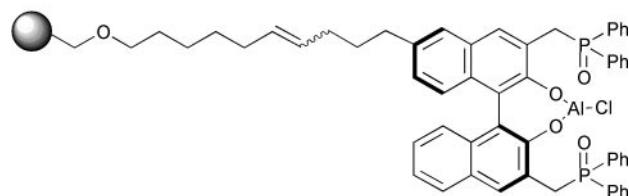


Scheme 7

(Scheme 8) was performed with the aid of a novel polymer-bound bifunctional catalyst **19**.³⁴ The catalyst (with both Lewis acidic and Lewis basic sites) was covalently attached to JandaJEL™ *via* a long spacer, and was found to be recyclable (up to five runs) and comparable to the homogeneous analogue in activity.



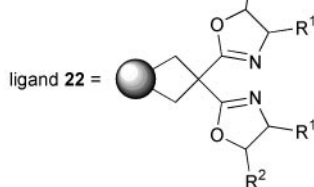
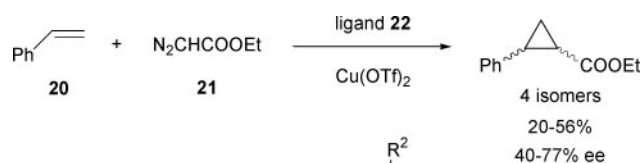
catalyst 19 =



Scheme 8

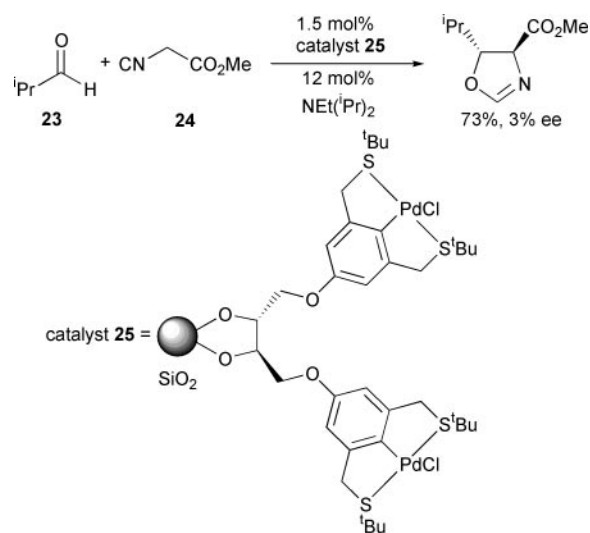
The preparation of a supported bis(oxazoline) copper catalyst from ligand **22** and copper triflate (Scheme 9) has been reported.³⁵ Its activity has been studied in the cyclopropanation of styrene **20** with diazoacetate **21**. Its enantioselectivity is higher than that of the corresponding unsupported counterparts, but lower than that of the homogeneous catalyst with no methylene substituents. In addition, it has been possible to recover and reuse this polymer-bound catalyst.

Finally, a silica-supported bimetallic palladium complex **25** has been prepared³⁶ and investigated as a catalyst for the

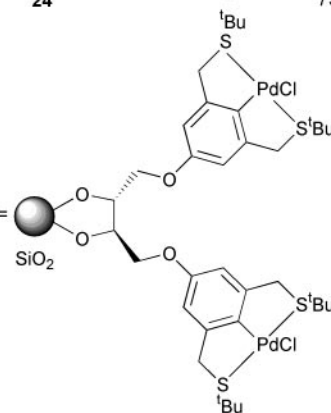


Scheme 9

aldol reaction between aldehydes **23** and isocyanoacetate **24** (Scheme 10). The product was obtained in good yield with the *trans* isomer as the major product (95 : 5). However the supported catalyst displayed very poor enantioselectivity, as did the homogeneous analogues.



catalyst 25 =

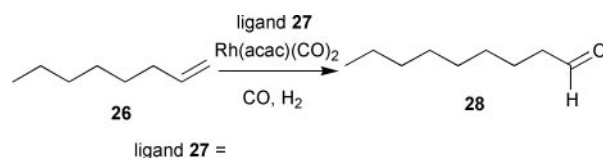


Scheme 10

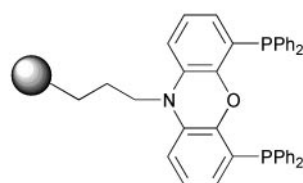
3 Non-chiral catalysts for C–C bond formation

3.1 Hydroformylation

Hydroformylation is a very powerful reaction for the generation of aldehydes **28** from the corresponding alkene **26** using a suitable catalyst and Syngas (carbon monoxide–hydrogen). Recently, a silica-supported rhodium catalyst formed by treatment of ligand **27** with a rhodium carbonyl complex (Scheme 11) has been reported³⁷ that can be used in supercritical carbon dioxide in a continuous hydroformylation process, without any metal leaching. This represents a major advance in the drive towards more environmentally benign chemistry.



ligand 27 =

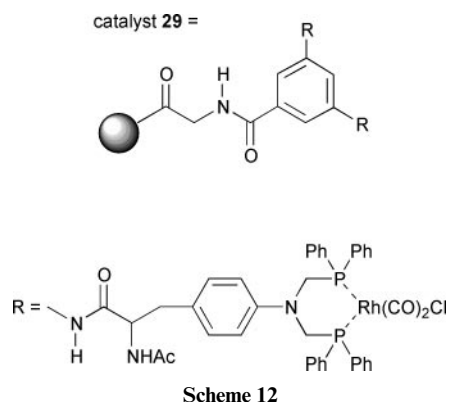


Scheme 11

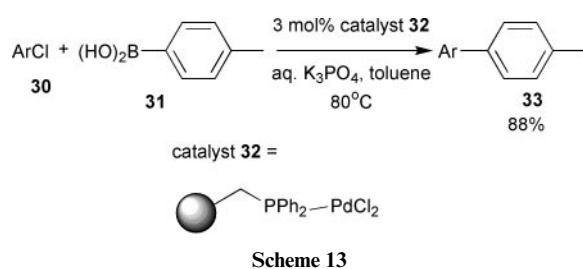
Other researchers³⁸ have also investigated a solid-supported catalyst for this reaction. They have successfully immobilised a recyclable rhodium catalyst **29** (Scheme 12) on to ligands situated at the end of dendritic chains attached to a polymer support. Shown here is the catalyst attached to the first generation supported dendrimer. However, the second generation, more highly branched dendrimer-bound catalyst was found to be superior with respect to recyclability. The study therefore showed that this biomimetic environment can lead to improved catalyst stability and thus reduced metal leaching.

3.2 Palladium catalysts

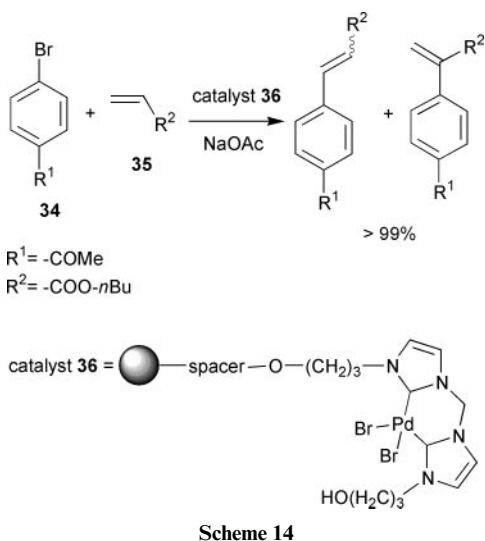
One of the most widely used strategies for C–C bond formation in this field involves the use of supported palladium catalysts.



Such a catalyst **32** bound to polystyrene has recently been developed³⁹ for use in the Suzuki reaction between electron-deficient chloroarenes **30** and arylboronic acids **31** (Scheme 13) to yield the corresponding biaryls **33** in high yields. The recycled catalyst retained its activity during several repeated experiments despite exposure to air during filtration.

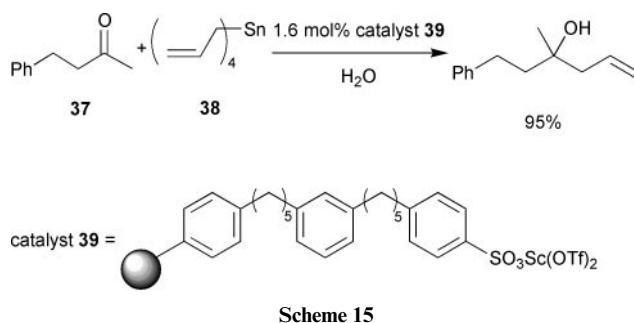


Other supported palladium complexes have been anchored on to silica (without the use of phosphine ligands), which display excellent recyclabilities in the Suzuki reaction.⁴⁰ An air-stable palladium-containing complex **36** prepared by derivatisation of Wang resin (Scheme 14) has also been reported⁴¹ as a recyclable catalyst for use in the Heck reaction between aryl halides **34** and alkenes **35**. Finally, Grigg and York⁴² have employed a supported palladium catalyst to carry out intramolecular Heck reactions in cascade fashion after ring closing metathesis (in solution) to generate bridged ring systems.



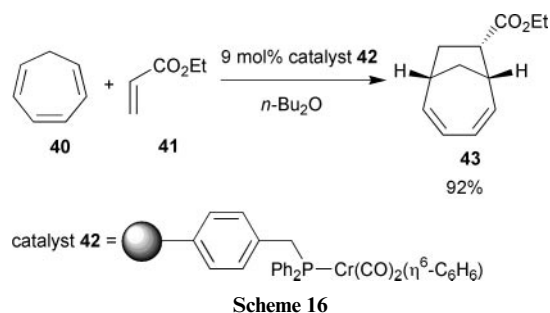
3.3 Miscellaneous C–C bond forming reactions

In their search for a supported scandium catalyst **39** that would display high activity in the allylation of carbonyl compounds **37** with tetraallyltin **38** in water (Scheme 15), Nagayama and Kobayashi⁴³ have developed a new polymeric support with long



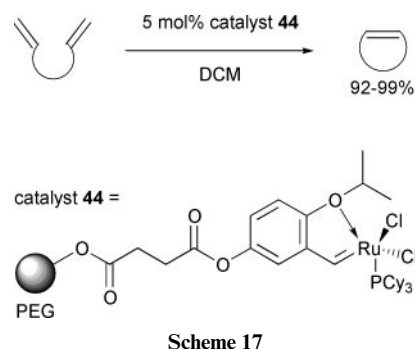
hydrophobic spacer chains. These moieties were included so that the nature of the resulting supported catalyst **39** would lead to increased concentrations of the reacting species within the polymer matrix. As well as high activity, the catalyst displayed excellent recyclability. Its use in other carbon–carbon bond forming reactions (*e.g.* Diels–Alder and Strecker-type reactions) has also been investigated.

The preparation of polycyclics by use of cycloaddition reactions catalysed by novel resin-bound chromium catalysts has been investigated.⁴⁴ The optimum catalyst **42** (Scheme 16) consisted of a chromium arene carbonyl complex anchored *via* a phosphine ligand onto polystyrene. The [6 π + 2 π] reaction between cycloheptatriene **40** and ethyl acrylate **41** gave the cycloadduct **43** in high yield. This result was comparable to that obtained from the photochemical version of this reaction. Leaching studies indicated that little chromium had been lost after five reuses.

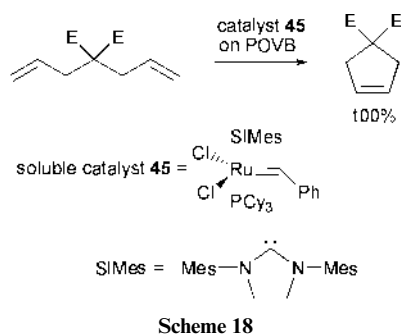


3.4 Olefin metathesis

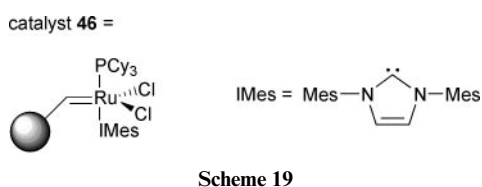
Many new catalysts for ring closing metathesis (RCM) continue to be developed, due to the great importance of this reaction in organic synthesis. Most reported catalysts involve ruthenium carbene complexes attached to a polymeric support. Yao *et al.*⁴⁵ have used a soluble polymer-bound catalyst **44** (Scheme 17) and shown that it was stable and could be readily recycled.



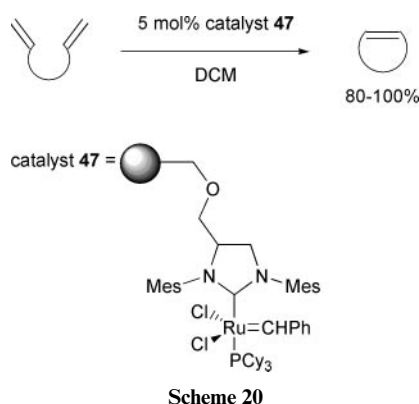
Another approach⁴⁶ involved the impregnation of a soluble catalyst **45** (Scheme 18) onto macroporous polydivinylbenzene (PDVB) to give a “boomerang” type catalyst that was released into solution during RCM. However this strategy led to leaching of ruthenium from the polymer.



A different version of this type of catalyst **46** (Scheme 19) has also been reported by Barrett and co-workers,⁴⁷ and has been compared to their earlier “boomerang” catalyst. This second generation catalyst shows excellent recyclability after four consecutive ring closing metathesis reactions. The best results were obtained when 1-hexene and triphenylphosphine were used as additives.



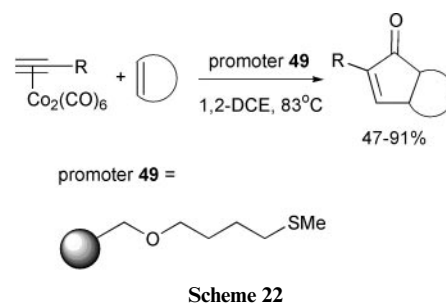
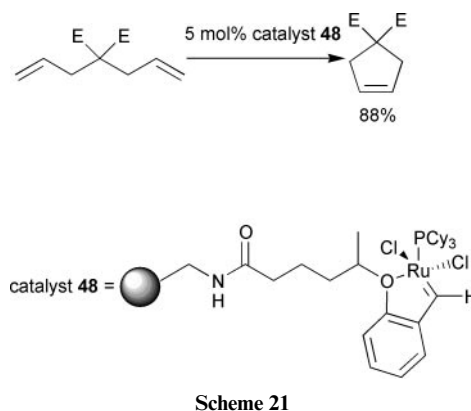
Covalent immobilisation of a catalytically active complex onto a cross-linked polystyrene support **47** (Scheme 20) has also been reported by Blechert and co-workers.⁴⁸ Its use in yne–ene cross-metathesis reactions was also demonstrated. The catalyst could be recovered by filtration under inert conditions, and recycled four times without loss of activity, but with increased reaction times.



Finally, another polystyrene-anchored catalyst **48** (Scheme 21) has been recently published,⁴⁹ which is more robust and can therefore be used without the need for degassing of the reaction mixture. In addition, recycling of **48** can be achieved for up to five cycles, but with a drop in yield of the RCM reaction.

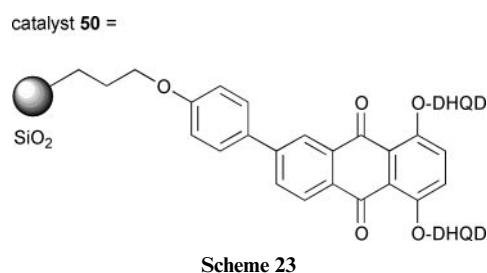
3.5 Pauson–Khand reactions

Further to a recent report⁵⁰ on the detailed study of their supported *N*-oxide promoter, Kerr *et al.*⁵¹ have reported investigations on the use of a new polymer-supported species in the Pauson–Khand reaction for the synthesis of cyclopentenones. A new alkyl methyl sulfide **49** (Scheme 22) has been prepared (from Merrifield resin) and shown to be a recyclable promoter for this reaction. The main advantages resulting from the immobilisation of this promoter were that it was odourless, it retained cobalt residues facilitating product purification and it could be easily regenerated at the end of the reaction.



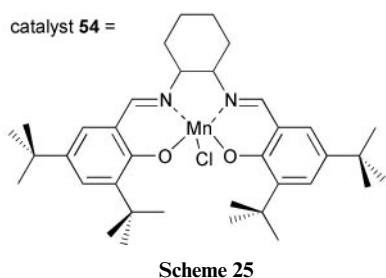
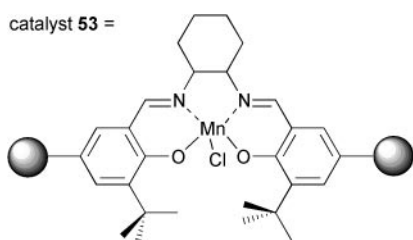
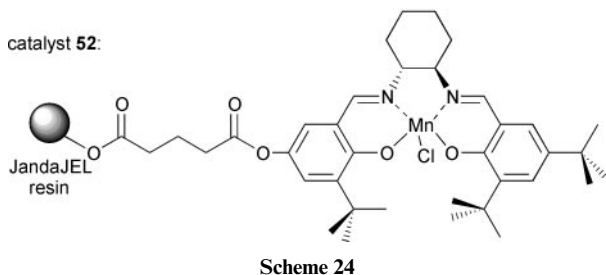
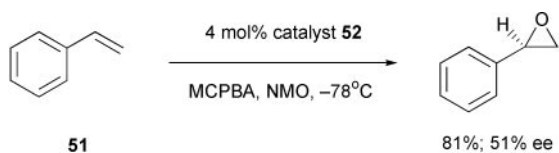
4 Enantioselective oxidation catalysts

Supported ligands for the synthesis of chiral diols (by asymmetric osmium-catalysed dihydroxylation of alkenes) continue to be developed.⁵² Bolm and Maischak have investigated the attachment of an anthraquinone derivative onto silica **50** (Scheme 23) as well as other supports. The use of this heterogeneous catalyst has led to moderate yields of diol products with good enantiomeric excesses; and the values obtained were comparable to those from the homogeneous system.



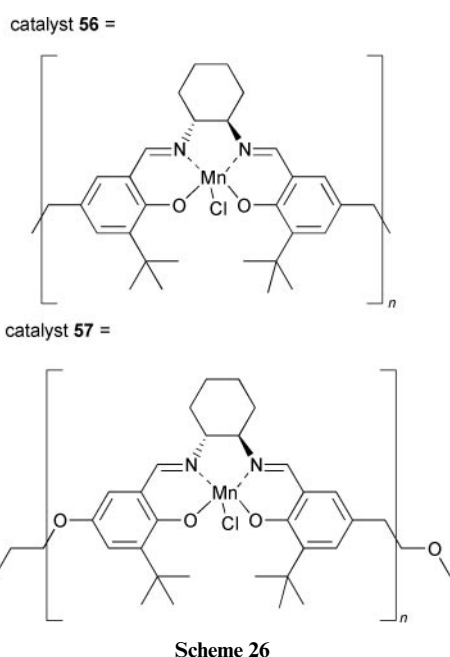
One of the areas of most intense research activity over the past year has been the development of supported metal catalysts for asymmetric epoxidation.⁵³ Chiral catalysts containing titanium and manganese have received much attention, and have been the subject of a recent review.⁵⁴ Janda's team⁵⁵ have recently reported the attachment of Jacobsen's manganese salen complex to a variety of soluble and insoluble supports, and found that the complex supported on JandaJEL™ **52** (Scheme 24) was a good catalyst for the epoxidation of styrene **51**. However the metal leaching after the reaction was considerably high in all cases and therefore led to poor recyclability. It has been suggested that this was due to ligand degradation under the reaction conditions.

Sherrington's report⁵⁶ has also described manganese salen complexes attached to a variety of supports and found that the polymethacrylate-supported species **53** (Scheme 25) displayed excellent enantioselectivities, comparable to those of the homogeneous catalyst **54**. However the selectivity and activity of this catalyst again decreased rapidly with reuse (despite the low levels of manganese leaching), and therefore



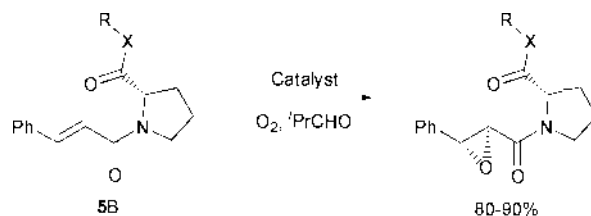
suggested that the intrinsic stability of the salen ligand was too poor.

Another team⁵⁷ has been able to prepare chiral poly-salen ligands and the corresponding manganese complexes **56** and **57** (Scheme 26). These catalysts, with the ligand as part of the polymeric backbone, resulted in moderate to good



yields and enantioselectivities in the epoxidation of a variety of alkenes. These catalysts displayed good stability and recyclability (by precipitation of the soluble polymer-supported catalyst) although there was a gradual deterioration in performance.

A polyaniline-bound cobalt salen catalyst has also been reported⁵⁸ for the highly diastereoselective aerobic epoxidation of the double bond in *N*-cinnamoylproline derived peptides **58** (Scheme 27).

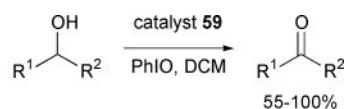


catalyst = Polyaniline supported Co(II) salen complex

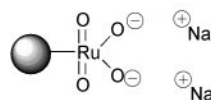
Scheme 27

5 Non-chiral oxidation catalysts

Immobilised catalysts have been developed for the oxidation of alcohols to the corresponding aldehydes and ketones. The sodium ruthenate **59** (Scheme 28) anchored onto polyvinylpyridine, reported by Friedrich and Singh,⁵⁹ has been shown to catalyse the oxidation of a wide variety of alcohols under mild conditions, in the presence of a suitable co-oxidant.

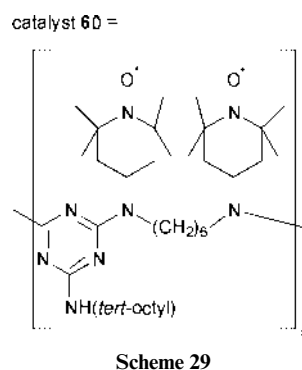


catalyst 59 =

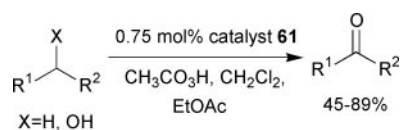


Scheme 28

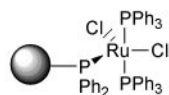
An environmentally-friendly, recyclable polymer-immobilised piperidinyloxy (PIPO) catalyst **60** (Scheme 29) has also been reported⁶⁰ for this reaction. The unusual polymer backbone imparts a beneficial effect on the nitroxyl species, which is twice as active in this case as the silica-supported analogue.



Another resin-bound complex **61** (Scheme 30) has been investigated⁶¹ as a recyclable catalyst in alcohol and hydrocarbon oxidations (as well as in transfer hydrogenations). In this case, the immobilised ruthenium complex was prepared by ligand exchange with the phosphine ligands on a cross-linked polystyrene resin.

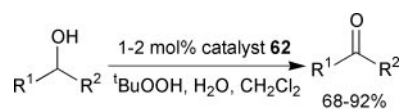


catalyst **61** =

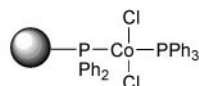


Scheme 30

Similarly, the analogous cobalt complex **62** (Scheme 31) has also been reported as an oxidation catalyst.⁶²



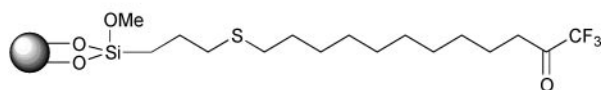
catalyst **62** =



Scheme 31

Other non-metal containing oxidation catalysts have also been developed. Two different perfluorinated ketones attached to silica supports have been reported for use in alkene epoxidation. In one case, excellent results have been reported for use in dioxirane-mediated epoxidations.⁶³ This catalyst could be recycled up to ten times without any loss of activity.

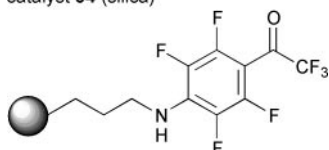
catalyst **63** =



Scheme 32

In the other case,⁶⁴ a supported perfluorinated acetophenone **64** (Scheme 33) could be used several times in the oxidation of alkenes (and amines) using aqueous hydrogen peroxide.

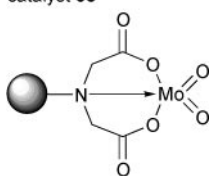
catalyst **64** (silica) =



Scheme 33

Molybdenum catalysts supported on ion exchange macroporous resins, such as **65** on Amberlite resin (Scheme 34), have been described by Kotov *et al.*⁶⁵ and used in the epoxidation of alkenes by organic hydroperoxides to give the corresponding epoxides; however these reactions suffered from the formation of side products.

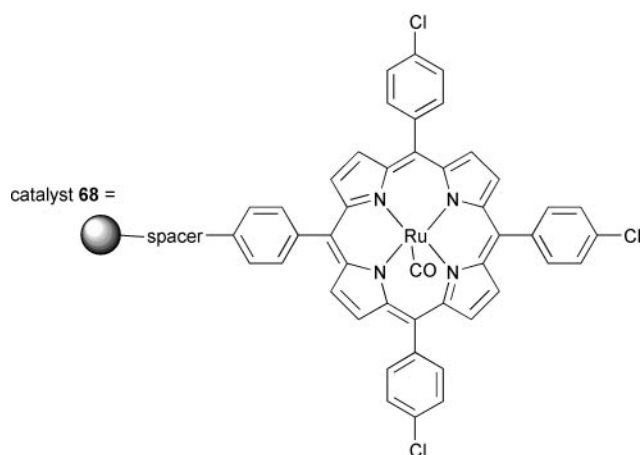
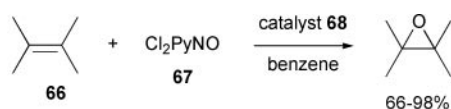
catalyst **65** =



Scheme 34

An environmentally-friendly alkene oxidation process involving silica-supported polyoxometalate epoxidation catalysts (prepared by treatment of modified silica supports with a tungstophosphate anion) has also been studied.⁶⁶ It has been reported that this catalyst could be used to epoxidise alkenes in water using hydrogen peroxide, with high selectivities; however no mention of the recyclability of this catalyst was made.

A ruthenium porphyrin has been supported onto polystyrene,⁶⁷ and the resulting highly stable and recyclable catalyst **68** (Scheme 35) has been used in the epoxidation of alkenes **66** with dichloropyridine *N*-oxide **67** as the oxidant. Finally, similar studies have been carried out⁶⁸ on alkene epoxidations with iodobenzene using polyionic manganese porphyrins electrostatically-anchored to silica surfaces.



Scheme 35

6 Enantioselective reduction catalysts

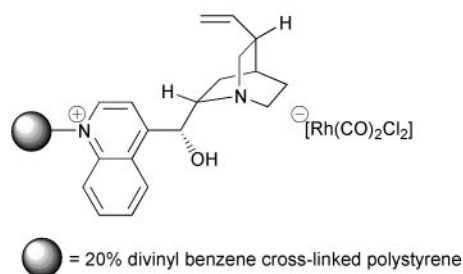
The previously described poly-NAP ligand⁶⁹ (*i.e.* polymerised BINAP) has now been successfully employed in the ruthenium-catalysed hydrogenation of olefinic substrates, such as dehydroamino acids, and has led to similar selectivities to those obtained with the homogeneous BINAP ligand. Soluble polymer supports have also been investigated for the covalent attachment of the BINAP ligand.⁷⁰

Supports based on acrylates have also been employed to support palladium catalysts for the hydrogenation of a variety of unsaturated substrates.⁷¹ A clay support has been used to immobilise a well-defined chiral iridium complex.⁷² In this case, the heterogeneous catalyst, which was tested for activity in the asymmetric hydrogenation of imines, was more enantioselective than the homogeneous counterpart. Surprisingly, the selectivity increased upon reuse.

Recently, many reports have focused on novel supported rhodium catalysts for use in hydrogenation reactions. In Bhaduri's strategy,⁷³ a simple rhodium carbonyl complex was ionically anchored onto a variety of cross-linked polystyrene resins containing chiral ammonium groups. The cinchonine-derived catalyst **69** (Scheme 36) was identified as the most active (from the small library of chiral catalysts) in the asymmetric hydrogenation of dehydroamino acids.

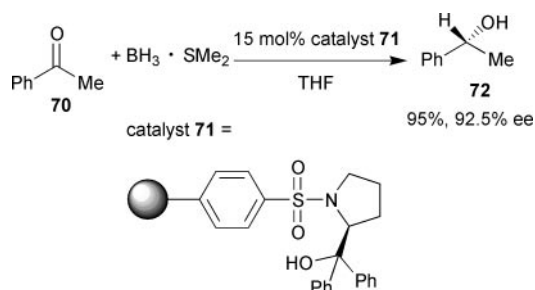
MCM-41 has been used for the non-covalent immobilisation of another rhodium complex [(*R,R*)-Me-(DuPHOS)Rh-(COD)].⁷⁴ This adsorbed catalyst was successfully used in asymmetric hydrogenation of prochiral enamides and was found to be stable in non-polar solvents, therefore allowing recycling. This silica-supported complex was found to be superior to the homogeneous catalyst.

catalyst **69** =



Scheme 36

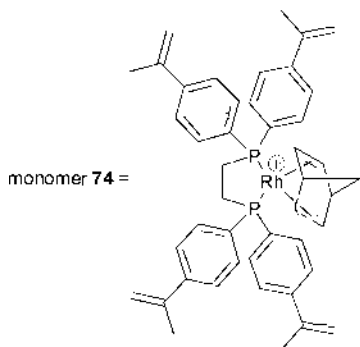
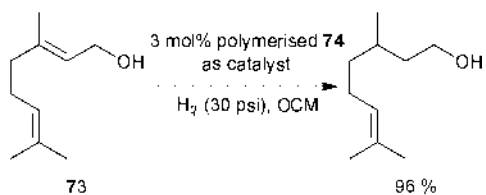
The asymmetric borane reduction of ketones **70** to the corresponding chiral alcohol products **72** catalysed by a polystyrene-supported sulfonamide **71** (Scheme 37) has been investigated.⁷⁵ This catalyst exhibited higher enantioselectivity than the unsupported analogue and could be recycled several times with only a slight loss of activity.



Scheme 37

7 Non-chiral reduction catalysts

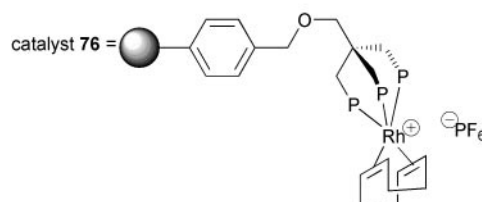
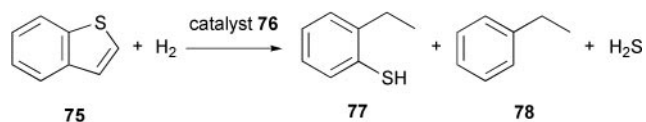
A highly cross-linked polymer was employed to support a rhodium catalyst for alkene hydrogenation and hydroboration.⁷⁶ The porous nature of the polymer network allowed the use of polar protic solvents. The reduction of the alkene **73** (Scheme 38) was achieved, in the presence of a supported catalyst (prepared by suspension polymerisation of the functionalised monomer **74**), in high yield. However the activity of the catalyst slightly decreased upon reuse (up to six times).



Scheme 38

The synthesis of a novel polystyrene-supported triphosphine ligand and the corresponding rhodium complex **76** (Scheme 39) has been reported by Bianchini and co-workers.⁷⁷ The hydro-

genolysis of 1-benzothiophene **75** to 2-ethylthiophenol **77** and ethylbenzene **78** was achieved in moderate yields in the presence of the supported catalyst. Finally, no leaching of the metal was detected and the catalyst could be readily recycled without loss of activity.

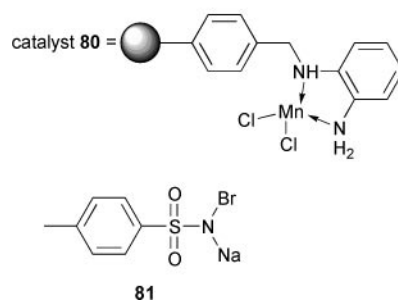
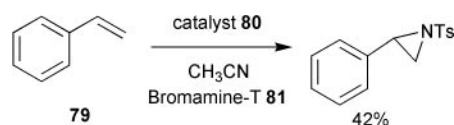


Scheme 39

Palladium catalysts have also been anchored onto a variety of functionalised ion-exchange resins for use in the hydrogenation of alkenes.⁷⁸ The activity of the supported catalysts was investigated and found to increase in cases where the resin contained amide groups, suggesting that these groups play a major role in this catalytic process.

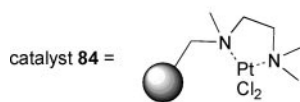
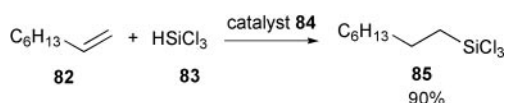
8 Non-chiral catalysts for C–X bond formation

The preparation of a polystyrene-supported manganese(II) complex **80** and its use in the aziridination of alkenes **79** with Bromamine-T **81** (Scheme 40) has been investigated.⁷⁹ Although the yields ranged from moderate to good, its reusability has been demonstrated for up to three runs.



Scheme 40

The hydrosilylation of alkenes **82** with trichlorosilane **83** to form alkylsilanes **85** (Scheme 41) can be achieved⁸⁰ with the use of a resin-bound platinum catalyst **84**. Furthermore, the reaction can be carried out at room temperature, under solvent-



Scheme 41

less conditions. This catalyst displayed similar activity to that of the commonly used homogeneous catalyst (Speier's catalyst) as well as improved selectivity. Finally, the ease of recyclability and low platinum leaching make this an attractive alternative to the soluble catalyst.

9 Conclusion

Most of the supported catalysts discussed in this review have been either transition metal complexes or chiral auxiliaries supported on polystyrene or silica. The methods used for catalyst immobilisation have ranged from co-polymerisation of functionalised monomers to the more commonly used approach of covalent or ionic anchoring of the ligand onto a preformed support. Over the past year, much progress has been made on the development of enantioselective catalysts with comparable activities and selectivities to their homogeneous counterparts. To this aim, many researchers⁸¹ have explored novel polymeric supports, often incorporating the chiral ligand onto the rigid polymer backbone. Metal leaching and catalyst recyclability are obviously important issues that need to be investigated. While the latter is routinely demonstrated for any supported catalyst under investigation, many reports still lack the actual evidence of metal loadings before and after catalysis.

Finally, there have been some reports on the identification of new supported catalysts by the screening of libraries of these catalysts. While this field is still in its infancy, and most reports have used the solid-phase parallel synthesis approach in order to optimise catalyst efficiency, there is great potential in this very powerful new tool, as has been demonstrated in the studies by Natarajan and Madalengoitia.^{82,83}

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11 References

- 1 Previous review covering the period of April 1999 to March 2000: Y. R. de Miguel, *J. Chem. Soc., Perkin Trans. 1*, 2000, **24**, 4213–4221.
- 2 A. Akelah and D. C. Sherrington, *Chem. Rev.*, 1981, **81**, 557.
- 3 A. Akelah and D. C. Sherrington, *Polymer*, 1983, **24**, 1369.
- 4 S. J. Shuttleworth, S. M. Allin and P. K. Sharma, *Synthesis*, 1997, 1217.
- 5 S. Kobayashi, *Curr. Opin. Chem. Biol.*, 2000, **4**, 338.
- 6 S. Kobayashi, *Chem. Soc. Rev.*, 1999, **28**, 1.
- 7 H. Fenniri, *Curr. Med. Chem.*, 1996, **3**, 343.
- 8 F. Balkenhohl, C. von dem Bussche-Hünnefeld, A. Lansky and C. Zechel, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2288.
- 9 N. K. Terrett, M. Gardner, D. W. Gordon, R. J. Kobylecki and J. Steele, *Tetrahedron*, 1995, **51**, 8135.
- 10 E. M. Gordon, M. A. Gallop and D. V. Patel, *Acc. Chem. Res.*, 1996, **29**, 144.
- 11 L. A. Thompson, *Curr. Opin. Chem. Biol.*, 2000, **4**, 324.
- 12 J. J. Parlow, R. V. Devraj and M. S. South, *Curr. Opin. Chem. Biol.*, 1999, **3**, 320.
- 13 R. J. Booth and J. C. Hodges, *Acc. Chem. Res.*, 1999, **32**, 18.
- 14 S. W. Kaldor and M. G. Siegel, *Curr. Opin. Chem. Biol.*, 1997, **1**, 101.
- 15 For a most comprehensive review: S. V. Ley, I. R. Baxendale, R. N. Bream, P. S. Jackson, A. G. Leach, D. A. Longbottom, M. Nesi, J. S. Scott, R. I. Storer and S. J. Taylor, *J. Chem. Soc., Perkin Trans. 1*, 2000, 3815.
- 16 S. J. Shuttleworth, S. M. Allin, R. D. Wilson and D. Nasturica, *Synthesis*, 2000, **8**, 1035.
- 17 B. Clapham and A. J. Sutherland, *Tetrahedron Lett.*, 2000, **41**, 2253.
- 18 J. Eames and M. Watkinson, *Eur. J. Org. Chem.*, 2001, **7**, 1213.
- 19 S. Bhattacharyya, *Comb. Chem. High Throughput Screening*, 2000, **3**, 65.
- 20 B. Altava, M. I. Burguete, E. Garcia-Verdugo, S. V. Luis, M. J. Vincent and J. A. Majoral, *React. Funct. Polym.*, 2001, **48**, 25.
- 21 J. H. Clark, *Pure Appl. Chem.*, 2001, **73**, 103.

- 22 H. Wennemers, *Comb. Chem. High Throughput Screening*, 2001, **4**, 273.
- 23 S. Senkan, *Angew. Chem., Int. Ed.*, 2001, **40**, 312.
- 24 M. T. Reetz, *Angew. Chem., Int. Ed.*, 2001, **40**, 284.
- 25 S. Abramson, M. Laspéras, A. Galarneau, D. Desplantier-Giscard and D. Brunel, *Chem. Commun.*, 2000, 1773.
- 26 S. Abramson, M. Laspéras and B. Chiche, *J. Mol. Catal. A*, 2001, **165**, 231.
- 27 X. Yang, W. Su, D. Liu, H. Wang, J. Shen, C. Da, R. Wang and A. S. C. Chan, *Tetrahedron*, 2000, **56**, 3511.
- 28 H. Sellner, C. Faber, P. B. Rheiner and D. Seebach, *Chem. Eur. J.*, 2000, **6**, 3692.
- 29 M. Bao, H. Nakamura and Y. Yamamoto, *Tetrahedron Lett.*, 2000, **41**, 131.
- 30 S. Kobayashi, K. Kusakabe and H. Ishitani, *Org. Lett.*, 2000, **2**, 1225.
- 31 B. Altava, M. Isabel Burgete, J. M. Fraile, J. I. Garcia, S. V. Luis, J. A. Mayoral and M. J. Vicent, *Angew. Chem., Int. Ed.*, 2000, **39**, 1503.
- 32 G. Sundararajan and N. Prabakaran, *Org. Lett.*, 2001, **3**, 389.
- 33 S. Matsunaga, T. Ohshima and M. Shibasaki, *Tetrahedron Lett.*, 2000, **41**, 8473.
- 34 H. Nogami, S. Matsunaga, M. Kanai and M. Shibasaki, *Tetrahedron Lett.*, 2001, **42**, 279.
- 35 M. I. Burguete, J. M. Fraile, J. I. Garcia, E. Garcia-Verdugo, S. V. Luis and J. A. Mayoral, *Org. Lett.*, 2000, **2**, 3905.
- 36 R. Gimenez and T. M. Swager, *J. Mol. Catal. A*, 2001, **166**, 265.
- 37 N. J. Meehan, A. J. Sandee, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. van Leeuwen and M. Poliakoff, *Chem. Commun.*, 2000, 1497.
- 38 P. Arya, G. Panda, N. Venugopal Rao, H. Alper, S. Christine Bourque and L. E. Manzer, *J. Am. Chem. Soc.*, 2001, **123**, 2889.
- 39 K. Inada and N. Miyaoura, *Tetrahedron*, 2000, **56**, 8661.
- 40 E. B. Mubofu, J. H. Clark and D. J. Macquarrie, *Green Chem.*, 2001, **3**, 23.
- 41 J. Schwarz, V. P. W. Böhm, M. G. Gardiner, M. Grosche, W. A. Herrmann, W. Hieringer and G. Raudaschl-Sieber, *Chem. Eur. J.*, 2000, **6**, 1773.
- 42 R. Grigg and M. York, *Tetrahedron Lett.*, 2000, **41**, 7255.
- 43 S. Nagayama and S. Kobayashi, *Angew. Chem., Int. Ed.*, 2000, **3**, 567.
- 44 J. H. Rigby, M. A. Kondratenko and C. Fiedler, *Org. Lett.*, 2000, **24**, 3917.
- 45 Q. Yao, *Angew. Chem., Int. Ed.*, 2000, **39**, 3896.
- 46 L. Jafarpour and S. P. Nolan, *Org. Lett.*, 2000, **2**, 4075.
- 47 M. Ahmed, T. Arnauld, A. G. M. Barrett, D. C. Braddock and P. A. Procopiou, *Synlett*, 2000, **7**, 1007.
- 48 S. C. Schürer, S. Gessler, N. Buschmann and S. Blechert, *Angew. Chem., Int. Ed.*, 2000, **39**, 3898.
- 49 J. Dowden and J. Savovic, *Chem. Commun.*, 2001, 37.
- 50 D. S. Brown, E. Campbell, W. J. Kerr, D. M. Lindsay, A. J. Morrison, K. G. Pike and S. P. Watson, *Synlett*, 2000, **11**, 1573.
- 51 W. J. Kerr, D. M. Lindsay, M. McLaughlin and P. L. Pauson, *Chem. Commun.*, 2000, 1467.
- 52 C. Bolm and A. Maischak, *Synlett*, 2001, **1**, 93.
- 53 D. C. Sherrington, *Catal. Today*, 2000, **57**, 87.
- 54 D. C. Sherrington, J. K. Karjalainen, L. Canali, H. Deleuze and O. E. O. Hormi, *Macromol. Symp.*, 2000, **156**, 125.
- 55 T. S. Reger and K. D. Janda, *J. Am. Chem. Soc.*, 2000, **122**, 6929.
- 56 L. Canali, E. Cowan, H. Deleuze, C. L. Gibson and D. C. Sherrington, *J. Chem. Soc., Perkin Trans. 1*, 2000, 2055.
- 57 X. Yao, H. Chen, W. Lü, G. Pan, X. Hu and Z. Zheng, *Tetrahedron Lett.*, 2000, **41**, 10267.
- 58 E. N. Prabhakaran, J. P. Nandy, S. Shukla and J. Iqbal, *Tetrahedron Lett.*, 2001, **42**, 333.
- 59 H. B. Friedrich and N. Singh, *Tetrahedron Lett.*, 2000, **41**, 3971.
- 60 A. Dijkstra, I. W. C. E. Arends and R. A. Sheldon, *Synlett*, 2001, **1**, 102.
- 61 N. E. Leadbeater, *J. Org. Chem.*, 2001, **66**, 2168.
- 62 N. E. Leadbeater and K. A. Scott, *J. Org. Chem.*, 2001, **65**, 4770.
- 63 C. E. Song, J. S. Lim, S. C. Kim, K. Lee and D. Y. Chi, *Chem. Commun.*, 2000, 2415.
- 64 K. Neimann and R. Neumann, *Chem. Commun.*, 2000, 487.
- 65 S. V. Kotov, S. Boneva and T. Kolev, *J. Mol. Catal. A*, 2000, **154**, 121.
- 66 T. Sakamoto and C. Pac, *Tetrahedron Lett.*, 2000, **41**, 10009.
- 67 X. Yu, J. Huang, W. Yu and C. Che, *J. Am. Chem. Soc.*, 2000, **122**, 5337.
- 68 H. C. Sacco, Y. Iamamoto and J. R. Lindsay Smith, *J. Chem. Soc., Perkin Trans. 2*, 2001, 181.
- 69 R. ter Halle, E. Schulz, M. Spagnol and M. Lemaire, *Tetrahedron Lett.*, 2000, **41**, 3323.

- 70 Q. Fan, G. Deng, X. Chen, W. Xie, D. Jiang, D. Liu and A. S. C. Chan, *J. Mol. Catal. A*, 2000, **159**, 37.
- 71 M. M. Dell'Anna, M. Gagliardi, P. Mastrorilli, G. P. Suranna and C. F. Nobile, *J. Mol. Catal. A*, 2000, **158**, 515.
- 72 R. Margalef-Català, C. Claver, P. Salagre and H. Fernández, *Tetrahedron: Asymmetry*, 2000, **11**, 1469.
- 73 S. Bhaduri, G. K. Lahiri and P. Munshi, *J. Organomet. Chem.*, 2000, **606**, 151.
- 74 F. M. de Rege, D. K. Morita, K. C. Ott, W. Tumas and R. D. Broene, *Chem. Commun.*, 2000, 1797.
- 75 J. Hu, G. Zhao, G. Yang and Z. Ding, *J. Org. Chem.*, 2001, **66**, 303.
- 76 R. A. Taylor, B. P. Santora and M. R. Gagné, *Org. Lett.*, 2000, **2**, 1781.
- 77 C. Bianchini, M. Frediani and F. Vizza, *Chem. Commun.*, 2001, 479.
- 78 M. Zecca, R. Fisera, G. Palma, S. Lora, M. Hronec and M. Kralik, *Chem. Eur. J.*, 2000, **6**, 1980.
- 79 R. Vyas, B. M. Chanda, A. A. Belhekar, D. R. Patel, R. N. Ram and A. V. Bedekar, *J. Mol. Catal. A*, 2000, **160**, 237.
- 80 R. Drake, R. Dunn, D. C. Sherrington and S. J. Thomson, *Chem. Commun.*, 2000, 1931.
- 81 For example C. Saluzzo, R. ter Halle, F. Touchard, F. Fache, E. Schulz and M. Lemaire, *J. Organomet. Chem.*, 2000, **603**, 30.
- 82 A. Natarajan and J. S. Madalengoitia, *Tetrahedron Lett.*, 2000, **41**, 5789.
- 83 A. Natarajan and J. S. Madalengoitia, *Tetrahedron Lett.*, 2000, **41**, 5783.