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Review

Asymmetric heterogeneous catalysis by metalloporphyrins

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Contents

Abstract

The synthesis of enantiomerically pure compounds is one of the major challenges in heterogeneous catalysis. The use of heterogeneous catalysts under ambient conditions offers several advantages compared with their homogeneous counterparts, such as ease of recovery and recycling and enhanced stability. Distinct methodologies have been developed for the immobilization of homogeneous catalysts or the creation of heterogeneous catalysts. The current applications of metalloporphyrins in heterogeneous catalytic asymmetric reactions will be herein reported. Preparation of chiral metalloporphyrin polymers and their uses in catalytic asymmetric syntheses will be described. Thus, cyclopropanation reactions using functionalized diazoalkanes as reagents lead to high enantioselectivity and high diastereoselectivity. Catalytic oxidation reactions will also be presented. Comparison between heterogeneous and homogeneous catalysis will be discussed from asymmetric synthesis point of view.

Keywords: Heterogeneous catalysis; Asymmetric; Porphyrins; Ruthenium

1. Introduction

Supporting transition metal catalytic complexes on insoluble supports have an important role in the development of heterogeneous catalysis [1,2]. Various methods are available for the heterogenization of homogeneous chiral catalysts [3]. Generally, immobilization may be obtained by formation of a covalent bond, by adsorption or ion-pair formation and, by encapsulation or entrapment. A preformed polymer is functionalized with a ligand which is used to bind the metal. However, under the conditions needed to catalyze organic reactions, desorption of the catalytic entity is possible if there is a labile coordination bond. If weakly coordinating solvents, reagents and products are present, metal leaching may be minimal, but coordinating solvents will accelerate catalyst leaching. Another synthetic approach involves the preparation of a monomer, which contains the ligand metal complex, followed by the polymerisation of the monomer to generate the desirable polymer. In this case, several

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key advantages exist. First, distribution of active sites throughout the polymer is assured at the microstructural level. Second the degree of crosslinking can be systematically varied. Finally, the nature of the polymer matrix can be varied depending on the number of polymerisation sites. However, this approach also presents problems. Monomers containing metal complexes may undergo undesirable reactions with radical, basic or acid initiators which preclude a good polymerisation behaviour. The support materials need to be thermally, chemically and mechanically stable during the reaction process. Inorganic supports present one major advantage over organic ones: improved mechanical properties. This makes them especially attractive for grafting of the catalyst that should be recycled many times. However, it is not always easy to avoid unwelcome interactions, as well as some leaching of the ligand and of the metal, if heterogenizations are realized through noncovalent interactions. There are recent review articles which have nicely covered this general topic [3–5].

Chiral metalloporphyrins have been successfully used in the asymmetric catalysis of cyclopropanation and oxidation reactions for the past decade [6–12]. However, these catalysts suffer from one major drawback: the tedious preparation of the chiral macrocycles with numerous steps, including resolving experiments of racemic intermediates. Their separation from the reacting mixture and the recycling are needed for their developments as useful systems. This review presents different methods for heterogeneization that have recently developed for the separation and recycling of chiral metalloporphyrins. The results are described below and arranged by reaction type.

2. Heterogeneous catalysis by metalloporphyrins: overview

Numerous methods for immobilizing metalloporphyrins under insoluble materials have been reported. They frequently involve fixation of metalloporphyrin catalysts on inorganic supports such as silica gel [13–22], molecular sieves [23,24], zeolites [25–27], montmorillonite [28–32], gold electrodes [33], rhenium clusters [34] and solid state metal phosphonates [35,36]. Manganese porphyrin has been recently immobilized as a monolayer film by a combination of Langmuir–Blodgett and self-assembled monolayer techniques that use zirconium phosphonate linkages [37]. Organic polymers, such as polystyrene [38], ion-exchange resins [39–43], Merrifield's peptide resin [44], isocyanide polymer [45] and polypeptides [46–49] have also been used to support metalloporphyrins. In some cases, the polymer is functionalized and the porphyrin is attached through a covalent bond or a coordinative bond to the material. In contrast, there are very few organic polymers containing metalloporphyrins prepared by chemical polymerization of metalloporphyrin monomers [50–53]. Soluble polymer-supported ruthenium porphyins [54–56] and dendritic metalloporphyrins [57,58] have also been used as catalysts for organic transformations.

It must be emphasized that the problem associated with hydrocarbon oxidations catalyzed by metalloporphyrins is the oxidative self-destruction of the catalyst under the very strong oxidising medium. One approach to reduce the metalloporphyrin degradation is to immobilise the catalyst by attachment to an organic or inorganic polymer. This strategy which has been largely developed with non-chiral catalysts, also prevents μ-oxo dimer formation and gives the benefit of easy catalyst recovery. Thus, efficient systems involving polymers with achiral metalloporphyrins bearing electron-withdrawing substituents on the aryl group have been reported [20,21]. It seems that anchoring the catalyst with a covalent bond appears to be a good strategy for supporting the porphyrin since the porphyrin is not leached into solution even in the strong oxidation conditions.

3. Asymmetric heterogeneous catalysis

3.1. Cyclopropanation

3.1.1. Introduction: homogeneous catalysis

Recent growth in the area of transition metal porphyrin chemistry has, in part, been driven by the increased interest associated with metal-catalyzed cyclopropanation. There are two recent reviews on this topic [9,10]. Thus, the renewal of interest in reactions catalyzed by ruthenium(II) porphyrin complexes, is related to the simultaneous development of new chiral ruthenium porphyrins [6,59–61]. In some cases asymmetric cyclopropanations were very successful. As a recent example, the intermolecular cyclopropanation of styrene and its derivatives with diisopropyl diazomethylphosphonate [62] afforded the corresponding cyclopropyl esters in up to 92% ee with high *trans*/*cis* ratios of up to 24 and high catalyst turnovers up to 2×10^2 (Fig. 1) [63]. We also investigated the cyclopropanation of *para*-substituted styrenes and *para*-substitution (*p*-Y-styrene, Y = Me, MeO, CF_3, and Cl) does not have a significant effect upon the enantioselectivity of styrene cyclopropanation. A similar effect was noted with asymmetric cyclopropanation with ethyl diazoacetate using a different chiral ruthenium catalyst [9]. Asymmetric intermolecular and intramolecular cyclopropanations of alkenes catalyzed by the same catalyst were also reported [64]. Chiral iron(II) porphyrins are also effective catalysts in the cyclopropanation of olefins with ethyl diazoacetate, however the enantioselectivities were modest [65,66]. New iron porphyrin carbene complexes, bearing alkoxycarbonyl groups have been recently characterized [67]. The development of new catalysts for asymmetric heterogeneous cyclopropanation reactions is of high current interest. Among the reported chiral catalysts, the supported bis-(oxazoline)-Cu complexes are the most extensively used [4]. Supported metalloporphyrins have also been used for heterogeneous catalysis. The results are described below and arranged by support type.

3.1.2. Heterogeneous cyclopropanation reactions with electropolymerized films

Since the first report of Macor and Spiro [68], the immobilization of metalloporphyrins onto electrodes has been carried out mainly by electropolymerization. Conducting metalloporphyrin polymers such as polypyrrole [69], polythiophene [70], and others [71] are attractive as possible materials for this approach [72]. However, pyrrole and its derivatives are the most frequently used

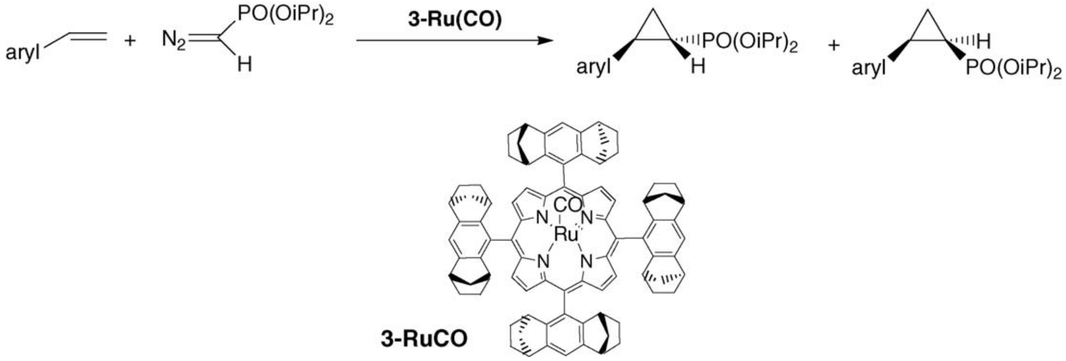


Fig. 1. Cyclopropanation reaction catalyzed by chiral ruthenium catalyst.

compounds for the formation of conducting polymers, mainly due to the high flexibility in its molecular design and its easy formation from different aqueous and non-aqueous solvents.

In this part, we describe the preparation of optically active electropolymerized films bearing chiral metalloporphyrins and asymmetric heterogeneous carbene transfer catalyzed by these polymers [73]. We have reported that anodic oxidation of ruthenium complexes of various spirobifluorenylporphyrins [52] and tetrafluorenylporphyrins [74] leads to the coating of the working electrode by insoluble optically active films. They were characterized by electrochemical behaviour and physicochemical properties. After removing from the electrode, the ruthenium-complexed polymers were evaluated as catalysts for the cyclopropanation of olefins by ethyl diazocetate. Extension of this method to optically active ruthenium porphyrins have also been recently reported [73]. It was decided to target porphyrins bearing spirobifluorenyl groups to allow polymerization and chiral groups for asymmetric induction, as monomers. The mixed aldehyde condensation is described in Fig. 2. The chiral group is a C2-symmetric group which contains two norbornane groups fused to the central benzene ring, previously reported by Halterman and Jan [6]. This chiral group is particularly interesting since the enantiomeric excesses are quite high (90%) when the catalytic reactions are undertaken under homogeneous conditions [63,64].

A schematic representation of the synthesis of optically active metallopolymers is shown in Fig. 3. The solid polymers resulting from the electrocopolymerization of 4-RuCO and 5-RuCO with spirobifluorene, respectively copoly(4-RuCO) and copoly(5-RuCO), were then tested as catalysts in the cyclopropanation reactions of styrene with ethyl diazoacetate (Fig. 4) at different temperatures (Table 1). The two polymers lead to diastereoselectivity and yields close to those obtained with the homogeneous catalysts [73]. The solid obtained by copolymerization of 4-RuCO with spirobifluorene leads to the best results in toluene, but the most significant difference with the monomer is the reduction of the enantioselectivity, decreasing from 76% (−20 °C, 4-RuCO) to 53% (Table 1, entry 3). If we except this

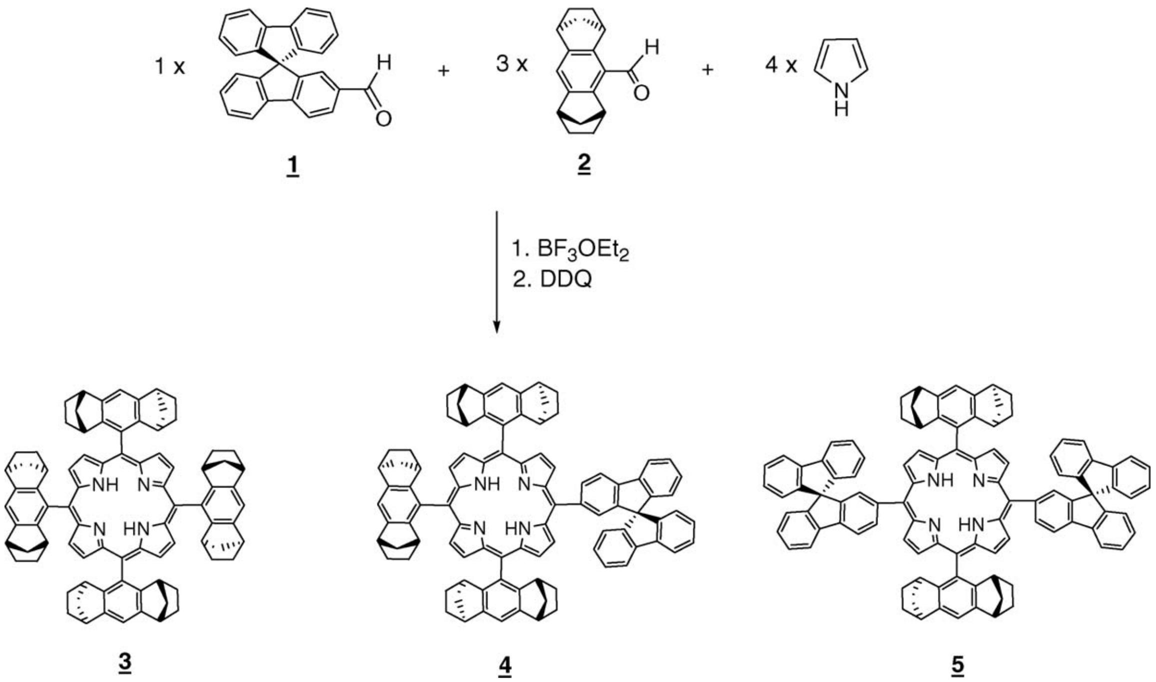
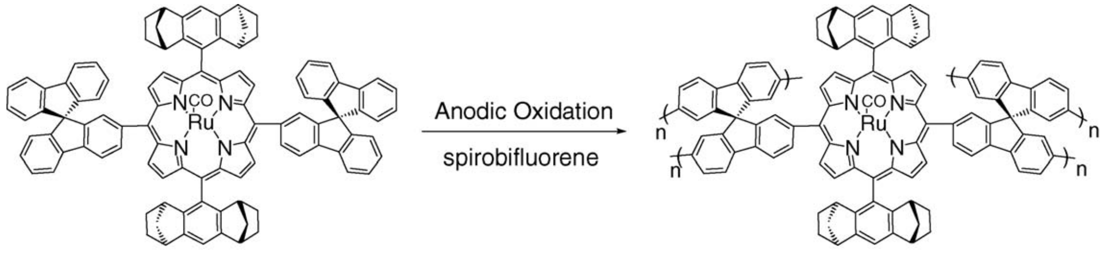


Fig. 2. Mixed aldehyde condensation of chiral dinorbornabenzaldehyde and 9,9′-spirobifluorene-2-carbaldehyde.



5-RuCO copoly(**5-RuCO**)

Fig. 3. Schematic representation of the synthesis of metalloporphyrin polymers by anodic oxidation.

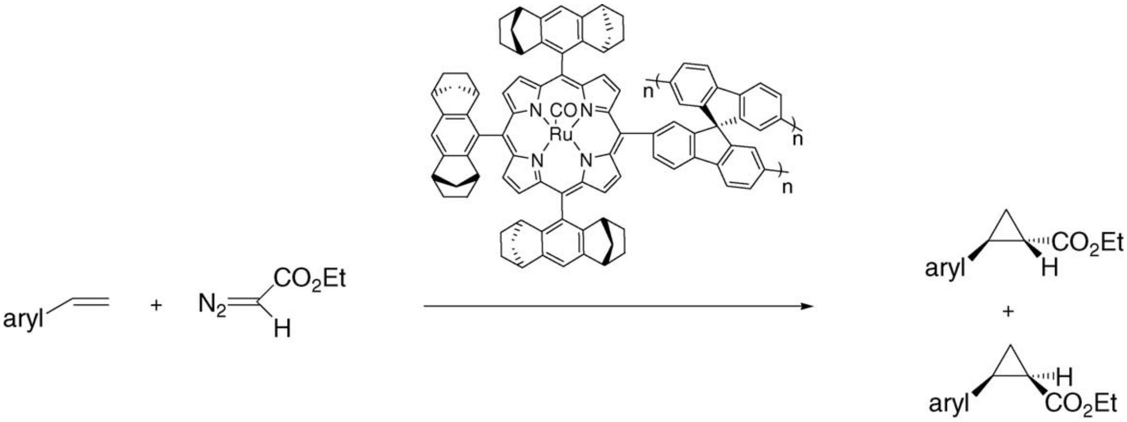


Fig. 4. Cyclopropanation of styrene with ethyl diazoacetate catalyzed by ruthenium polymers.

result at low temperature, surprisingly, the two polymers gave similar enantioselectivity and diastereoselectivity.

To prepare the catalytic system, it was necessary to introduce a non-chiral group, the spirobifluorene, to polymerise the monomer. A decrease of the enantiomeric excess was expected according to a decrease of the number of chiral groups if we compared the catalytic efficiency of a complex bearing four chiral groups, under homogeneous conditions. However, the enantioselectivity is reduced to 53%, a value which is lower than expected from the one obtained with the monomer 4-RuCO under homogeneous catalytic conditions. It is difficult to give an explanation for this effect, although it is clear that the polymer has a different influence on the energy of the transition states of the reaction. This effect may also be related to a diminished access of the substrates to the catalytic sites because of the cross-linked structure of the polymers. It must be noted that atropisomers were detected with ruthenium spirobifluorenylporphyrins [75]. Another explanation would be the presence of high oxidation state ruthenium species in the polymer, such as paramagnetic Ru(III) and Ru(IV) as reactive species, in the case of incomplete reduction after the electropolymerization. These reactive sites may also decrease the enantioselectivity.

3.1.3. Heterogeneous cyclopropanation reactions with chiral monolithic resins

We also explore the heterogeneization of these enantioselective catalysts using monolithic resins [76]. The starting point of the work consisted in the introduction of a vinyl group into an optically active porphyrin followed by metal insertion, with the aim of preparing polymers using the chiral metalloporphyrin as a co-monomer. Fig. 5 shows an example, using ethylene glycol dimethacrylate for copolymerization, as previously reported with non-chiral porphyrins [51]. Thus, several block copolymerizations were possible with divinyl benzene using a protocol

Table 1
Asymmetric cyclopropanation of styrene by ethyl diazoacetate catalyzed by porphyrin polymers[a]

Catalyst	Solvent	Temperature (°C)	Yield[b] (%)	*Trans*/*cis*	ee$_{trans}$[c] (%) (1*S*,2*S*)	ee$_{cis}$[c] (%) (1*S*,2*R*)
Copoly(4-RuCO) (25%)	Toluene	25	82	82/18	25	7
		0	50	85/15	40	9
		−40	35	77/23	53	7
Copoly(5-RuCO) (25%)		25	89	88/12	29	5
		0	80	89/11	30	8

[a] Reactions were performed in CH_2Cl_2 for 24 h with a catalyst:diazo:substrate molar ratio of 1:200:1000.

[b] Yields were based on styrene consumed.

[c] Determined by gas chromatography.

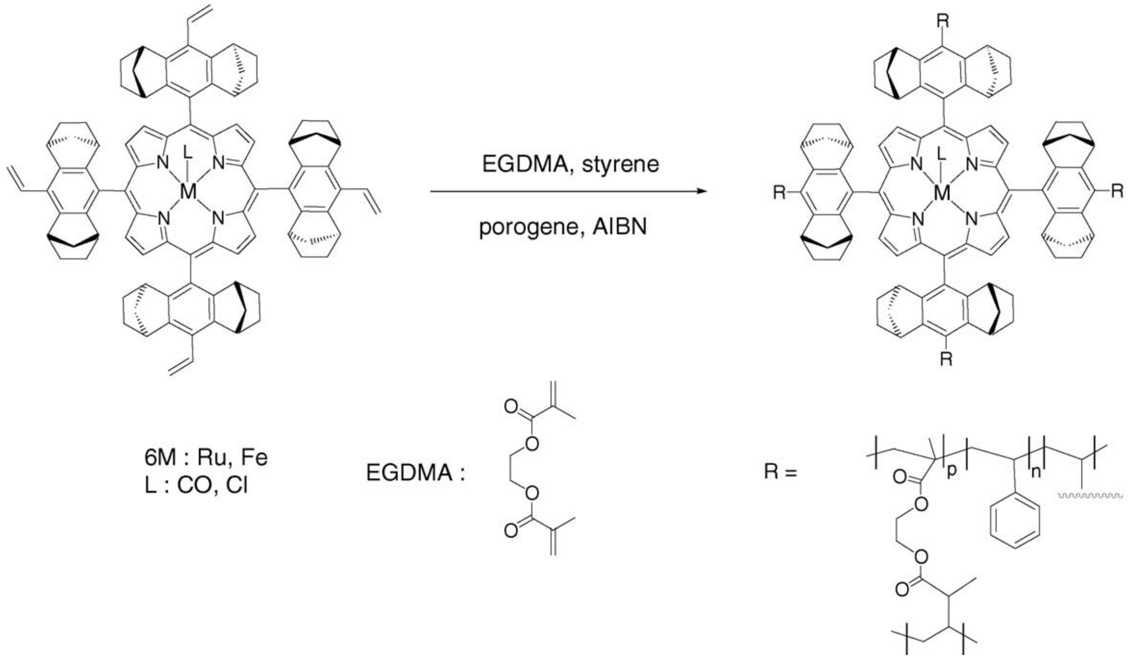


Fig. 5. Copolymerisation of chiral metalloporphyrins with styrene and ethylene glycol dimethacrylate.

described by Svec and Fréchet [77] or with ethylene glycol derivatives [51] for the preparation of monolithic resins. Different chiral ruthenium polymers were prepared from a monomer by changing the degree of cross-linking and the porogen, using AIBN as a radical initiator (Table 2) [78].

Table 2
Polymerization conditions used for preparation of Ru catalysts

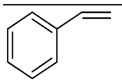
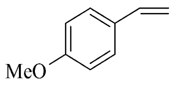
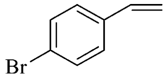
Polymer	Monomer (w/w)	DVB/styrene	Porogenic solvent	AIBN (%)
P1-(RuCO)	**6** (10 %)	1.2	Toluene	3
P2-(RuCO)	**6** (10 %)	5.0	Toluene	3
P3-(RuCO)	**6** (10 %)	1.2	$CHCl_3$/dodecane	3
P4-(RuCO)	**6** (10 %)	1.2[a]	Toluene	3

In an oven dried hemolysis tube, metalloporphyrin **5** was dissolved in the porogenic solvent (toluene 1.5 mmol). Then, styrene and divinylbenzene were added to the solution. The polymerization reaction was iniated by AIBN (60 μmol). The mixture was heated at 65 °C for 16 h without stirring.

[a] EGDMA/styrene.

The bench-mark reaction between styrene and ethyl diazoacetate to give cyclopropane esters was tested (Fig. 4). In all cases, the polymer catalyst was filtered off and an additional quantity of substrates was added to the solution to confirm the heterogeneous character of the catalyst. We chose these two reagents, extensively used molecules both in homogeneous and heterogeneous processes, as suitable substrates to show difference in terms of enantioselectivity, diastereoselectivity and reactivity [5]. Using P1-(RuCO) as heterogeneous catalyst, the cyclopropane was formed with good yield (77%), high diastereoselectivity (*trans*/*cis*: 92/8) and good enantioselectivity for the *trans* isomer (82%) (entry 1, Table 3). It can also be seen from the Table 3 that the use of $CHCl_3$/dodecane as a porogenic mixture: P3-(RuCO) seems to be detrimental to the enantiomeric excess, the diastereoselectivity and the yield (entry 3). This may be due to the reduced accessibility of the sites, as also demonstrated

Table 3
Asymmetric cyclopropanation of styrene by ethyl diazoacetate catalyzed by Ru macroporous polymers[a]

Substrates	Catalysts	Yield[b] (%)	*Trans*/*cis* (%)	ee_{trans}[c] (1*S*,2*S*)	ee_{cis}[c] (1*R*,2*S*)	Turnover
	P1-(RuCO)	77	92/8	82	8	1075
	P2-(RuCO)	66	85/15	76	8	905
	P3-(RuCO)	60	82/18	71	11	820
	P4-(RuCO)	62	89/11	77	8	850
	P1-(RuCO)	88	92/8	80	14	1205
	P4-(RuCO)	81	91/9	79	16	1110
	P1-(RuCO)	75	93/7	90	10	1030
	P4-(RuCO)	74	93/7	83	17	1010

[a] Reactions were performed in CH_2Cl_2 at room temperature for 24 h with a catalyst/diazo/substrate molar ratio of 0.5/600/500.

[b] Isolated yields based on substrates.

[c] Determined by chiral GC.

by the results obtained with P2-(RuCO), a polymer prepared with a high DVD/styrene ratio (entry 2). To shed some light on this area, we also carried out a comparative study with a different polymer P4-(RuCO), using a different cross-linker, ethylene glycol dimethacrylate. As can be see in Table 3 (entries 4, 6 and 8), the results are only slightly lower than those obtained with P1-(RuCO).

We also investigated the cyclopropanation of *para*-substituted styrenes. As shown in Table 3, *para*-substitution (*p*-Y-styrene, Y = MeO and Br) has a weak effect upon the enantioselectivity of styrene cyclopropanation, the best ee (90%) being obtained with the bromo derivative. A similar effect was noted with asymmetric cyclopropanation with ethyl diazoacetate using a different chiral ruthenium catalyst [78].

The recovery and recyclability of P1-(RuCO) polymer have been also examined. The polymer was tested for enantioselectivity and reactivity in the cyclopropanation of styrene with ethyl diazoacetate leading three recycling steps with a weak progressive decrease of enantioselectivity (from 82% to 78%) and a decrease of yield (from 90% to 71%). However, the yield markly decreased to 53% after the eighth run whereas the enantioselectivity was maintained at ∼68%.

These different chiral ruthenium polymers were also used for asymmetric cyclopropanation with diazoacetonitrile [78]. Diazoacetonitrile does not appear to have many applications in the field of organic synthesis and, as far we are aware, only a single example of enantioselective intermolecular cyclopropanation is known [79]. The asymmetric cyclopropanation was applied with success to the synthesis of optically enriched D-phenylalanine as the key asymmetric step. Asymmetric cyclopropanation of a ketene acetal catalyzed by a chiral rhodium complex afforded optically active cyclopropanes with a *cis*/*trans* ratio of 90/10. The enantiomeric excess of the *cis* isomer was 66% [79]. This situation may be due to the small size of the *cyano* substituent, which disfavors high diastereoselectivity for the *trans* isomer. A few publications also exist on the racemic synthesis of cyanocyclopropane by means of reaction of diazoacetonitrile with alkenes or cyanoalkenes with tosylhydrazones (see Ref. [78]). Thus, it was quite exciting to explore the catalytic properties of these polymers toward diazoacetonitrile addition to olefinic bonds. The results demonstrate that the asymmetric cyclopropanation using diazoacetonitrile catalyzed by chiral metalloporphyrins, both under homogeneous and heterogeneous conditions, occurs in a good stereoselective manner, offering for the first time, a general access to optically active *trans* cyanocyclopropanes, with possible biological applications after subsequent reduction with $LiAlH_4$. With the inserted ruthenium porphyrins, porous solids exhibited moderate activity and correct enantioselectivity in heterogeneous cyclopropanation of styrene with diazoacetonitrile. The best ee (71%) was obtained with P1-(RuCO) and is similar to those obtained with the homogeneous chiral ruthenium porphyrins [78]. Furthermore, the crude material can be readily enriched by recrystallization in a mixture of dichloromethane/pentane to give *trans* cyanocyclopropanes in 50% isolated yield and 99% ee.

We previously reported the use of optically active electropolymers bearing chiral metallospirobifluorenylporphyrins for asymmetric heterogeneous catalysis [73]. However, despite their good stability and recyclability, these polymeric catalysts suffer from the drawback of moderate enantioselectivity compared to the homogeneous counterpart. These novel chiral ruthenium porphyrin monolithic resins for asymmetric heterogeneous carbene transfer to olefins show much higher enantioselectivity for the cyclopropanation reaction. The best ee was obtained with the less cross-linked polymer and it should emphasized that the results obtained with this polymer P1-(RuCO) are similar to those obtained with the homogeneous chiral ruthenium porphyrins. However, with all series, the rigidity of the chiral macrocycle seems to be maintained. Thus, the polymer morphology, which is controled by the degree of cross-linking, the nature of the porogen and the cross-linker determines the performance of the polymer catalyst. This situation was previously observed with the immobilization of pyridine–bis(oxazoline) chiral ligand and bis(oxazoline)–copper complexes [5] but much larger influence of the polymeric matrix on the stereochemical course of the reaction was observed, due to a weak rigidity of the catalytic sites, grafted on the support.

3.1.4. Heterogeneous cyclopropanation reactions with mesoporous molecular sieves

The first chiral intramolecular cyclopropanation using silica supported metal porphyrin catalysts was reported by Che and co-workers [80]. The authors used chiral ruthenium porphyrins encapsulated in ordered mesoporous molecular sieves (MCM-41 and MCM-48). Since the structure of solid support could play an important role in the catalytic reaction, they chose two different supports. In contrast to the MCM-41 silica phase with a one-dimensional straight channel system, MCM-48 contains a three dimensional network, which provides a large surface area for high accessibility of reactants to active sites within the porous structure [80]. In order to prevent the problem encountered in the structural modification of the porphyrin ligand, the link between the catalytic site and the support was realized by coordinative grafting (Fig. 6). Intramolecular cyclopropanation of *trans*-cinnamyl diazoacetate (Fig. 7) was found to proceed with high enantioselectivity (85%) and high product turnover numbers. The heterogeneous catalyst could be used four times and, after two cycles, enantiomeric excess decreased to 76%.

3.2. Oxidation

3.2.1. Introduction: homogeneous catalysis

The desire to mimic the hemoprotein enzymes like cytochromes P450 led to a large development of research involving synthetic porphyrins as models of the active sites [81]. These enzymes are potent oxidants that are able to catalyze the hydroxylation of saturated carbon–hydrogen bonds, the epoxidation of double bonds, the oxidation of heteroatoms, dealkylation reactions and oxidation of aromatics. A general review on these enzymes has been recently reported [81]. This area continues to be very attracting and is still mainly based on the catalytic oxidation reactions. This fact is related to the presence of a high valent oxo-iron species, which are important intermediates in numerous catalytic cycles of cytochromes P450 and peroxidases

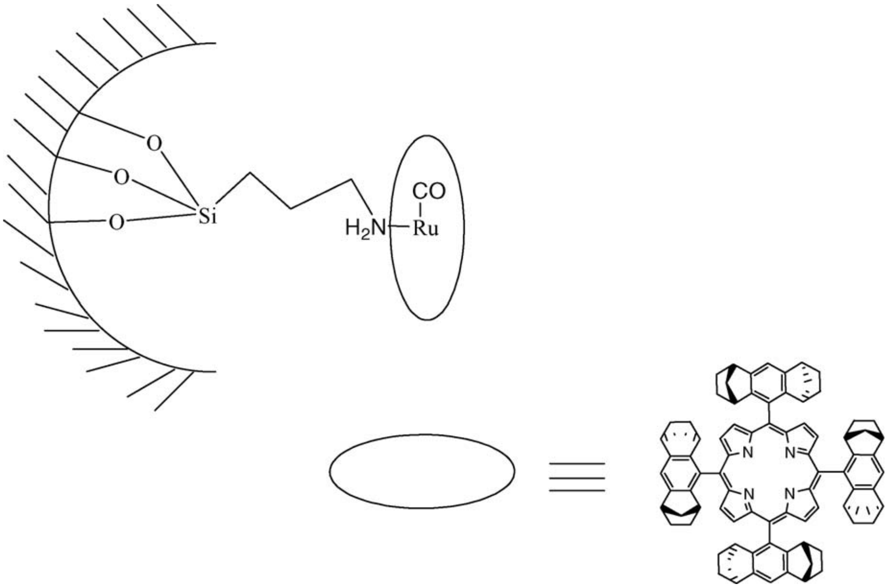


Fig. 6. Chiral ruthenium porphyrin encapsulated in molecular sieves (adapted from Ref. [80]).

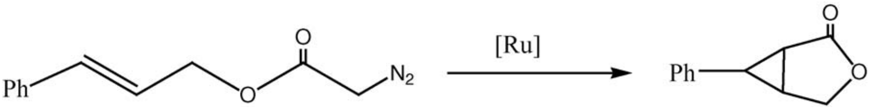


Fig. 7. Intramolecular cyclopropanation of *trans*-cinnamyl diazoacetate catalyzed by ruthenium polymers (adapted from Ref. [80]).

[82]. Dramatic improvements have been described in catalytic asymmetric epoxidation of akenes by iron [83,84], ruthenium [7,11,85] and manganese [6,86] chiral porphyrins since the first report of asymmetric oxidation of styrene by Groves and Myers [87]. All these studies have enriched the knowledge on the coordination chemistry of metal–peroxo and metal–oxo species. Thus, the necessary modifications that are required to enable the iron–peroxo and iron–oxo porphyrin complexes are now largely identified, in particular highly electron-deficient macrocycles. Different mechanisms for oxidation reactions have been debated by many authors and recent articles also provide a rather exhaustive survey of these oxidation reactions [81,82]. However, a potential catalyst for practical applications is still missing due to the tedious preparations of the present chiral metalloporphyrins. Immobilizing chiral metalloporphyrins may offer a solution, though few of its potential uses have yet been exploited.

3.2.2. Heterogeneous asymmetric catalysis

Che et al. heterogeneized a chiral dichlororuthenium(IV) porphyrin complex in sol–gel matrix [88]. Compared to other solid support materials for catalyst immobilization, inorganic sol–gel supports are superior in their thermal stability, inertness toward the entrapped molecules and large surface areas of several hundreds of $m^2\,g^{-1}$ [89]. This sol–gel catalyst was prepared by hydrolysis and condensation of tetraethyl orthosilicate in the presence of the chiral metalloporphyrin in an aqueous–ethanol mixture. The heterogeneous catalyst is highly active toward asymmetric epoxidation of styrene using 2,6-dichloropyridine-*N*-oxide (Cl2pyNO), producing styrene epoxide (Fig. 8) in 69% enantiomeric excess [88]. This system was quite efficient for the first run (10 800 turnovers) and the enantiomeric excess was close to that obtained in solution (70%) Unfortunately, the authors observed a gradual decrease of the activity over four successive reactions and largely inactive at the fourth run. The diminishing activity of this sol–gel catalyst was ascribed to catalyst leaching or deactivation through a blocking of the reactant to the active sites of the amorphous silica.

In a more recent publication, Che et al. [80] reported an alternative method of immobilization of a similar chiral catalyst on the surface of the ordered inorganic meso-porous silicate materials MCM-41 and MCM-48. Coordinative grafting through an amino ligand may prevent metal leaching and high accessibility of reactant to actives sites through large pores may be expected in such molecular sieves [90]. The authors prepared the catalytic

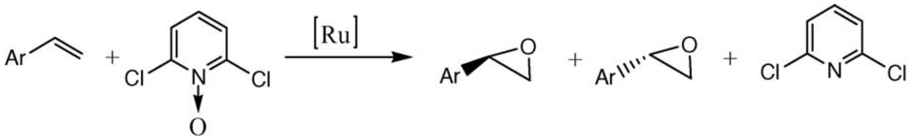


Fig. 8. Epoxidation of styrene catalyzed by ruthenium porphyrin polymers.

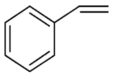
system as shown in Fig. 6. As previously reported by the same authors with no chiral ruthenium catalyst [23,24,44], treatment of chiral ruthenium porphyrin with surface modified mesoporous silica, by 3-aminopropyltriethoxyethane, led to immobilization of the metalloporphyrin on the solid support through ligand exchange. This heterogeneous system was shown to be highly active toward asymmetric styrene epoxidation producing styrene epoxide in 74% ee with up to 13 500 turnovers. No attempt to reuse the catalyst was mentioned for this reaction.

Very few other metalloporphyrin polymers bearing chiral groups have been tested in the heterogeneous catalytic oxidation reactions. One of them is our monolithic resins bearing ruthenium porphyrins, previously used in asymmetric cyclopropanation [78]. We employed the system previously reported by Hirobe et al. [91], that is 2,6-dichloro-pyridine *N*-oxide as the oxygen donor in dichloromethane at room temperature, and the chiral ruthenium porphyrin polymers. This system was preferred to the iodosylbenzene with iron catalyst since this oxidant is only weakly soluble in organic solvents. It must be emphasized that a different system, supporting non-chiral ruthenium porphyrins, has been recently reported by Nestler and colleagues for the epoxidation of olefins and oxidation of alcohols [51,92].

The results obtained in epoxidation catalysis are summarized in Table 4. A large number of chiral polymers were screened and the less cross-linked polymers gave satisfactory results for epoxidation of styrene with 2,6-dichloropyridine-*N*-oxide (ee $\sim$75%) [93]. Thus, the epoxide was formed with 70% yield and 71% enantioselectivity from unsubstituted styrene with P-RuCO (entry 2). We also investigated oxidation of *ortho*-, *meta*- and *para*-trifluoromethyl substituted styrenes with the same polymer but *para*- or *meta*-substitution does not have a significant effect upon the enantioselectivity of styrene epoxidation and the ee (74%) for the epoxide was maintained with the *para*- and *meta*-CF3 derivatives.

It can also be seen from the Table 4 that the use of P2-(RuCO), a polymer prepared with a high DVD/styrene ratio seems to be detrimental to the enantiomeric excess and the yield (entry 3). This may be due to the high cross-linking and consequently, a reduced accessibility of the sites. In contrast, changing P1-(RuCO) to P3-(RuCO) has only a weak influence, as demonstrated by the results obtained with CHCl$_3$/dodecane as a porogenic mixture, since the amount of cross-linking is maintained in this case. These polymers could be reused two times without a significant decrease of the enantioselectivity but, after two cycles, a decrease of the yield from 78% to 60% was observed. The simplicity of the process (room temperature, catalyst easily recovered), the yields and correct enantioselectivity render this heterogeneous process an attractive alternative to the few existing heterogeneous methods for metal–porphyrin-catalyzed asymmetric oxidation.

Table 4
Asymmetric epoxidation of styrene catalyzed by macroporous ruthenium polymers[a]

Substrate	Catalysts	Yields[b] (%)	ee[c] (%)	Turnover
	3-RuCO	78	76	257
	P1-(RuCO)	70	71	231
	P2-(RuCO)	13	74	43
	P3-(RuCO)	72	72	238

[a] Reactions were performed in CH$_2$Cl$_2$ at room temperature for 24 h with a catalyst/oxidant/substrate molar ratio of 0.5/600/500.

[b] Isolated yields based on substrates.

[c] Determined by chiral GC.

A Ru–porphyrin catalyst which was obtained by co-polymerization of a ruthenium porphyrin complex having four polymerizable 4-vinylbenzoxy groups with an excess of ethylene glycol dimethacrylate has recently been reported [92]. This polymeric catalyst was found to be by far superior to the homogeneous counterpart for the oxidation of alkanes and secondary alcohols. Furthermore, the activity of the supported catalyst could be increased significantly by using the technique of molecular imprinting. Development of such a system with optically active metalloporphyrins may offer rich opportunities to improve the enantioselectivity and chemoselectivity of the asymmetric oxidation.

Dendritic metalloporphyrin catalysts, first reported by Suslick and co-workers [94], are still continuing to be attractive features. They can induce a steric protection of the metal center and regioselectivity in catalysis by creating specific binding sites. As examples, attachment of Fréchet-type poly(benzyl ether) dendrons to ruthenium porphyrins yielded efficient catalysts for selective epoxidation of alkenes with 2,6-dichloropyridine *N*-oxide [95]. Using optically active metalloporphyrins could be a nice application of these dendritic polymers in asymmetric synthesis. Although attaching dendritic wedges to porphyrin macrocycles does not lead to an heterogeneous system, the molecules of the resulted dendritic metalloporphyrin catalysts could be large enough to allow facile separation by membrane or nanofiltration techniques.

4. Conclusion

In this review, we have shown the recent evolution from asymmetric homogeneous catalysis to asymmetric heterogeneous catalysis, using metalloporphyrins as active sites. As enantioselective catalysis using chiral metalloporphyrins has largely progressed in the last decade, the field of asymmetric heterogeneous catalysis has become more attractive.

Although some progress has been made in heterogeneous organic oxidations catalyzed by soluble and insoluble polymer-supported metal porphyrins, a similar strategy was not suitable for the development of polymer-supported chiral metalloporphyrins because of the difficulty involved in attaching a chiral porphyrin ligand, particularly D_4-symmetric porphyrin, onto a polymer chain [3]. An alternative method was previously reported by Che and colleagues [80]. It is to attach a ruthenium chiral porphyrin to meso-porous silica material by coordinative grafting. We describe herein a different system that circumvents the problem encountered in the structural modification of the chiral porphyrin ligand [76,78,93]. It is the introduction of a vinyl group into an optically active porphyrin with the aim of preparing polymers using the chiral metalloporphyrin as a co-monomer.

Some approaches have been used to pursue high enantioselectivity and catalytic activity, as well as facile separation and recycling of the chiral catalysts. Although the polymer-supported and sol–gel catalyses have shown high enantioselectivity in some cases, much work remains to be done. With regard to oxidation catalysis, the resistance to degradation merits further work since this factor is usually determinant on catalytic activity and selectivity. Water-tolerant chiral catalysts are still needed in asymmetric heterogeneous processes with environmental as well as economic benefits.

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