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Heterogeneous enantioselective epoxidation of olefins catalysed by unsymmetrical (salen)Mn(III) complexes supported on amorphous or MCM-41 silica through a new triazine-based linker†

Franca Bigi,* Leni Moroni, Raimondo Maggi and Giovanni Sartori

Department of Organic and Industrial Chemistry, University of Parma, Parco Area delle Scienze 17/A, 43100 Parma, Italy. E-mail: bigi@unipr.it; Fax: +390521905472; Tel: +390521905411

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High enantioselectivity (ee up to 84%) has been achieved in heterogeneous asymmetric epoxidation using a silica-bound unsymmetrical (salen)–manganese(III) complex; amorphous silica can be used in the same way as MCM-41, showing a positive effect in the catalyst recycling.

The importance of chiral building blocks, such as optically active epoxides, for pharmaceutical and agrochemical synthesis accounts for the impressive amount of papers published in recent years on homogeneous Jacobsen-type complexes.[1]

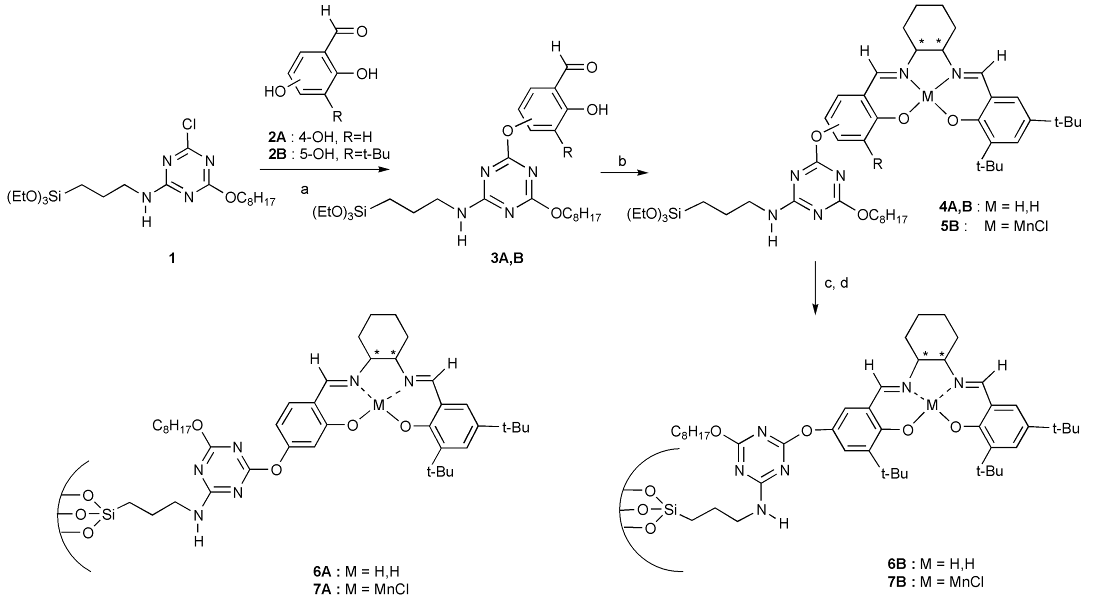
There is also increasing interest in the preparation of immobilised catalysts on solid supports, since they allow easy separation from the reaction mixtures by simple filtration and possible recycling. Recently, several papers have appeared on the immobilisation of (salen)Mn(III) complexes on heterogeneous supports. Considerable progresses has been made by using polymer-supported catalysts,[2] but inorganic supports have received much less attention.[3]

Our interest in heterogeneous catalysis for fine chemicals syntheses,[4] has prompted us to prepare new supported chiral (salen)Mn(III) catalysts. We have designed a salen ligand covalently bound to silica through a single linker in order to allow the maximum conformational mobility of the complex necessary to obtain a high level of asymmetric induction. Unsymmetrical salen derivative **4** containing a substituted triazine arm was chosen. We hypothesized that this spacer, longer than those usually employed and partially rigid to prevent possible chain folding, would allow facile access of the olefinic substrate to the metal center, placed sufficiently away from the solid surface.

By a common reaction pathway we synthesised two different salen ligands **4A** and **4B** (Scheme 1). Starting from cyanuric chloride we accomplished the subsequent and selective substitution of the three chlorine atoms. Compound **1** was first prepared in 80% yield from a one-pot two-step reaction of cyanuric chloride with octanol[5a] followed by (3-aminopropyl-)triethoxysilane.[5b] Despite the known low reactivity of the chlorine atom in compounds like **1** and the presence of two reactive hydroxy groups in the salicylic reagent **2**, compounds **3A** and **3B** were prepared in high yields and selectivities: they were isolated in 65% yield (83% selectivity) and 82% yield (99% selectivity) respectively by reacting the monolithium derivative of **2A** and **2B** with **1** in tetrachloroethene at reflux for 45 min in the presence of TMEDA to enhance the hydroxy nucleophilicity.

The salen ligands **4A** and **4B**, prepared according to the Jacobsen procedure,[6] were anchored to mesoporous MCM-41 or amorphous KG60 silica by refluxing in toluene affording the yellow materials **6A** and **6B**.

The supported salen complexes **7A** and **7B** differ in the substitution of one phenolic unit, in particular the linker position and the presence or not of a *tert*-butyl group at the 3-position. The solid materials **6** and **7** were characterised by surface area determination, elemental analyses, X-ray diffraction, inductively coupled plasma atomic emission, FTIR and UV–Vis diffuse reflectance spectroscopies, that evidenced the effective ligand and complex heterogenization, with a loading in the range 0.3–0.06 mmol g^{-1}. FTIR spectra were in good



Scheme 1 *Reagents*: (a) BuLi, TMEDA in C_2Cl_4, reflux, 45 min; (b) 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde, 1,2-diaminocyclohexane, CH_2Cl_2, rt, 12 h; (c) silica, toluene, 110 °C, 20 h; (d) $Mn(OAc)_2 \cdot 4H_2O$, EtOH, reflux, 4 h, air, LiCl.

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† Electronic supplementary information (ESI) available: synthesis of compounds **1**, **3A**, **3B**, **4A**, **4B** and ^{1}H NMR spectra. See http://www.rsc.org/suppdata/cc/b1/b110991j/

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Table 1 Asymmetric epoxidation of olefins catalysed by silica-bound chiral (salen)Mn(III) complexes[a]

Run	Catalyst	Silica	Mn loading/ mmol g^{-1}	Olefin[b]	Yield (%)[c]	Ee (%)[d]	Abs. config.[e]
1	(*S*,*S*)-**7A**	MCM-41	0.3	W	40	26	1*R*, 2*R*
2	(*S*,*S*)-**7A**	MCM-41	0.1	W	31	34	1*R*, 2*R*
3	(*R*,*R*)-**7B**	MCM-41	0.1	W	49	82	1*S*, 2*S*
4	(*R*,*R*)-**7B**	MCM-41	0.08	W	38	84	1*S*, 2*S*
5	(*R*,*R*)-**7B**	MCM-41	0.06	W	36	84	1*S*, 2*S*
6	(*R*,*R*)-**7B**	KG60	0.06	W	42	82	1*S*, 2*S*
7	(*R*,*R*)-**5B**	Homog.	—	W	71	89	1*S*, 2*S*
8	(*R*,*R*)-**7B**	MCM-41	0.06	X	70	30	*R*
9	(*R*,*R*)-**7B**	MCM-41	0.06	Y	48	45	1*R*, 2*S*
10	(*R*,*R*)-**7B**	MCM-41	0.06	Z	68	70	1*R*, 2*S*
11	(*R*,*R*)-**7B**	KG60	0.1	Y	55	43	1*R*, 2*S*
12	(*R*,*R*)-**7B**	KG60	0.1	Z	73	65	1*R*, 2*S*
13	(*R*,*R*)-**7B**	KG60	0.1	W	43	81	1*S*, 2*S*

[a] According to literature procedure (0 °C, 4 h). [b] Olefin employed: W = 1-phenylcyclohexene, X = styrene, Y = 1,2-dihydronaphthalene, Z = indene. [c] Determined by GC after 4 h using PhBr as internal standard or by ^{1}H NMR using $(CHCl_2)_2$ as internal standard. [d] Determined by GC using Chiraldex B chiral column or by ^{1}H NMR with chiral Eu(hfc)$_3$. [e] Confirmed by polarimetry.

agreement with the expected chemical structure of the organic moieties. In particular the formation of the supported complex *e.g.* MCM-**7A** was confirmed by the shift from 1628 cm^{-1} to a lower wavenumber of the imine stretching vibration, that cannot be resolved from the triazine band at 1600 cm^{-1}, and by a band typical of metallosalen complexes at 1537 cm^{-1}.[7]

The electronic spectra of supported salens **6** presented the same absorption bands as the corresponding free ligand in methanolic solution (*e.g.* MCM-**6B** λ = 228, 260, 336, 410 nm and **5B** λ = 225, 258, 327 nm). As expected, after metal complexation there is a d–d transition band at about 500 nm, characteristic for Mn(III) in these complexes.[8]

Then we tested the activity of the prepared catalysts in the model epoxidation reaction of 1-phenylcyclohex-1-ene with MCPBA–NMO in CH_2Cl_2 at 0 °C and in the presence of 4 mol% of the catalyst. The data reported in Table 1 show that the catalyst **7B** is an efficient promoter of the enantioselective reaction, giving the 1,2-epoxy-1-phenylcyclohexane in ee higher than 82% (entries 3–5). In our opinion the lower asymmetric induction of the catalyst **7A** is mainly due to the lack of a *tert*-butyl group at the 3-position, that is known to strongly affect the enantioselectivity,[1a] although the variation in the electronic properties could be important too.[9]

As a control experiment we investigated the catalytic efficiency of the soluble analogue **5B** of the supported catalyst **7B** (entry 7). We could observe that this catalyst was only slightly less effective than Jacobsen's catalyst (yield 84%, ee 95%), probably due to the electron-withdrawing effect of the linker.

Comparing entries 5 and 7 we can see that the heterogenisation of the catalyst did not cause a significant decrease of asymmetric induction, a problem commonly reported in the literature, while the yield was more affected.

The reaction was extended to different conjugated olefins (entries 8–10) and moderate to high enantioselectivities were obtained. The degree of chirality transfer depends on the olefin structure, in agreement with the literature,[2b,10] and the stereochemistry of the epoxides is in accordance with the findings in homogeneous catalysis, suggesting that the transition states are quite similar. The lower yields could be attributed to diffusion limitation usually present when a heterogeneous catalyst is employed.[11] The alkenes different reactivity could probably be due to steric effects that play a role in heterogeneous epoxidation.

The good results obtained with catalyst **7B** supported on amorphous silica KG60 indicate that the structure of the solid support does not influence the activity of the catalyst with low Mn-loading. Lastly we examined the problem of catalyst recycling. Whereas the MCM-41-supported catalyst used three times gave progressive reduction of yield and ee,[12] as often observed by other authors for similar supported catalysts,[13,2a,c] interesting results were obtained for catalyst **7B** supported on silica-gel. Indeed in the second cycle there was a modest reduction of yield and ee (from 82 to 78%).

In summary, we have prepared a promising class of silica supported catalysts for heterogeneous epoxidation of alkenes, characterised by a new type of single linker bounding salen ligands to a cheap solid support. The asymmetric induction is good, being higher or comparable with results obtained using MCPBA with similar catalysts supported on silica or an organic polymer.[2a,b,10b]

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