Catalysis Letters Vol. 98, Nos. 2–3, November 2004 (© 2004)

Use of ionic liquids as solvents for epoxidation reactions catalysed by a chiral Katsuki-type salen complex: enhanced reactivity and recovery of catalyst

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Received 23 July 2004; accepted 27 July 2004

The Katsuki-type catalyst 2 has been recycled several times following its use in a model epoxidation reaction of 1,2-dihydronaphthalene in an ionic liquid, **3a** or **3b**. The enantioselectivity was comparable to that in dichloromethane, but recovery of the catalyst was easier, activity was higher, and activity and enantioselectivity were retained in recovered ionic liquid fractions to a much greater extent than those for the Jacobsen-type catalyst 1.

KEY WORDS: ionic liquids; Katsuki-type chiral catalyst; two-phase systems; epoxidation; 1,2-dihydronaphthalene.

1. Introduction

Enantioselective epoxidation catalysed by chiral (salen)Mn(III) complexes has become a useful preparative method in organic synthesis [1,2]. Jacobsen [1] and Katsuki [2] have explored, respectively, several valuable types of epoxidation catalysts in this field. However, although such catalysts offer a high level of activity and enantioselectivity in homogeneous systems, they are not easily separated from the products and are thus difficult to recover. Therefore, much effort has been spent on attempting to support catalysts on solids to generate heterogeneous catalysts, or to use two-phase liquid systems in order to offer a simplified separation of catalyst from product. Thus, for example, attempts have been made to immobilise salen catalysts by:(a) non-covalent immobilisation on a zeolite [3], clay [4] or polydimethylsiloxane (PDMS) membrane [5]; (b) grafting onto silica [6] or MCM-41 [7]; (c) copolymerisation of a functionalised salen ligand or catalyst with other organic monomers [8,9]; and (d) attachment of a salen ligand or catalyst to a preformed polymer [10–14] or dendrimer [15]. However, there are drawbacks with all of these strategies, probably because of the nature of heterogeneous reactions (non-linear kinetic behaviour, unequal distribution of and/or access to the reactive centres, solvation problems, etc. For example, the use of a zeolite "ship-in-a-bottle" catalyst was limited to a narrow range of substrates and gave poor enantioselectivity in some cases [3]; use of a PDMS membrane led to an unavoidable leaching of catalyst from the membrane [5]; coplymerisation of a salen ligand or catalyst with styrene and divinylbenzene resulted in a cross-linked catalyst which offered a promising yield and recycled catalyst, but showed very poor enatioselectivity [8,9]; and although use of a polymer-supported, singly-bound catalyst was effective and the catalyst could be recycled, synthesis of the specifically-substituted ligand was tedious [14].

Due to the limitations of solid-supported catalysts, a two-phase liquid system, known as Fluorous Biphase System (FBS), was used by Pozzi and his co-workers [16]. However, in order to take advantage of relatively easy phase separation and catalyst recovery, it was necessary to modify the salen ligand by incorporation of a perfluorinated alkyl chain to help to provide better solvation of catalyst in the FBS solvent. Moreover, a reasonable enantioselectivity was obtained for only one substrate, indene [16]. Therefore, we decided to investigate alternative approaches.

Over the last several years, ionic liquids (called ILs hereafter) have generated much excitement in the field of organic synthesis, particularly for metal complex catalysis, because of their potential as green solvents. Up to date, a number of reactions have been carried out in such solvents, including: Fries rearrangements; Friedel–Crafts, Diels–Alder, nitration, hydrogenation, hydroformylation and Heck reactions; Suzuki cross-coupling; Trost–Tsuji coupling; and so on [17–26].

Recently, Song *et al.* have investigated the epoxidation of 2,2dimethylchromene with a Jacobsen-type chiral Mn^{III} (salen) complex, [N,N' bis(3,5-di- *tert*-butylsalicylidene)-1,2-cyclohexanediamine]manganese-(III) chloride (1), in 4 mol% proportion in a mixture of an IL, 1butyl3methylimidazolium hexafluorophosphate

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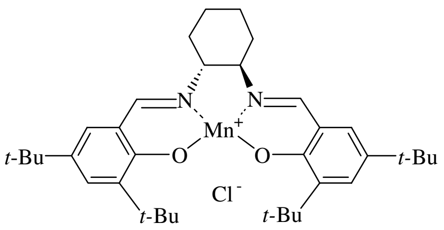
([bmim]PF_6, 3a) and CH_2Cl_2(1:4 v/v), providing a good yield, high enantiomeric excess and a recoverable catalyst [27]. Unfortunately, the yield and enantioselectivity became progressively lower with each recovery.

As part of our continuing interest in the development of clean chemical processes [28–37], we became interested in epoxidation of 1,2-dihydronaphthalene catalysed by a Katsuki-type catalyst, **2**, which is more stable and offers higher enantionomeric excess compared to the Jacobsen-type catalyst **1**, in an ionic liquid. We therefore wish to disclose the results of our own epoxidation of 1,2dihydronaphthalene (1,2-DHN) in two air- and moisture-stable ionic liquids, [bmim]PF_6 (**3a**) and [bmim]BF_4 (**3b**), using commercial sodium hypochlorite as the terminal oxidant and 4phenypyridine *N*-oxide (4-PPNO) as a co-ligand, according to the reaction in Scheme 1.



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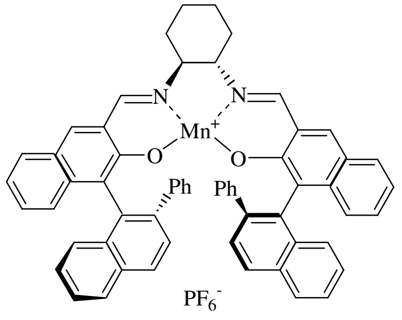

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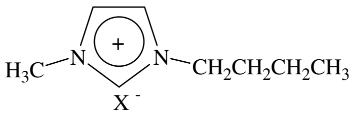
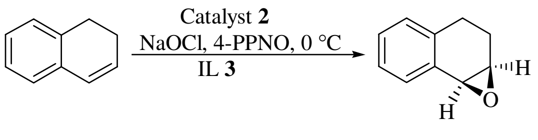


3a: X = PF_6
3b: X = BF_4



Scheme 1. Catalytic epoxidation of 1,2-dihydronaphthalene.

2. Experimental

2.1. Materials

1-Methylimidazole, 1-bromobutane, ammonium tetrafluoroborate, sodium hexafluorophosphate, 13% aqueous sodium hypochlorite, 1,2-dihydronaphthalene, 4phenypyridine *N*-oxide and hexadecane were purchased from Aldrich Chemical Company or Lancaster Research Chemicals and used without further purification.

2.2. Analysis and characterisation of the product and ionic liquids 3

^1H and ^{13}C NMR spectra were recorded on an AV400 Bruker spectrometer operating at 400 MHz for ^1H and 100 MHz for ^{13}C measurement. ^{11}B, ^{19}F and ^{31}P NMR were recorded on an AC250 Bruker spectrometer. Chemical shifts are reported in parts per million relative to tetramethylsilane. Assignments of signals are based on coupling patterns and expected chemical shift values and have not been rigorously confirmed. Signals with similar characteristics might be interchanged. Electrospray mass spectra were recorded on a Quattro II spectrometer.

Product mixtures from the epoxidation reaction (Scheme 1) were subjected to gas chromatography on a Hewlett Packard HP 5890 (series II) gas chromatograph, fitted with an RTX-1 (100% dimethylpolysiloxane; 30 m, 0.32 mm ID) column. The GC conditions used for analysis were: 100 °C for 2 min, ramped to 250 °C at 10 °C/min and held for 10 min. The injection temperature was 250 °C and the detection temperature 300 °C. Hexadecane was used as an internal standard.

The epoxide 1,2-epoxy-1,2,3,4-tetrahydronaphthalene was characterised by its ^1H and ^{13}C NMR spectra, which were identical to those reported in the literature [38].

The ionic liquids **3a** and **3b** were synthesised according to literature procedures [39–41]. Their structures were confirmed by comparison of their ^1H and ^{13}C NMR spectra with those reported [39–41] and also by ^{19}F and ^{11}B or ^{31}P NMR spectroscopy and by electrospray mass spectrometry.

Ionic liquid **3a**, NMR (d_6-acetone), ppm:^1H, 8.89 (1 H, s, H2), 7.70 (1 H, d, $J = 2$ Hz, H4), 7.65 (1 H, d, $J = 2$ Hz, H5), 4.33 (2 H, t, $J = 7$ Hz, NCH_2), 4.02 (3 H, s, NCH_3), 1.90 (2 H, apparent pentet, $J = 7$ Hz, CH_2), 1.36 (2 H, apparent sextet, $J = 7$ Hz, CH_2), 0.93 (3 H, t, $J = 7$ Hz, CH_3); ^{13}C, 137.3 (d, C2), 124.7 (d, C4), 123.3 (d, C5), 50.1 (t, NCH_2), 36.5 (q, NCH_3), 32.6 (t, CH_2), 19.9 (t, CH_2), 13.6 (q, CH_3); ^{19}F, −71.4 (d); ^{31}P, −90.2 (septet); MS: ES^+, *m*/*z*, 139 (M–PF_6^-); ES^-, *m*/*z*, 145 (PF_6^-).

Ionic liquid **3b**, NMR (d_6-acetone), ppm:^1H, 8.91 (1 H, s, H2), 7.71 (1 H, d, $J = 2$ Hz, H4), 7.65 (1 H, d, $J = 2$ Hz, H5), 4.30 (2 H, t, $J = 7$ Hz, NCH_2), 3.99 (3 H, s, NCH_3), 1.88 (2 H, apparent pentet, $J = 7$ Hz, CH_2), 1.34 (2 H, apparent sextet, $J = 7$ Hz, CH_2), 0.91 (3 H, t, $J = 7$ Hz, CH_3); ^{13}C, 137.4 (d, C2), 124.5 (d, C4), 123.2 (d, C5), 49.9 (t, NCH_2), 36.4 (q, NCH_3), 32.6 (t, CH_2), 19.8 (t, CH_2), 13.7 (q, CH_3); ^{19}F, −150 (two peaks, ratio, 4:1); ^{11}B, −0.26; MS:ES$^+$, m/z, 139 ($M–BF_4^-$); ES$^-$, m/z, 87 (BF_4^-).

2.3. *Typical procedure for epoxidation of 1,2-dihydronaphthalene in IL* **3a**–*CH_2Cl_2 or IL* **3b**–*CH_2Cl_2*

To a solution of 1,2-DHN (21.6 mg, 0.16 mmol), 4-PPNO (6.8 mg, 0.04 mmol) and hexadecane (10 mg, 0.044 mmol) in IL **3a**–CH_2Cl_2 or IL **3b**–CH_2Cl_2 (2:3, v/v; 1.0 ml) was added the catalyst **2** (4.1 mg, 4 μmol) and the mixture was cooled to 0 °C, followed by addition of precooled (0 °C) NaOCl solution (1.4 ml, 0.588 M, 0.82 mmol, pH = 11.3, obtained by buffering commercial household bleach using 0.05 M Na_2HPO_4 and 0.5 M NaH_2PO_4) (note: CH_2Cl_2 was added because ILs are highly viscous and hard to stir at the reaction temperature). The two-phase solution was stirred at 0 °C and the reaction was monitored by GC. After complete conversion of the substrate, the organic phase was separated from the aqueous NaOCl layer and the CH_2Cl_2 was evaporated off. The residual IL phase, containing both catalyst and products, was washed with hexane (3 × 10 ml). The combined hexane extracts were concentrated by rotary evaporation. The product was purified by column chromatography (SiO_2, petroleum ether 40–60 °C/ethyl acetate, 5:0.4, $R_f = 0.45$) to give the pure epoxide as a white needlelike solid (23.3 mg, 83%). The enantiomeric excess (95%) was measured by ^1H NMR using Eu(hfc)$_3$ as a shift reagent. In other reactions, the amount of solvent and the concentrations of components in the organic phase were varied (Table 2). The residue containing IL **3a** and catalyst **2** was reused, in combination with fresh alkene, 4-PPNO and CH_2Cl_2, which were added in quantities the same as those used in the first epoxidation process.

2.4. *Procedure for epoxidation of 1,2-dihydronaphthalene in IL* **3b** *without CH_2Cl_2*

The procedure was identical to that used with an IL **3a**–CH_2Cl_2 mixture, except that the volume of IL **3b** used was greater (1.0 ml) and the dichloromethane was removed under reduced pressure after dissolution of the catalyst. The residual viscous mixture of IL **3b**-catalyst was employed as both catalyst and solvent in the epoxidation process.

2.5. *Procedure for epoxidations using a stoichiometric amount of NaOCl in a solvent mixture of dichloromethane or ethyl acetate and IL* **3a**

2.5.1. *In the IL* **3a**–*CH_2Cl_2 (2:3, v/v) mixture*

To a solution of 1,2-DHN (54 mg, 0.40 mmol), 4-PPNO (17 mg, 0.10 mmol) and hexadecane (20 mg, 0.088 mmol) in IL **3a**–CH_2Cl_2 (2:3, v/v; 0.25 ml), catalyst **2** (10.24 mg, 10 μmol) was added and the mixture was cooled to 0 °C, followed by addition of precooled (0 °C) NaOCl solution (0.7 ml, 0.588 M, pH = 11.3, 0.40 mmol). The twophase solution was stirred at 0 °C and the process of the reaction was monitored by GC. After complete conversion of the substrate, the organic phase was separated from the aqueous NaOCl phase using a separating funnel, washed with distilled water (2 × 5 ml) and the CH_2Cl_2 was then evaporated. The remaining IL phase, containing catalyst, products, hexadecane, and perhaps some 4-PPNO, was washed with hexane (3 × 10 ml). Thus, the residue contained IL, catalyst and some 4-PPNO, and the hexane extract contained the products and hexadecane. The combined hexane extracts were concentrated by rotary evaporation, and the desired product was purified as described in Section 2.3. The enantiomeric excess was measured by ^1H NMR.

After the first use, the residue containing catalyst **2**, 4-PPNO and IL **3a** was reused, in combination with fresh alkene and CH_2Cl_2, which were added in quantities the same as those in the first epoxidation process.

2.5.2 *In the IL* **3a**–*EtOAc (4:1, v/v) mixture*

The procedure was similar to that used in an IL **3a**–CH_2Cl_2 (2:3, v/v) mixture, except that the proportion of IL **3a** to EtOAc was 4:1. In addition, after the reaction, hexane (3 ml) and distilled water (2 ml) were directly added to the reaction mixture without removal of EtOAc. A triphasic system formed. The upper layer was a hexane phase, containing the products, hexadecane and some unreacted starting material. The medium layer was an aqueous phase, containing the by-product NaCl and perhaps some unreacted NaOCl. The bottom layer was IL **3a**, containing catalyst and co-ligand, 4-PPNO. The upper two layers were decanted into a separating funnel, and the viscous bottom layer was washed with hexane (3 ml) and water (2 ml) twice more. The washings were decanted into the same separating funnel each time. After that, the hexane phase was separated from the water phase and dried over anhydrous $MgSO_4$, then monitored by GC. The IL **3a** phase, containing catalyst **2** and 4-PPNO, was recovered and employed for further use.

3. Results and discussions

Initially, a series of standard reactions was conducted using CH_2Cl_2as solvent and either the Jacobsen-type complex **1**, or the Katsuki-type complex **2** as catalyst. Various catalyst proportions and reagent concentrations were used in order to provide baseline results and to allow selection of optimum conditions for subsequent reactions. The results are given in Table 1. It was found that the reaction was effective and provided good yields

Table 1
Asymmetric epoxidation of 1,2-dihydronaphthalene in CH_2Cl_2[a]

1,2-DHN (mmol)	4-PPNO (mmol)	Catalyst (mmol)	NaOCl (ml)	CH_2Cl_2 (ml)	Time (h)	Yield (%)[b]	Ee (%)[c]
0.16	0.04	0.004[d]	1.4	1.0	2	57	84
0.16	0.04	0.004	1.4	1.0	8	87	96
0.16	0.04	0.0004	1.4	1.0	30	78	100
0.16	0.04	0.004	1.4	0.5	6	84	96
0.80	0.20	0.002	7.0	0.5	18	81	100

[a] 1,2-DHN, 4-PPNO, catalyst **2**, CH_2Cl_2 and *aq*. NaOCl (0.588 M, pH = 11.3) at 0 °C for the indicated reaction time to achieve 100% conversion.
[b] Calculated from GC using hexadecane as an internal standard.
[c] Determined by ^1H NMR analysis using Eu(hfc)$_3$ as a chiral shift reagent.
[d] Jacobsen-type catalyst **1** was used instead of Katsuki-type catalyst 2.

and enantioselectivities with both catalysts. However, the Jacobsen-type complex **1** underwent complete conversion within a shorter reaction time and gave a lower yield and poorer enantioselectivity than Katsuki-type complex **2**, which provided a high yield and good enantioselectivity, though over a longer reaction time under an indentical reaction conditions. As would be expected, larger quantities of catalyst or higher concentrations of reactants resulted in shorter reaction times.

Similar experiments were then carried out in a mixture of IL **3a** or IL **3b** with CH_2Cl_2(2:3, v/v) or in pure IL **3b** using the Katsuki-type complex **2** as a catalyst. The results, listed in Table 2, show that reactions performed in IL **3a**–CH_2Cl_2 (2:3, v/v) provided good conversions, yields and enantioselectivites, comparable to those in CH_2Cl_2 alone, but over much shorter reaction times. For instance, the reaction catalysed by 2.5 mol% of catalyst was complete in 2 h in IL **3a**–CH_2Cl_2, while it required 8 h to go to completion in CH_2Cl_2 alone. Similarly, the reaction catalysed by 0.25 mol% of catalyst was complete in 20 h in IL **3a**–CH_2Cl_2, while it required 30 h to go to completion in CH_2Cl_2 alone. It is noteworthy that both the enantioselectivity (33%) and the yield (64%) were much lower in IL **3b**–CH_2Cl_2 than in IL **3a**–CH_2Cl_2. That might be because IL **3b** is water miscible, which leads to a higher proportion of the catalyst or the epoxide in the aqueous phase, in which the catalyst or epoxide might be unstable. Therefore, in order to avoid that drawback, we decided to conduct a reaction in pure IL **3b**. Surprisingly, when the reaction was conducted in pure IL **3b** (no CH_2Cl_2 present), the yield was improved to 83% and the enantioselectivity was improved to 90%. Furthermore, the catalyst could be recycled more easily by simple decantation or washing with hexane (see experimental section). Nevertheless, both the yield and enantioselectivity were still lower in pure IL **3b** than in IL **3a**–CH_2Cl_2 (2:3, v/v).

Not surprisingly, it needed a longer reaction time, 108 h in IL **3a**–CH_2Cl_2 (2:3, v/v), to convert all of the alkene into the corresponding epoxide when the quantity of catalyst was reduced to 0.025 mol%. At the same time, a lower yield, 35%, and a poorer enantioselectivity, 68%, were achieved. We suspected that over the longer reaction time, greater opportunity for decomposition of the catalyst or epoxide accounted for the poorer results. Therefore, we decided to increase the concentrations of components, such as alkene, catalyst and other related starting materials in the organic phase and expected the reactions would proceed faster.

The results of reactions conducted at tenfold concentrations in 0.5 ml IL **3a**–CH_2Cl_2 (2:3, v/v) are given in Table 3. As shown in Table 3, the reaction catalysed by 0.25 mol% of catalyst was complete in 10 h at higher concentrations whereas it needed 20 h (Table 2) at lower concentrations. Similarly the reaction catalysed by 0.025 mol% of catalyst was complete in 54 h at higher concentrations while it took 108 h to complete at lower concentrations (Table 2). Furthermore, improved results were also obtained for a reaction conducted at higher

Table 2
Asymmetric epoxidation of 1,2-dihydronaphthalene in an Ils **3**[a]

Solvent	Catalyst **2** (mol% of substrate)	Time (h)	Conversion (%)[b]	Yield (%)[b]	Ee (%)[c]
IL **3a**–CH_2Cl_2 (2:3, v/v)	2.5	2.0	100	100	95
IL **3b**–CH_2Cl_2 (2:3, v/v)	2.5	2.0	91	64	33
IL **3b**	2.5	2.0	100	83	90
IL **3a**–CH_2Cl_2 (2:3, v/v)	0.25	20	100	77	96
IL **3a**–CH_2Cl_2 (2:3, v/v)	0.025	108	93	35	68

[a] 1,2-DHN (21.6 mg, 0.16 mmol), 4-PPNO (6.8 mg, 0.04 mmol), catalyst **2**, solvent (1.0 ml), NaOCl (0.588 M, 1.4 ml, 0.82 mmol, pH = 11.3) at 0 °C for the indicated reaction time.
[b,c] See footnotes b and c to Table 1.

Table 3
Asymmetric epoxidation of 1,2-dihydronaphthalene in an IL **3a**–CH_2Cl_2 mixture under concentrated conditions [a]

Catalyst **2** (mmol% of substrate)	Time (h)	Conversion (%)^b	Yield (%)^b	Ee (%)^c
0.25	10	100	82	100
0.025	54	99	58	95
0.0125	100	99	47	66
0.0100	65	99	41	43

[a] 1,2-DHN (108.0 mg, 0.80 mmol), 4-PPNO (34 mg, 0.20 mmol), catalyst 2, IL **3a**–CH_2Cl_2 (2:3, v/v; 0.5 ml), NaOCl (0.588 M, 7.0 ml, 4.1 mmol, pH = 11.3) at 0 °C for the indicated reaction time.

[b,c] See footnotes b and c to Table 1.

concentration when a lower quantity of catalyst was used. For example, 58% yield and 95% enantiomeric excess were attained in a reaction performed at tenfold concentration and catalysed by 0.025 mol% of catalyst, while only 35% yield and 68% enantiomeric excess (Table 2) were attained in a reaction carried out under identical reaction conditions except at lower concentration. Even when the amount of catalyst was reduced to 0.0125 or 0.0100 mol%, significant yields and enantioselectivities were obtained, though it was clear that reactions were best performed with at least 0.025 mol% of catalyst.

In the light of the enhanced reaction rates, yields and enantioselectivities resulting from reactions conducted in solvents containing ILs, we attempted to recycle both the catalyst and the ionic liquids following epoxidation reactions involving 2.5 mol% catalyst. The results are listed in Table 4. As shown, IL **3a**/catalyst could be recycled up to six times with promising enantioselectivity, even though the yield of epoxide progressively decreased. Furthermore, even the IL **3b**/catalyst system could be recycled twice with reasonable yield and enantioselectivity. However, by the third run, the IL **3b**/catalyst mixture became sticky and difficult to stir and thus gave rise to a poorer result. It should be noted that the decreasing yield during successive runs with the recovered solvent-catalyst system was possibly due to the decreased amount of catalyst, caused by loss during each work-up or decomposition under the basic conditions.

Table 4
Recycling of both catalyst and ionic liquid in asymmetric epoxidation of 1,2 dihydronaphthalene

Solvent	Recycling (run)	Time (h)	Conversion (%)^c	Yield (%)^c	Ee (%)^e
IL 3a–$CH_2Cl_2^a$	1	1.25	100	92	96
IL 3a–$CH_2Cl_2^a$	2	2.0	100	91	95
IL 3a–$CH_2Cl_2^a$	3	2.5	87	76	95
IL 3a–$CH_2Cl_2^a$	4	3.0	78	57	91
IL 3a–$CH_2Cl_2^a$	5	4.0	60	40	90
IL 3a–$CH_2Cl_2^a$	6	5.0	60	38^d	84
IL 3b^b	1	2.0	100	83	90
IL 3b^b	2	3.0	100	82	79
IL 3b^b	3	3.0	44	5.2	50

[a] 1,2-DHN (43.2 mg, 0.32 mmol), 4-PPNO (13.6 mg, 0.08 mmol), catalyst 2 (0.008 mmol, 2.5 mol% in the first run), IL 3a–CH_2Cl_2 (2:3, v/v; 1.0 ml), NaOCl (0.588 M, 2.8 ml, 1.64 mmol, pH = 11.3 at 0 °C for the indicated reaction time.

[b] 1,2-DHN (21.6 mg, 0.16 mmol), 4-PPNO (6.8 mg, 0.04 mmol), catalyst 2 (0.004 mmol, 2.5 mol% in the first run), IL 3b (1.0 ml), NaOCl (0.588 M, 1.4 ml, 0.82 mmol, pH = 11.3) at 0 °C for the indicated reaction time.

[c] See footnote b Table 1.

[d] Isolated yield.

[e] See footnote c to Table 1.

From the results obtained so far, it is clear that ionic liquids IL **3a** and IL **3b** can be used successfully as a solvent or part solvent in the epoxidation of 1,2-dihydronaphathalene catalysed by Katsuki-type catalyst **2** and oxidised by a five times excess of aqueous sodium hypochlorite. Indeed, enhanced reactivities and enantioselectivites in comparison to those in a molecular solvent (CH_2Cl_2) could be achieved and the ionic liquid–catalyst system could be recovered successfully several times.

However, for atom economy, the use of excess oxidant would still be a disadvantage, especially for reactions on an industrial scale. Therefore, we attempted to reduce the amount of oxidant to a stoichiometric level (Table 5).

As can be seen from Table 5, the reaction was still successful either in dichloromethane as solvent (entry 1) or in a mixed IL–dichloromethane solvent (entry 2). We therefore attempted to leave out the co-ligand (4-PPNO) and/or co-solvent (CH_2Cl_2) to provide an even greener and more economical process. For this purpose, 1,2-dihydronaphthalene was first treated with a stoichiometric amount of aqueous NaOCl and a quantity of catalyst **2** in pure IL **3a**(entry 3) or an IL **3a**–CH_2Cl_2 (2:3, v/v) mixture (entry 4), respectively, in the absence

Table 5
Asymmetric epoxidation of 1,2-dihydronaphthalene using one equivalent of NaOCl under various conditions[a]

Entry	Solvent/co-ligand	Time (h)	Conversion (%)^b	Yield (%)^b	Ee (%)^c
1	CH_2Cl_2/4-PPNO	3.0	100	83	95
2	IL 3a–CH_2Cl_2 (2:3, v/v) /4-PPNO	1.0	100	81	93
3	IL 3a/none^d	3.5	80	48^e	68
4	IL 3a–CH_2Cl_2 (2:3, v/v)/none	2.0	46	41	82
5	IL 3a/4-PPNO^d	3.0	84	47	82

[a] 1,2-DHN (54 mg, 0.40 mmol), 4-PPNO (17 mg, 0.10 mmol), catalyst 2 (10.24 mg, 10 μmol, 2.5 mol%), solvent (0.25 ml), NaOCl (0.588 M, 0.7 ml, 0.40 mmol, pH = 11.3) at 0 °C for the indicated reaction time.

[b,c] See footnotes b and c to Table 1.

[d] Ethanol was used as co-solvent in order to enable solubility of the catalyst in IL 3a, but then was evaporated under reduced pressure; the reaction was conducted at 22 °C.

[e] Isolated yield.

Table 6
Recycling of IL **3a**/catalyst **2**/4-PPNO mixture in asymmetric epoxidation of 1,2 dihydronaphthalene involving a stoichiometric amount of NaOCl[a]

Number of uses (run)	Time (h)	Conversion (%)[b]	Yield (%)[b]	Ee (%)[c]
1	1.0	100	81	93
2	1.5	88	81	94
3	2.0	93	79	91
4	2.5	86	75	91
5	2.5	69	63	90
6	3.0	83	67	91
7	3.0	71	59	90
8	3.0	71	53	87
9	5.0	83	50	79

[a] 1,2-DHN (54 mg, 0.40 mmol), 4-PPNO (17 mg, 0.10 mmol), catalyst **2** (10.24 mg, 10 μmol, 2.5 mol%), IL 3a–CH_2Cl_2 (2:3, v/v; 0.25 ml), NaOCl (0.588 M, 0.7 ml, 0.40 mmol, pH = 11.3) at 0 °C for the indicated reaction time.

[b,c] See footnotes b and c to Table 1.

of 4-PPNO. Neither of the reactions was very successful. We then attempted a reaction in the presence of 4-PPNO but without dichloromethane (entry 5). This was also not very successful, so for further study we decided to retain both 4-PPNO and the molecular co-solvent.

As the above results show, 4-PPNO is a crucial additive in this reaction system, even when IL **3a** is used as solvent or part of the solvent. In view of the enhanced reaction rate, the good yield and the comparable enantioselectivity resulting from a reaction conducted in IL **3a**–CH_2Cl_2/4-PPNO mixture, we decided to attempt recovery of both the catalyst and ionic liquid following the epoxidation reaction involving 2.5 mol% catalyst in the first run (Table 5, entry 2). In addition, from the preceding studies we had found that the final washings (hexane phase, see experimental section) showed only a very weak signal for the co-ligand, 4-PPNO. This suggested that the coligand might also be retained in the IL phase. Therefore, we decided to try to recycle the 4-PPNO together with the IL **3a**/catalyst **2** mixture, instead of adding fresh coligand in each recycled run. The results of such tests are given in Table 6.

As the results in Table 6 show, the catalyst **2**/IL **3a**/4-PPNO mixture could be recycled at least seven times with only modest reduction of the ee of the product, from 94% to 87%, although there was a progressive drop in yield of epoxide, from 81% to 53%. Even in the eighth recycled run, 83% conversion with 50% yield and 79% enantiomeric excess was obtained over a 5 h reaction time. By comparison of the results in Table 6 to those in Table 4, it was found that a lower amount of oxidant favours recovery of the catalyst and therefore offers better yields and ees of the epoxide.

Although these results are exciting and much better than those from the reactions with excess oxidant (Table 4), the reaction was still conducted in a mixed solvent involving a halogen-containing molecular co-solvent (CH_2Cl_2) that is considered to be unfriendly to the environment. Therefore, we decided to attempt to use a non-halogen solvent instead.

The ideal biphasic solvent-system should usually comprise a lower phase that can dissolve both the catalyst and substrate and an upper phase that is environmentally friendly, can dissolve the substrate and products, can be easily removed from the products, and has negligible ability to extract the lower solvent or the catalyst. Based on this requirement, various solvents, such as diethyl ether, hexane, cyclohexane and ethyl acetate, were all tested. In the end, ethyl acetate was chosen as the best alternative because of its moderate polarity. In order to build up a suitable two-phase system when an IL **3a**–ethyl acetate mixture was mixed with aqueous NaOCl (0.588 M, pH = 11.3), the proportion of IL **3a** versus EtOAc was also optimised. It was considered desirable that the IL **3a**–EtOAc mixture should remain as the lower layer in the IL **3a**–EtOAc/NaOCl mixture. Therefore, mixtures of different proportions of IL **3a** versus EtOAc were mixed with aqueous NaOCl. It was found that when the organic phase comprised IL **3a** and EtOAc in the proportion 4:1 (v/v), the IL **3a**–EtOAc mixture was the lower layer (as for the IL **3a**–CH_2Cl_2 mixture) while the aqueous phase was the upper layer in the static mixture. By contrast, when the organic phase comprised IL **3a** and EtOAc in the proportion 1:4 (v/v), the IL **3a**–EtOAc mixture was the upper layer and the aqueous phase was the lower layer in the static mixture. When the organic phase comprised IL **3a** and EtOAc in an intermediate proportion (2:3, v/v), an organic phase (perhaps an IL **3a**–EtOAc mixture) was the bottom of three layers, the aqueous phase was the middle layer and an EtOAc phase formed at the upper layer. Therefore, we decided to use IL **3a**–EtOAc (4:1, v/v) as the solvent for further study of the epoxidation of 1,2-DHN. The results obtained from the reactions carried out in such a solvent are given in Table 7.

As the results in Table 7 show, the alkene was converted into the corresponding epoxide with 72% yield and 92% ee at 96% conversion within 1 h when

Table 7
Asymmetric epoxidation of 1,2-dihydronaphthalene in IL **3a**–EtOAc using a stoichiometric amount of aqueous NaOCl[a]

Catalyst 2 (mmol% of substrate)	Time (h)	Conversion (%)[c]	Yield (%)[c]	Ee (%)[c]
2.5	1.0	96	72	92
1.25 (1st use)	2.0	98	77	90
1.25 (2nd use)	2.5	100	71	91
1.25 (3rd use)	2.5	90	62	81
1.25 (4th use)	2.5	81	57	85

[a] 1,2-DHN (54 mg, 0.40 mmol), 4-PPNO (17 mg, 0.10 mmol), catalyst **2**, IL **3a**–EtOAc (4:1, v/v; 0.25 ml), NaOCl (0.588 M, 0.7 ml, 0.40 mmol, pH = 11.3) at 0 °C for the indicated reaction time.

[b,c] See footnotes b and c to Table 1.

2.5% mmol of catalyst was used and in 77% yield and 90% ee at 98% conversion within 2 h when 1.25 mol% catalyst was used. These results are comparable with those from the reactions conducted in IL **3a**–CH_2Cl_2(2:3, v/v) in the presence of 2.5 mol% catalyst (Table 5).

It was pleasing to obtain such results in a much greener and more economical reaction system involving EtOAc as a co-solvent. On the basis of these results, we attempted to recycle catalyst/IL **3a**/4-PPNO following a reaction involving 1.25 mol% catalyst, as we previously did in the IL **3a**–CH_2Cl_2/4-PPNO system. The results are also listed in Table 7. It can be seen that catalyst/IL **3a**/4-PPNO could be effectively recycled, while retaining substantial enantioselectivities, in the range of $85 \sim 91\%$. As with other systems, the yield decreased in each further recycled run, from 77% in the first run to 57% in the fourth run. It is worth noting, however, that a very simple procedure was offered when ethyl acetate was used as cosolvent (see experimental section).

4. Conclusions

In summary, ionic liquids [bmim]PF_6 and [bmim]BF_4 were used successfully as co-solvent or solvent in the epoxidation of 1,2-dihydronaphathalene catalysed by Katsuki-type catalyst **2**, using aqueous sodium hypochlorite, NaOCl, as the oxidant. Under reaction conditions involving either excess or a stoichiometric amount of the oxidant, the enantioselectivities were achieved comparable to those in dichloromethane, but recovery of the catalyst was easier and activity was higher. In addition, it was thought that IL **3a**–EtOAc (4:1, v/v) would be more economical and greener for the environment.

Acknowledgments

We thank the University of Wales Swansea and the Chinese Government for financial support, and the EPSRC Mass Spectrometry Centre at Swansea for mass spectra. We also thank the EPSRC, the Higher Education Funding Council for Wales (ELWa-HEFCW) and the University of Wales Swansea for grants that enabled the purchase and upgrading of NMR equipment used in the course of this work. G.A. El-Hiti thanks the Royal Society of Chemistry for an international author grant.

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