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Manganese/Bicarbonate-Catalyzed Epoxidation of Lipophilic Alkenes with Hydrogen Peroxide in Ionic Liquids

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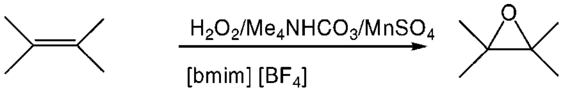
ABSTRACT



Effective epoxidation of lipophilic alkenes using hydrogen peroxide was accomplished with the manganese sulfate/bicarbonate catalytic system in an ionic liquid at room temperature.

In view of the industrial importance of epoxides, environmentally friendly methods for the epoxidation of alkenes have been a subject of current research interest. Much attention has been focused on the use of hydrogen peroxide as a green oxidant because it is cheap and gives water as the only byproduct.[11] Many catalytic systems based on different metals have been employed in conjunction with hydrogen peroxide for the epoxidation of alkenes.[22] Noteworthy among them are the recent reports by Burgess, which showed that a catalytic amount of manganese sulfate with sodium bicarbonate is quite effective in promoting the epoxidation of alkenes with hydrogen peroxide in aqueous media.[33] Since both the manganese and the bicarbonate salts are inexpensive and relatively nontoxic, the reaction may have practical applications. A common drawback for most reactions in aqueous media is the fact that an organic cosolvent is often required for water-insoluble lipophilic substrates. In the case of manganese/bicarbonate-catalyzed epoxidation of lipophilic alkenes, cosolvents such as DMF or *t*-BuOH were used. This defeats the aim of reducing the environmental burden of volatile organic contaminants.

Recently, the use of ionic liquids as environmentally benign solvents for a broad range of chemical processes has been advocated.[4] This is due to a number of intriguing properties of ionic liquids: high thermal and chemical stability, no measurable vapor pressure, nonflammability, and high loading capacity. In many cases, the ionic liquids can be recycled. Numerous catalytic reactions, including biocatalytic reactions, can be carried out in ionic liquids.[5] Epoxidation reactions in ionic liquids have been explored. In two reports where Mn complexes were used as catalysts, CH_2Cl_2 was used as a cosolvent and halogenated oxidants as the oxidizing agent; both were undesirable on environmental grounds.[6] When aqueous hydrogen peroxide was used as the oxidant with other catalysts, either the substrates were limited to electrophilic alkenes with strongly electron-withdrawing substituents,[7] hydrolysis of the epoxide was

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(1) For recent review, see: Grigoropoulou, G.; Clark, J. H.; Elings, J. A. *Green Chem.* **2003**, *5*, 1.

(2) Lane B. S.; Burgess, K. *Chem. Rev.* **2003**, *103*, 2457.

(3) (a) Lane, B. S.; Burgess, K. *J. Am. Chem. Soc.* **2001**, *123*, 2933. (b) Lane, B. S.; Vogt, M.; DeRose, V. J.; Burgess, K. *J. Am. Chem. Soc.* **2002**, *124*, 11946.

(4) (a) *Ionic Liquids. Industrial Applications to Green Chemistry*; Rogers, R. D., Seddon, K. R., Ed.; ACS Symposium Series 818; American Chemical Society: Washington, DC, 2002. (b) Wasserscheid, P.; Welton, T. *Ionic Liquids in Synthesis*; Wiley-VCH: Weinheim, 2003.

(5) For examples, see: (a) Sheldon, R. A.; Lau, R. M.; Sorgedrager, M. J.; van Rantwijk, F.; Seddon, K. R. *Green Chem.* **2002**, *4*, 147. (b) Bortolini, O.; Conte, V.; Chiappe, C.; Fantin, G.; Fogagnolo, M.; Maietti, S. *Green Chem.* **2002**, *4*, 94. (c) Lau, R. M.; van Rantwijk, F.; Seddon, K. R.; Sheldon, R. A. *Org. Lett.* **2000**, *2*, 4189.

(6) (a) Song, C. E.; Roh, E. J. *Chem. Commun.* **2000**, 837. (b) Li, Z.; Xia, C. G. *Tetrahedron Lett.* **2003**, *44*, 2069.

(7) Bortolini, O.; Conte, V.; Chiappe, C.; Fantin, G.; Forgagnolo, M.; Maietti, S. *Green Chem.* **2002**, *4*, 94.

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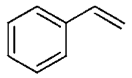
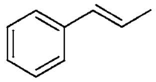
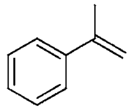
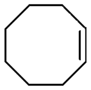
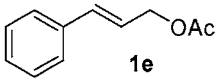
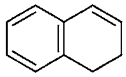
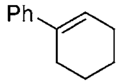
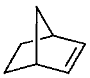
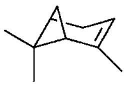
Table 1. Epoxidation of Alkenes

Entry	Substrate (0.15 mmol)		35% H_2O_2 (eq)	Time (hr)	Conversion (%)	Yield (%)[a]
1[b]		**1a**	10	8	0	0
2		**1a**	10	2	>99	98
3[c]		**1a**	10	8	10	>99
4[d]		**1a**	10	8	7	>99
5		**1a**	4.5	4	97	96
6		**1a**	2	24	20	99
7		**1a**	1	24	12	99
8[e]		**1a**	2	24	25	97
9		**1b**	10	5	>99	99(93)
10		**1c**	10	5	>99	99(92)
11		**1d**	10	2	53	99
12		**1e**	10	4	>99	(95)
13		**1f**	10	3	>99	99 (95)
14		**1g**	10	5	>99	80[f]
15		**1h**	10	4	82	>99
16		**1i**	20	3	53	>99
17	$CH_3(CH_2)_7CH{=}CH_2$	**1j**	20	23	0	0

[a] Conditions: 0.15 mmol of alkene, 0.15 mmol of TMAHC, 0.2 mol % $MnSO_4$, and 300 uL of [bmim][BF_4]. Yields were calculated on the basis of converted alkenes and determined by NMR or GC-MS versus an internal standard. [b] Performed with 0.15 mmol of $NaHCO_3$. [c] Without $MnSO_4$. [d] Without [bmim][BF_4]. [e] Salicylic acid (4 mol %) was added. [f] 3-Phenyl-2-cyclohexene-1-one was observed in 20% yield.

observed,[8] or the reaction had to be carried out with CH_2Cl_2 in a two-phase system.[9] Herein, we report the epoxidation of lipophilic alkenes using the manganese sulfate/bicarbonate catalytic system with hydrogen peroxide in ionic liquids at room temperature.

Epoxidations were carried out at room temperature utilizing 1-butyl-3-methylimidazolium tetrafluoroborate ([bmim]-[BF_4]) as the solvent. This ionic liquid was chosen on the basis of its ease of preparation and stability in the presence of oxygen and water.[10] Styrene (**1a**, 0.15 mmol) was used as the standard substrate with 10 equiv of H_2O_2 (200 μL, 35%) in [bmim][BF_4] (300 μL) at room temperature. Manganese sulfate (0.2 mol %) and sodium bicarbonate (0.15 mmol) were added as the catalyst. Under these conditions, no epoxidation was observed (Table 1, entry 1).

We attributed the lack of reaction to the poor solubility of sodium bicarbonate in the ionic liquid. Insoluble sodium bicarbonate could be observed as a powder in the mixture even after prolonged stirring. However, when tetramethylammonium hydrogen carbonate (TMAHC, 0.15 mmol) was used in its place, the reaction proceeded readily to give styrene oxide in excellent yield after 2 h at room temperature (entry 2). Manganese sulfate was found to be essential for the reaction, as the reaction gave little product in the absence of the manganese salt (entry 3). The ionic liquid, [bmim][BF_4], was also needed since in its absence; the reaction gave very low conversion of the styrene to the epoxide (entry 4). When only 4.5 equiv of H_2O_2 was used, the conversion of styrene to epoxide was still very effective, but the reaction took slightly longer time (entry 5). However, when the amount of H_2O_2 was reduced to 1 or 2 equiv, only low conversion of the styrene was observed even after a prolonged reaction time (entries 6 and 7). Coadditives such as salicylic acid did not improve the rate of reaction (entry 8), contrary to the results of the aqueous reaction.[3b] A number of representative lipophilic alkenes were epoxidized under the standard conditions (entries 9−16). In general, good to excellent yields of the epoxides could be obtained. As expected, terminal alkenes were not epoxidized (entry 17), in agreement with the observations by Burgess in the aqueous reaction.[3] In general, terminal alkenes are less reactive toward electrophiles than internal alkenes due to the electron-donating effect of the alkyl substituents.[11]

In the aqueous reaction, the reactive oxidizing species is believed to be the peroxymonocarbonate HCO_4^-, which is formed by the reaction of hydrogen peroxide with the bicarbonate ion according to eq 1.[12] The peroxymonocarbonate species then combine with the Mn^{2+} ion in a yet to be defined manner to effect the epoxidation.[3] We were able to demonstrate by ^{13}C NMR that when TMAHC was dissolved in [bmim][BF_4], the bicarbonate anion HCO_3^- could be readily observed at 160.9 ppm (Figure 1a). When hydrogen peroxide was added to the solution, the peroxymonocarbonate HCO_4^-, at 157.9 ppm, was formed as the major species (Figure 1b). Under the same reaction conditions as in entry 3, Table 1, with the absence of $MnSO_4$ catalyst, the peroxymonocarbonate species persisted more

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(8) Owens, G. S.; Abu-Omar, M. M. *Chem. Commun*. **2000**, 1165.

(9) Srinivas, K. A.; Kumar, A.; Chauhan, S. M. S. *Chem. Commun*. **2002**, 2456.

(10) For the preparation of [bmim][BF_4], see: (a) Law, M. C.; Wong, K. Y.; Chan, T. H. *Green Chem*. **2002**, *4*, 328. (b) Park, S.; Kazlauskas, R. J. *J. Org. Chem*. **2001**, *66*, 8395.

(11) Murphy, A.; Dubois, G.; Stack, T. D. P. *J. Am. Chem. Soc*. **2003**, *125*, 5250.

(12) Richardson, D. E.; Yao, H.; Frank, K. M.; Bennett, D. A. *J. Am. Chem. Soc*. **2000**, *122*, 1729.

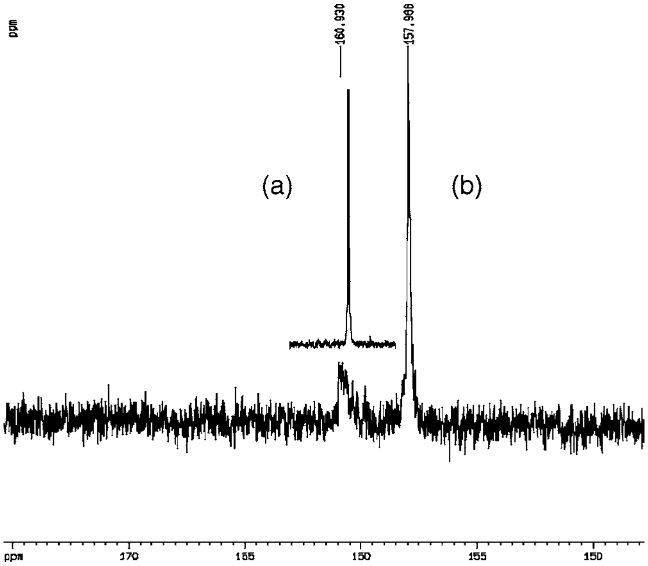
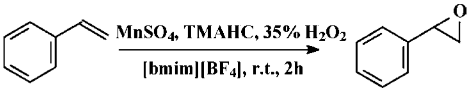


Figure 1. ^{13}C NMR spectra for a solution at 25 °C of (a) 0.49 M TMAHC in 300 μL of [bmim][BF_4] and (b) 0.42 M TMAHC and 1.6 M H_2O_2 in 300 μL [bmim][BF_4].

or less unchanged overnight in the presence of styrene according to ^{13}C NMR. However, when a catalytic amount of $MnSO_4$ was added to the mixture as in entry 2, Table 1, the peroxymonocarbonate species quickly declined in intensity, with the concomitant formation of styrene epoxide. This suggests that the same mechanism may well be operative in both the aqueous and the ionic liquid media.

$$H_2O_2 + HCO_3^- \rightleftharpoons H_2O + HCO_4^- \qquad (1)$$

Table 2. Recovery and Reuse of [bmim][BF_4] for the Epoxidation of Styrene



cycle	1	2	3	4	5[a]	6	7[b]	8	9[c]	10
yield (%)[d]	95	92	45	10	96	93	30	10	95	97

[a] Addition of 0.2 mol % $MnSO_4$. [b] Addition of 0.2 mol % $MnSO_4$. [c] Addition of 0.08 g of TMAHC. [d] Yield was determined by GC-MS.

With [bmim][BF_4] as the solvent, the lipophilic product epoxide was easily extracted by pentane.[13] Since the ionic liquid is likely to be the most expensive among all the components in the reaction system, we examined the recycling of [bmim][BF_4] for the reaction. The results are summarized in Table 2. After pentane extraction in the first cycle, the recovered yellowish oily ionic liquid containing $MnSO_4$ and TMAHC could be reused for the same reaction by adding the alkene and more hydrogen peroxide to give 92% yield of the epoxide. However, the yield was diminished on the third and the fourth cycles. This could be rectified, however, simply by adding a catalytic amount of $MnSO_4$ to return to the same high yield of epoxide. By the seventh or eighth cycle, addition of TMAHC together with $MnSO_4$ was found to be necessary. However, it is clear that the ionic liquid itself can be reused up to at least 10 cycles without any diminished capacity to act as the media for the reaction.

In summary, we have shown that ionic liquids can be used as solvents for the effective epoxidation of lipophilic alkenes using hydrogen peroxide with the manganese/bicarbonate catalytic system. With the recycling of the ionic liquid, the reaction can be considered as a cheap, catalytic, scalable, and environmentally benign method for alkene epoxidations.

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Supporting Information Available: Experimental procedures and detailed results of the control experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

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(13) It is generally assumed that, if necessary, pentane can be replaced by supercritical carbon dioxide for the extraction of lipophilic substrates. See: (a) Blanchard, L. A.; Hancu, D.; Beckman, E. J.; Brennecke, J. F. *Nature* **1999**, *399*, 28. (b) Blanchard, L. A.; Brennecke, J. F. *Ind. Eng. Chem. Res.* **2001**, *40*, 287.