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# A $Na_2WO_4$/$H_2WO_4$-Based Highly Efficient Biphasic Catalyst towards Alkene Epoxidation, using Dihydrogen Peroxide as Oxidant

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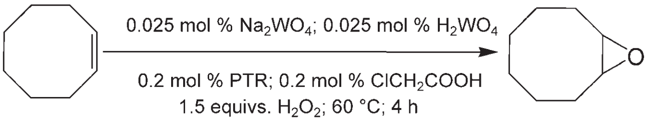
**Abstract:** The tungsten-containing biphasic catalytic system [$Na_2WO_4$/$H_2WO_4$/PTR/chloroacetic acid] effectively epoxidizes alkenes with 50% $H_2O_2$ as terminal oxidant, under organic solvent-free conditions. The catalytic process is proposed to proceed *via* a dinuclear tungsten peroxo species with coordinated chloroacetic acid, as suggested by ESI-MS measurements. The catalytic system is suggested to involve tungsten-peroxo and/or peracetic acid type of epoxidation catalyzed by the tungsten(VI) in the presence of an organic acid and $H_2O_2$. The reaction conditions employed for various alkenes for epoxidation are mild compared to the earlier studies and result in high product selectivity and conversion rate.

**Keywords:** alkenes; chloroacetic acid; epoxidation; hydrogen peroxide; tungsten

The development of efficient and clean processes for the epoxidation of alkenes on a million-ton-per-year scale remains an important objective in the fine chemical industry.[1–5] There is an increasing need for the elaboration of selective catalytic systems involving cheap, readily available, and ecologically friendly oxidants, such as hydrogen peroxide.[6,7] In this context, polyoxotungstates have been extensively and successfully used during the past 20 years.[8–11] A key experiment was performed by Venturello who selectively epoxidized 1-octene with a turnover number (TON, defined as mol product per mol catalyst) of 20 (82% yield based on $H_2O_2$) using a $Na_2WO_4$-$H_3PO_4$-quaternary ammonium chloride catalyst.[12] Since then, this system has been intensely studied.[13,14] Nevertheless, this catalytic biphasic procedure is less desirable, as it requires the use of chlorinated solvents such as 1,2-dichloroethane.[15–17] A first breakthrough occurred in 1996 when Noyori[18] reported a significant improvement of the original Venturello system. The epoxidation of terminal alkenes could be carried out within 4 hours, without organic solvents, and with up to 49.5 TON (99% yield, based on the olefin), using a catalytic mixture of $Na_2WO_4$ dihydrate, (aminomethyl)phosphonic acid and the phase transfer reagent (PTR) methyltri-*n*-octylammonium hydrogen sulfate.[19] Recently, outstanding procedures involving tungsten-containing catalysts for the production of propylene oxide[20] and the epoxidation of allylic alcohols[21] were reported.

The new catalytic system reported here consists of easily available, low-cost chemicals [$Na_2WO_4$/$H_2WO_4$/Aliquat 336 (PTR)/chloroacetic acid], which can be easily handled (Scheme 1). Typically, 200 mmoles of *cis*-cyclooctene were reacted with 300 mmoles of hydrogen peroxide (50%) at 60 °C. The epoxidation is catalyzed by 0.025 mol % of $Na_2WO_4$ and 0.025 mol % $H_2WO_4$ with 0.2 mol % of chloroacetic acid in the presence of methyltri-*n*-octylammonium chloride (0.2 mol %) as PTR (Scheme 1). A maximum TON of as high as 1800 is reached after 4 hours with 99% selectivity. This rate of the epoxidation is compared under similar experimental conditions as above, to the one of Noyori et al., i.e., using sodium tungstate and (aminomethyl)phosphonic acid at 60 °C where a TON of 800 was reached af-



**Scheme 1.** Epoxidation of *cis*-cyclooctene.

ter 4 hours. In addition, the system with (aminomethyl)phosphonic acid is not very active at room temperature. On the contrary, the new catalytic system acts very efficiently even at 20 °C with high conversion rates (Figure 1, **3b**). This condition is advantageous over that of (aminomethyl)phosphonic acid, as the latter needs a high temperature of 90 °C, as described for various substrates[18] and ammonium hydrogen sulfate[18] rather than the typical, readily available, chlorides as PTR for an efficient catalytic activity. Experiments were performed with various combinations of the catalytic mixture, i.e., $Na_2WO_4$(0.4 mol %) **1**, $Na_2WO_4$ (0.4 mol %) + $ClCH_2COOH$ (1.6 mol %) **2**, $Na_2WO_4$ (0.2 mol %) + $H_2WO_4$ (0.2 mol %) + $ClCH_2COOH$ (1.6 mol %) **3**, $H_2WO_4$ (0.4 mol %) + $ClCH_2COOH$ (1.6 mol %) **4**, and $H_2WO_4$ (0.4 mol %) **5**. The results depicted in Figure 1 show that the system **3** is the most efficient catalyst, even at ambient temperature. Furthermore, no incubation period is observed, while it is required for pure $H_2WO_4$, due to the poor solubility of tungstic acid in aqueous $H_2O_2$ at ambient temperature.[22] From a very recent report,[22] it is clear that the residual acidity of the aqueous medium acts eventually upon the rate enhancement and/or in activating the W-based biphasic catalytic species. Thus, it is expected that the rate enhancement of cyclooctene epoxidation, in combination with the tungsten precursors, $Na_2WO_4$ and $H_2WO_4$, is due to the presence of a source of protons, from $ClCH_2COOH$. To confirm that the rate enhancement is due to the acidity of the aqueous phase, the pH of the aqueous medium has been followed and varied from 1.8 to 3.2 by using different ratios of $ClCH_2COOH/ClCH_2COONa$ and using the catalytic system **2** (see Supporting Information, Figure S1; Table S1). As the pH is increased, the catalytic activity decreases linearly. When the weak acid $CH_3COOH$ is used and the pH is maintained at values of 3.7 and 4.7, using $CH_3COOH/CH_3COONa$, again the catalytic activity decreased at high pH values (see Supporting Information, Table S1). This clearly suggests that the role of the organic acid is different from that of maintaining an acidic pH of the aqueous medium, as $ClCH_2COOH$ ($pK_a = 2.7$) and $CH_3COOH$ ($pK_a = 4.76$) have totally different $pK_a$ values. The low catalytic activity at higher pH of both $ClCH_2COOH$ and $CH_3COOH$ buffers is attributed to an overall increase in the ionic strength of the aqueous medium. Therefore, other chloro-substituted acetic acids like $Cl_2CHCOOH$ and $Cl_3CCOOH$ were tested for catalytic activity which have lower $pK_a$ values than $ClCH_2COOH$, but they resulted in lower conversions compared to the above ones. Also when benzoic acid was used, a lower activity compared to chloroacetic acid was achieved (Figure 2).

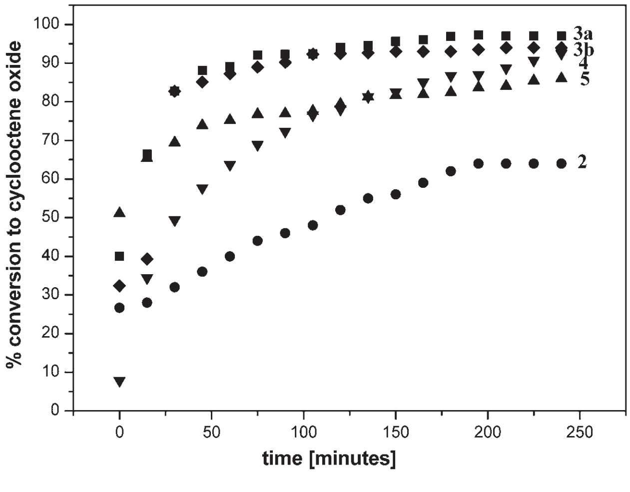


**Figure 1.** Epoxidation of cyclooctene using different catalytic systems, $Na_2WO_4$ (0.4 mol %) + $ClCH_2COOH$ (1.6 mol %) **2**, $Na_2WO_4$ (0.2 mol %) + $H_2WO_4$ (0.2 mol %) + $ClCH_2COOH$ (1.6 mol %) **3a**, system 3 at 20 °C **3b**, $H_2WO_4$ (0.4 mol %) + $ClCH_2COOH$ (1.6 mol %) **4**, $H_2WO_4$ (0.4 mol%) **5** at room temperature. Experiment **3a** has been performed with system **3** at 60 °C for comparison. System 1 is not included in the graph, because of the very low conversion.

If $Na_2WO_4$ (0.4 mol %) is used alone, only 6% cyclooctene oxide is detected after 4 hours and only 23% of cyclooctene is epoxidized when 1 equivalent of $ClCH_2COOH$ (0.4 mol %) per W atom is added to this reaction mixture, illustrating the importance of the chloroacetic acid to form the active species. This system can be used repeatedly by adding new substrate and hydrogen peroxide with 94% conversion after 4 h (selectivity > 99%) after separating the organic phase.[23] To the best of our knowledge, this catalytic system is more efficient and simple than all others reported so far for the epoxidation of alkenes with a tungsten-based catalyst at room temperature. $ClCH_2COOH$ without tungsten also results in lack of activity. When the catalytic system (**2**) is used in the presence of peracetic acid (diluted in acetic acid) the epoxidation rate is very high in

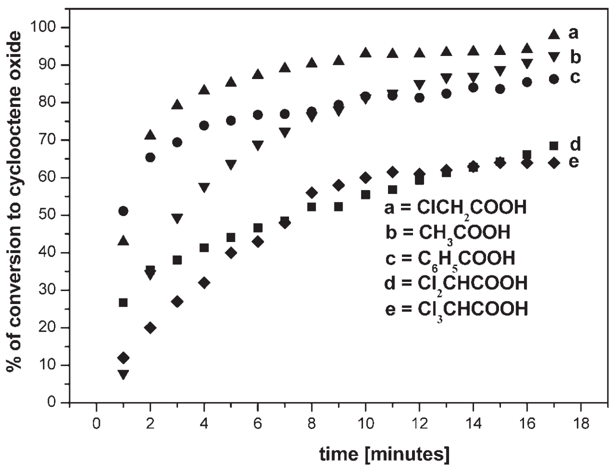


**Figure 2.** Epoxidation of cyclooctene using different organic acids (1.6 mol %) at room temperature with 0.2 mol % of $Na_2WO_4$ and 0.2 mol % of $H_2WO_4$.

the presence of tungsten at 60 °C and reaching 90% conversion after 15 minutes whereas without tungsten only 10% conversion is obtained after the same period of time (see Supporting Information; Figure S2). As the rate of epoxidation is higher than the analogous system with hydrogen peroxide, the peracid itself and not only the smaller amount of hydrogen peroxide present in the peracetic acid solution, is activated by the W species. This would suggest that the epoxidation may involve the *in situ* formation of peracids catalyzed by tungsten precursors and/or tungsten-peroxo species in the presence of an organic acid and hydrogen peroxide. Certain iron complexes have indeed been reported to show enhanced epoxidation and selectivity on the addition of more equivalents of acetic acid over diol formation in the case of cyclooctene and 1-decene.[24,25]

Negative ion ESI-MS experiments with the catalytic mixture (**3**) ($Na_2WO_4$ – 2 mmol; $H_2WO_4$ – 2 mmol; $ClCH_2COOH$ – 16 mmol; 50% $H_2O_2$ – 40 mmole is stirred in 10 mL of $H_2O$, pH 2.2, at room temperature, and diluted as described in the experimental part for electrospray experiments) yielded two major peaks at $m/z$ = 735 and 408, respectively, which were assigned to a dinuclear peroxo-tungsten species with $ClCH_2COOH$, $[W_2(ClCH_2COO)_2(O_2)_4(O)_3]$ and a mononuclear peroxo-tungsten species with $ClCH_2COOH$, $[W(ClCH_2COO)(O_2)_2(O)_2]$ (Figure 3). The obtained isotopic pattern is very similar to the theoretical pattern for the above proposed mono/di-peroxo species (see Supporting Information; Figure S3). A series of products was also observed resulting from the loss of peroxo, oxo and $ClCH_2COOH$ from the dinuclear tungsten species (see Supporting Information; Figure S4). At this point, it has to be mentioned that no peaks corresponding to the formation of isopolytungstates, and peroxotungstates of high nuclearity were observed, supporting a low-nuclearity tungsten-containing active species for the catalytic activity.[26,27] The epoxidation of cyclooctene performed in the presence of benzoquinone, a known radical trap, did not lead to an inhibition of the epoxidation. Consequently, the mechanism involved is expected to involve direct oxygen transfer rather than be radical-based.

Thus, system **3** which contains equivalent amounts of $Na_2WO_4$ and $H_2WO_4$ in the presence of chloroacetic acid efficiently enhances the rate of the epoxidation of various alkenes as illustrated in Table 1. Cyclooctene and cyclopentene are converted to the corresponding epoxides within 30 minutes with high selectivity (entry 2) at 60 °C. An even more interesting observation is the activity of system 3 towards 1-octene (entry 3), an alkene known to be difficult to epoxidize. After 4 hours, a TON (based on tungsten species) of 135 is reached (selectivity $>$ 99%) with 0.4 mol % of the tungsten catalyst (0.2 mol % $Na_2WO_4$ and 0.2 mol % $H_2WO_4$); this is a significant rate enhancement compared to the ones reported in the literature for this substrate.[28,29] Another

**Table 1.** Epoxidation of different alkenes catalyzed by $Na_2WO_4/H_2WO_4/ClCH_2COOH$ (**3**).[a]

| Entry | Alkene | Product | Conv. [%] | Selectivity [%] | Time [h] | TON | TOF [$h^{-1}$] |
|---|---|---|---|---|---|---|---|
| 1 | Cyclooctene | Cyclooctene oxide | 90 | 99 | 0.5 | 225 | 450 |
| 2 | Cyclopentene | Cyclopentene oxide | 92 | 99 | 0.5 | 230 | 460 |
| 3 | 1-Octene | 1,2-Epoxyoctane | 54 | 92 | 4 | 135 | 34 |
| 4 | 1-Hexene | 1,2-Epoxyhexane | 60 | 94 | 4 | 150 | 38 |
| 5 | 3-Methyl-3-buten-1-ol | 2-(2-Methyloxiran-2-yl)ethanol | 82 | 90 | 4 | 205 | 52 |
| 6 | Geraniol | 3-Methyl-3-(4-methylpent-3-enyl)oxiran-2-yl)methanol | 100 | 97 | 0.5 | 250 | 250 |

[a] All epoxidation reactions were performed at 60 °C with 0.2 mol % $Na_2WO_4$, 0.2 mol % $H_2WO_4$, and $ClCH_2COOH$ (1.6 mol %), 1.5 equivalents of $H_2O_2$ were used to oxidize 200 mmoles of alkene. For the substrates 1 and 2, epoxides are the main products, the corresponding dicarboxylic acids could be observed by GC but they are $<$0.1%. For the substrates 3, 4 and 5 only the epoxides are obtained.

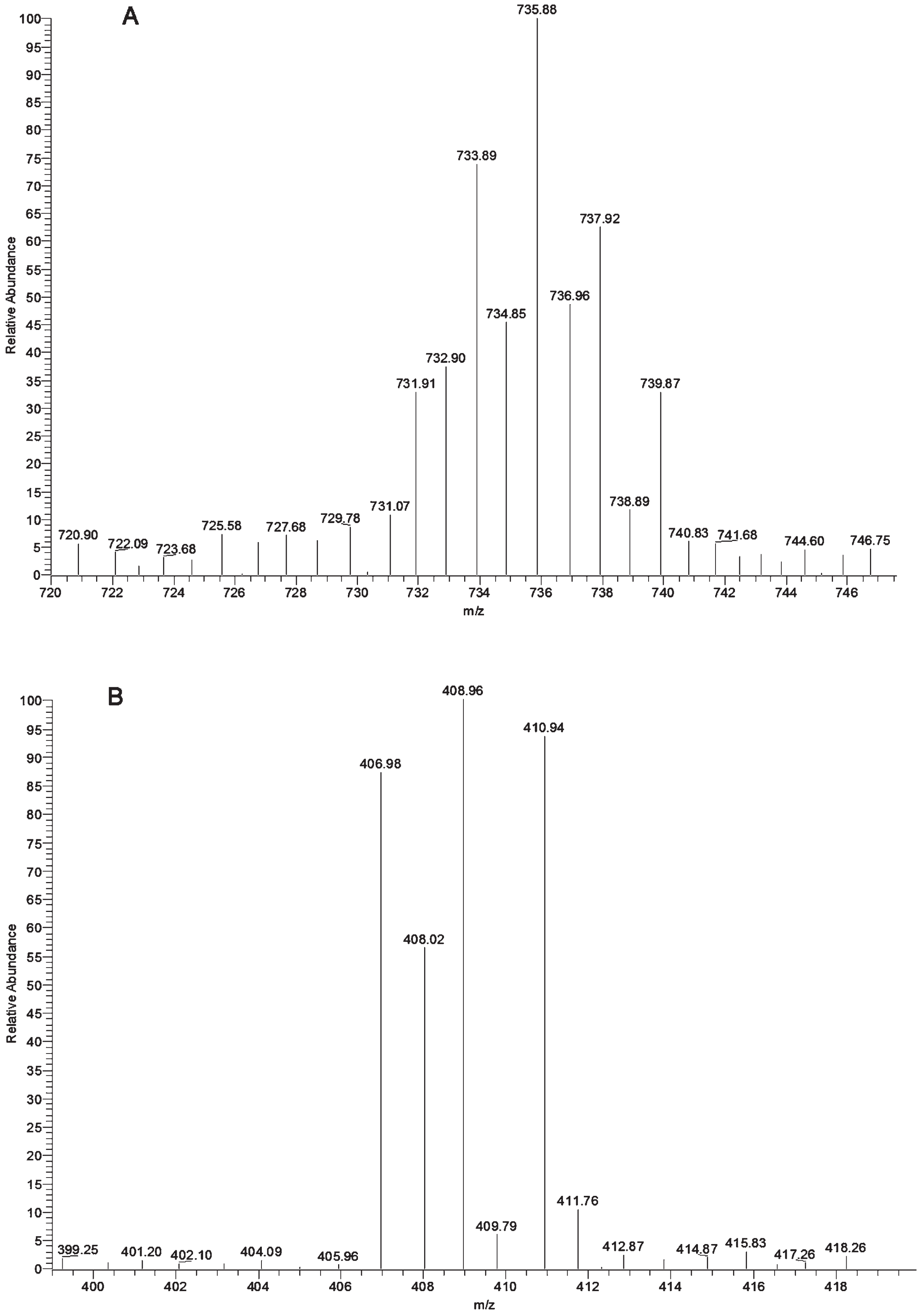


**Figure 3.** The ESI mass spectra of the catalytic mixture at 20 °C (**3**). (**A**) Pattern observed for a dinuclear tungsten peroxo species with two $ClCH_2COOH$ $[W_2(ClCH_2COO)_2(O_2)_4(O)_3]$. (**B**) Pattern observed for a mononuclear tungsten peroxo species with one $ClCH_2COOH$ $[W(ClCH_2COO)(O_2)_2(O)_2]$.

terminal alkene, i.e., 1-hexene, can also be selectively oxidized with a high TON of 150 (entry 4). The homoallylic alcohol, 3-methyl-3-buten-1-ol (entry 5) is converted to the epoxide with good yield and selectivity after a reaction time of 4 hours. Finally, the more reactive allylic alcohol geraniol is also totally epoxidized to [3-methyl-3-(4-methylpent-3-enyl)oxiran-2-yl]methanol within 30 minutes, with a high selectivity of 97% (entry 6).

In conclusion, a very effective biphasic catalytic system involving readily available and inexpensive catalytic precursors, namely sodium tungstate, tungstic acid, methyltri-*n*-octylammonium chloride (Aliquat 336) and chloroacetic acid has been developed for solvent-free alkene epoxidations using hydrogen peroxide as oxidant. Detailed studies on the mechanism and other organic substrates are currently in progress.

## Experimental Section

All reactants and solvents were used as received without any further purification. The oxidations were carried out in air in a 100-mL, three-necked round-bottom flask equipped with a magnetic stirrer and reflux condenser.

Typically, 0.132 g (0.2 mol %) of $Na_2WO_4 \cdot 2\,H_2O$ and 0.112 g (0.2 mol%) of $H_2WO_4$ were stirred for 2 minutes in 1 mL of distilled water and then 1.5 equivalents per alkene (300 mmol) of $H_2O_2$ (50%) were added followed by 1.6 mol % of $ClCH_2$ COOH. This mixture was stirred for 5 more minutes followed by the addition of 200 mmoles of the alkene and 0.2 mol% of methyltri-*n*-octylammonium chloride (Aliquat 336, PTR). The oxidation reaction started without any incubation period. Samples were collected from the organic phase regularly to monitor the oxidation by GC (1,4-dibromobenzene; 1 mg · $mL^{-1}$ in $CH_2Cl_2$; GC internal standard) for analyses. The products of the reaction were determined by comparison with the commercially available compounds.

ESI-MS experiments were carried out using a Finnigan Aqa Mass Spectrometer equipped with an electrospray ionization source. The sample solution was prepared using $Na_2WO_4$ – 2 mmol; $H_2WO_4$ – 2 mmol; $ClCH_2COOH$ – 16 mmol; 50% $H_2O_2$ – 40 mmole in 10 mL of $H_2O$, pH 2.2, at room temperature. The solution was diluted to 1 mg/mL, in $H_2O$ and was introduced in the ESI source by using a HPLC auto-sampler and an acetonitrile/water (50/50) mixture as eluent running at 0.2 mL/min. Mass spectra were acquired by scanning from $m/z = 1600$ to 100. Approximately 25 scans were summed to give the mass spectra.

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