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Efficient and selective oxidation of methyl substituted cycloalkanes by heterogeneous methyltrioxorhenium–hydrogen peroxide systems

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Abstract—Polymer-supported methyltrioxorhenium (MTO) systems are efficient catalysts for the oxidative functionalisation of cyclohexane and cyclopentane derivatives with H_2O_2 as oxygen donor. Using poly(4-vinyl)pyridine and poly(4-vinyl)pyridine-*N*-oxide as MTO supports, cycloalkanol, cycloalkanediol, cycloalkanone and ω-hydroxy methyl ketone derivatives were obtained in different yields depending on the experimental conditions. Interestingly, cycloalkane dimers were selectively recovered in acceptable to good yields when the oxidation was performed with polystyrene-microencapsulated MTO catalyst. The EPR investigation suggests that the homolytic cleavage of the CH_3–Re bond with formation of $CH_3^{\bullet}$ radicals occurs inside the polystyrene capsule, indicating a possible role of methyl radical in the cycloalkane dimerisation pathway.

1. Introduction

In the last years increasing attention was directed to the use of methyltrioxorhenium (CH_3ReO_3, MTO)[1] in oxidative reactions, in conjunction with hydrogen peroxide (H_2O_2) as oxygen donor, due to the excellent catalytic properties showed by this system.[2] Among the various MTO catalysed reactions, the oxidation of hydrocarbons to alcohols and ketones is of relevant interest because of industrial and environmental concerns.[3,4] This reaction proceeds through the formation of the monoperoxo [$MeRe(O)_2O_2$] (**A**) and the bis-peroxo [$MeReO(O_2)_2$] (**B**) η^2-rhenium complexes that have been isolated and fully characterised by single-crystal X-ray analysis (Fig. 1).[5] In molecular solvents, the complex **A** was found to be more reactive than **B**, while the opposite occurs for reactions driven in ionic liquids.[6] Theoretical and computational studies have been performed to elucidate the geometrical features of the transition state involved in this oxidation. Specifically, the oxygen transfer from complexes **A** and/or **B** to the substrate was always described by a concerted process requiring a butterfly-like transition state similar to that previously suggested for cyclic organic peroxides such as dimethyldioxirane (DMDO).[7,8] Heterogeneous rhenium catalysts behave in a similar way:[9] for example, the same **A** and **B** complexes were intermediates in the epoxidation of alkenes with H_2O_2, catalysed by MTO supported on silica tethered with polyethers.[9c] The heterogenation of MTO on polymeric supports is an important tool because it allows an easier recovery of the catalyst, decreases the toxicity of reaction wastes and sometimes improves the reactivity.[10] The heterogeneous systems used in the present paper have been prepared either by heterogenation of MTO on easily available polymers bearing nitrogen atoms as anchorage sites, such as poly(4-vinylpyridine) (PVP) and poly(4-vinylpyridine)-*N*-oxide (PVPN), [2% or 25% cross-linked with divinylbenzene (PVP-2/MTO **I**, PVP-25/MTO **II** and PVPN-2/MTO **III**, respectively; Fig. 2)][11] or by physical microencapsulation on polystyrene of both MTO or its adduct with 2-aminomethyl pyridine (PS/MTO **IV** and PS/MTO-L **V**, respectively; Fig. 2).[12]

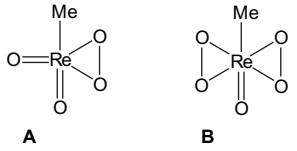

Figure 1. Peroxo η^2-rhenium complexes.

Keywords: Heterogeneous catalysis; Methyltrioxorhenium; Radical reactions; EPR spectroscopy.
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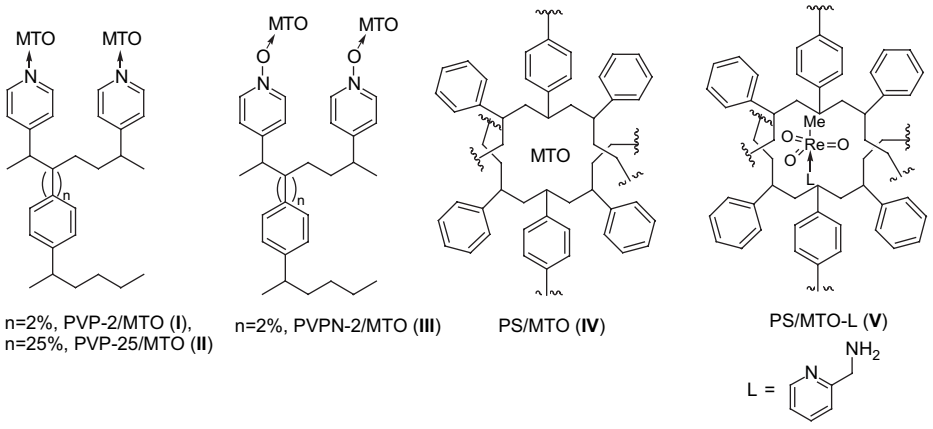
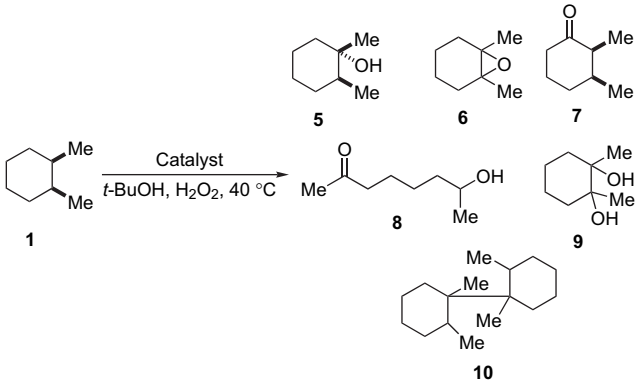
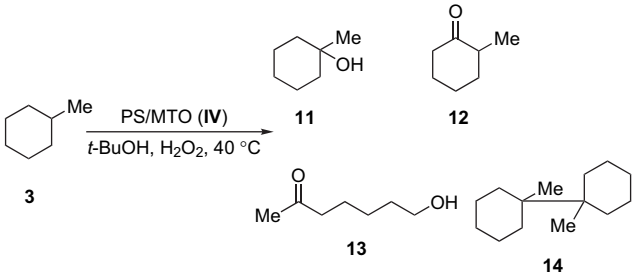


Figure 2. Sketches of polymer-supported MTO catalysts **I**–**V**.

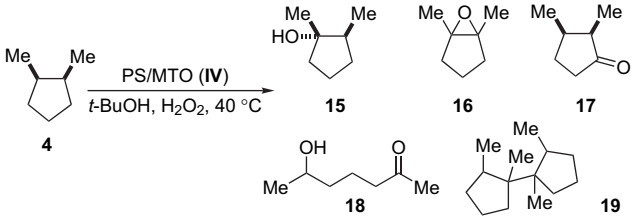
These systems showed high catalytic activity and selectivity in the oxidation of aromatic derivatives,[13] pyrrolidines,[14] alkenes and terpenes,[15] including the oxygen atom insertion into the C–H sigma bond of hydrocarbons, both in molecular solvents[16] and ionic liquids.[17] As a result of our ongoing studies, herein we report on the oxidative derivatisation of different cycloalkane derivatives, namely stereoisomeric *cis*- and *trans*-1,2-dimethylcyclohexanes **1** and **2**, methylcyclohexane **3** and *cis*-1,2-dimethylcyclopentane **4**, with heterogeneous MTO and H_2O_2 in *tert*-butanol (*t*-BuOH). A different reaction pathway was observed depending on the catalyst used for the transformation. Alcohols or products obtained from further oxidation of alcohols, including ring-opened ω-hydroxy methyl ketones were obtained with poly(4-vinylpyridine) catalysts **I**–**III**. The oxidation of the same substrates with the PS/MTO **IV** catalytic system afforded, unexpectedly, cycloalkane dimers in appreciable amounts (**10**, **14** and **19**, Schemes 1–4). The Electron Paramagnetic Resonance (EPR) investigation showed that the homolytic cleavage of the Re–CH_3 bond preferentially occurs inside the polystyrene capsule, thus suggesting



Scheme 1. Products from catalytic MTO-based oxidations of *cis*-1,2-dimethylcyclohexane **1**.

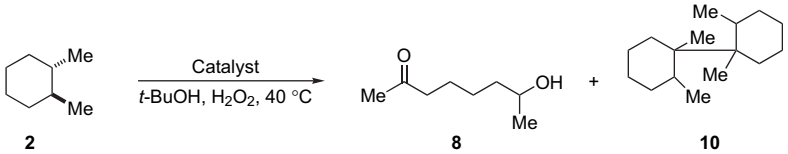


Scheme 3. Products from catalytic MTO-based oxidation of methylcyclohexane **3**.



Scheme 4. Products from catalytic MTO-based oxidation of *cis*-1,2-dimethylcyclopentane **4**.

a possible role of the methyl radical in the cycloalkane dimerisation pathway. To the best of our knowledge this is the first example in the literature dealing with the presence of a radical pathway in oxidation reactions with MTO and H_2O_2. Noteworthy, the effect of the polystyrene microcapsule environment on the reactivity of MTO appears to be finely tuned by the presence of nitrogen containing ligand bonded to rhenium atom and able to change its stereoelectronic properties. As an example, cycloalkane dimers were not recovered when the oxidation was repeated in the presence of the catalytic system PS/MTO-L **V**, obtained by the microencapsulation of previously formed complex between MTO and 2-aminomethyl pyridine[15a] (Fig. 2).



Scheme 2. Products from catalytic MTO-based oxidations of *trans*-1,2-dimethylcyclohexane **2**.

2. Results and discussion

The results of the oxidation of stereoisomeric *cis*- and *trans*-1,2-dimethylcyclohexanes **1** and **2**, methylcyclohexane **3** and *cis*-1,2-dimethylcyclopentane **4** in *t*-BuOH with H_2O_2, catalysed by heterogeneous MTO-based catalysts, are reported in Schemes 1–4 and Tables 1–3. Oxidations with MTO under similar homogeneous conditions were performed as references. In the absence of catalyst, less than 5% conversion of substrates took place under otherwise identical conditions.

2.1. Homogeneous MTO catalysed reactions

The oxidation of stereoisomeric *cis*- and *trans*-1,2-dimethylcyclohexanes, **1** and **2** was initially studied as a representative example of oxidation of cycloalkane derivatives with MTO under homogeneous conditions. Treatment of **1** (1.0 mmol) with an excess of H_2O_2 (4.0–6.0 equiv) and MTO (2% w/w) in *t*-BuOH at 40 °C, afforded a quantitative conversion of the substrate to give (*E*)-1,2-dimethylcyclohexanol **5** as the main reaction product, besides 1,6-dimethyl-7-oxabicyclo[4.1.0]heptane (1,2-dimethyl cyclohexan-oxide) **6**, 2,3-dimethylcyclohexanone **7** and the ω-hydroxy methyl ketone **8** as side-products (Scheme 1, Table 1, entry 1).[18] The 1,2-dimethylcyclohexandiol **9** was also detected in very low amount by gas-chromatography–mass-spectrometry (GC–MS) analysis.

Table 1. Oxidation of *cis*-1,2-dimethylcyclohexane **1** with MTO and heterogeneous MTO catalysts **I–V**

Entry	Catalyst	Conversion (%)	Yield (%)[a]					
			5	**6**	**7**	**8**	**9**	**10**
1	MTO	>98	65	18	7[b]	5[b]	—	—
2	PVP-2/MTO (**I**)	>98	22	—	—	68	—	—
3	PVP-25/MTO (**II**)	>98	48	9[b]	—	3[b]	35	—
4	PVPN-2/MTO (**III**)	45	60	—	—	—	—	—
5	PS/MTO (**IV**)	>98	12[b]	26	—	4[b]	—	53
6[c]	PS/MTO (**IV**)	9	—	—	—	—	—	12[b]
7	PS/MTO-L (**V**)	80	65	—	—	—	—	—

[a] Calculated from isolated product.
[b] Calculated by GC–MS analysis.
[c] Without hydrogen peroxide.

Table 2. Oxidation of *trans*-1,2-dimethylcyclohexane **2** with MTO and heterogeneous MTO catalysts **I–IV**

Entry	Catalyst	Conversion (%)	Yield[a] (%)	
			8	**10**
1	MTO	>98	>98	—
2	PVP-2/MTO (**I**)	>98	>95	—
3	PVP-25/MTO (**II**)	>98	>98	—
4	PVPN-2/MTO (**III**)	>98	>98	—
5	PS/MTO (**IV**)	>98	7[b]	78

[a] Calculated from isolated product.
[b] Calculated by GC–MS analysis.

Cyclohexanol **5** was clearly formed by oxygen atom insertion at the tertiary C–H bond. Such selectivity is similar to that previously observed during the oxidation of 1,2-dimethylcycloalkanes with stoichiometric DMDO derivatives, invoking the formation of a concerted butterfly-like transition state.[19] The appearance of epoxide **6** is notable and suggests a multifunctional catalytic behaviour for MTO under these experimental conditions. In fact, compound **6** was probably obtained via epoxidation of 1,2-dimethylcyclohexene (not shown) generated in situ by elimination of a water molecule from **5**, due to the known Lewis and Brönsted acidity of MTO.[2] In agreement with this hypothesis, appreciable amounts of 1,2-dimethylcyclohexene were obtained by treating **5** with catalytic amount of MTO in the absence of H_2O_2. A similar behaviour was previously observed in the oxidation of dimethylcyclohexane derivatives with H_2O_2 in the presence of Fe(II) complexes.[20] The remarkable selectivity of oxygen atom insertion at the tertiary over secondary C–H bonds, despite the high reactivity of MTO, is confirmed by the higher yield of tertiary alcohol **5** and its derivative **6**, in comparison with cyclic ketone **7** (necessarily produced by the oxidation of the secondary C–H bond) (see Table 1, entry 1). The presence of little amounts of ω-hydroxy methyl ketone **8** is worthy of note. It is reasonable to suggest that this compound arises from the over-oxidation of the diol **9** followed by C–C oxidative ring-cleavage. To the best of our knowledge, with the exception of our recent study on the degradation of aromatic moieties to ring-opened muconic acid derivatives in lignin and lignin model compounds,[21] no further data were reported in literature dealing with the oxidative cleavage of the C–C bond by H_2O_2 and MTO. The highest selectivity was observed during the oxidation of *trans*-1,2-dimethylcyclohexanes **2** under similar experimental conditions. In this latter case, the ω-hydroxy methyl ketone **8** was obtained as the only recovered product, with quantitative conversion of substrate and high yield (Scheme 2, Table 2, entry 1). The highest reactivity of the carbon atoms bearing an axial hydrogen towards the approaching metal peroxides **A** and **B**, explains the selective formation of this over-oxidation product from substrate **2**. It must be emphasised that, beyond the synthetic interest due to their potential biological applications, as far as we are aware there are no examples of chemical procedures to obtain ω-hydroxy ketones starting from saturated cyclic hydrocarbons.

2.2. Polymer-supported MTO catalysed reactions

The oxidation of stereoisomeric *cis*- and *trans*-1,2-dimethylcyclohexanes, **1** and **2** (1.0 mmol) was performed with an excess of H_2O_2 (4.0–6.0 equiv) and the appropriate catalyst

Table 3. Oxidation of methylcyclohexane **3** and *cis*-1,2-dimethylcyclopentane **4** with MTO supported on polystyrene (PS/MTO, **IV**)

Entry	Catalyst	Substrate	Conversion (%)	Yield (%)[a]								
				11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1	PS/MTO (**IV**)	**3**	>98	3[b]	16	35	42	—	—	—	—	—
2	PS/MTO (**IV**)	**4**	>98	—	—	—	—	4[b]	6[b]	2[b]	20	68

[a] Calculated from isolated product.
[b] Calculated by GC–MS analysis.

(10% w/w) in *t*-BuOH at 40 °C. All polymer-supported MTO systems **I**–**V**[11,12,15a] showed high efficiency in the oxidation of stereoisomeric *cis*- and *trans*-1,2-dimethylcyclohexanes, **1** and **2**, giving a different distribution of products depending on the chemical and physical properties of the catalyst used in the transformation (Schemes 1 and 2, Tables 1 and 2). In particular, in the family of poly(4-vinylpyridine)-based catalysts **I**–**III**, the reticulation grade of the polymeric support as well as its oxidation state appeared to be relevant parameters for the selectivity of the reaction. Thus, the oxidation of **1** with low-reticulated PVP-2/MTO **I** afforded the ω-hydroxy methyl ketone **8** as the main reaction product besides low amount of cyclohexanol **5** (Table 1, entry 2). On the other hand, treatment of **1** with high-reticulated PVP-25/MTO **II** afforded alcohols **5** and **9** in high yields, compounds **6** and **8** being recovered as side-products (Table 1, entry 3). Finally, cyclohexanol **5** was obtained as the only recovered product in the presence of PVPN-2/MTO **III**. Only in this last case a low conversion of the substrate was observed (Table 1, entry 4). The significant effects of the reticulation grade and of the oxidation of pyridine nitrogen atom of the support, on the reactivity and selectivity of MTO, are in accordance with the data previously obtained in the oxidation of alkanes, alkenes and phenol derivatives.[11,12,16] Unexpectedly, when the oxidation of **1** was performed using microencapsulated catalyst PS/MTO **IV**, the dimeric derivative, 1,1′,2,2′-tetramethyl-1,1′-bi(cyclohexyl) **10**, was obtained as the main reaction product in 53% yield (Table 1, entry 5). Bis-cyclohexane derivatives are usually obtained by photochemical oxidation of the corresponding cyclohexanes through a radical pathway[22a] but, to date, there are no examples of the possible appearance of a radical mechanism during oxidations performed with MTO and H_2O_2. Moreover, compound **10** was recovered, even if in low yield, also in the absence of H_2O_2 by treating compound **1** with PS/MTO **IV** (Table 1, entry 6). This involves a direct role of microencapsulated MTO in the dimerisation process. As known, the reactivity of MTO in several oxidative functionalisations can be tuned by the presence of Lewis bases coordinating the metal centre. This trend was confirmed by the result obtained in the oxidation of **1** with microencapsulated catalyst PS/MTO-L **V** (Table 1, entry 7): in this case no trace of dimeric derivative **10** was detected, alcohol **5** being recovered in 65% yield.

We then studied the oxidation of *trans*-1,2-dimethylcyclohexane **2**: in this case the ω-hydroxy methyl ketone **8** was obtained as the only recovered product, with both quantitative conversion of substrate and high yield, independent of the poly(4-vinylpyridine)-based catalyst used for the reaction (Scheme 2, Table 2, entries 2–4). Under homogeneous conditions the system evidenced quite an analogous behaviour (Table 2, entry 1). Again, the dimer 1,1′,2,2′-tetramethyl-1,1′-bi(cyclohexyl) **10** was obtained as the main reaction product in the presence of microencapsulated PS/MTO **IV** catalyst, thus confirming the peculiar reactivity of this system.

To further evaluate the generality of the dimerisation process, we studied two novel methyl substituted cycloalkanes, such as methylcyclohexane **3** and *cis*-1,2-dimethylcyclopentane **4**, in the presence of PS/MTO **IV** and H_2O_2. Treatment of **3** (1.0 mmol) with an excess of H_2O_2 (4.0–6.0 equiv) and PS/MTO **IV** (10% w/w) in *t*-BuOH at 40 °C afforded a quantitative conversion of substrate to give the ring-opened derivative 7-hydroxy-2-heptanone **13** and the dimeric compound 1,1′-dimethyl-1,1′-bi(cyclohexyl) **14** as the main reaction products, besides low amount of 2-methylcyclohexanone **12** and 1-methylcyclohexanol **11** (Scheme 3, Table 3, entry 1).

In a similar way, the dimeric compound 1,1′,2,2′-tetramethyl-1,1′-bi(cyclopentyl) **19** was obtained in high yield, by the oxidation of *cis*-1,2-dimethylcyclopentane **4** with PS/MTO **IV** and H_2O_2, besides the 6-hydroxyheptan-2-one **18** as side product, and traces of 1,2-dimethylcyclopentanol **15**, 1,5-dimethyl-6-oxabicyclo[3.1.0]hexane **16** and 2,3-dimethylcyclopentanone **17** (Scheme 4, Table 3, entry 2). Thus, the oxidative dimerisation of cycloalkane derivatives during the oxidation with the PS/MTO **IV** and H_2O_2 system, was an operative process irrespective of the substitution pattern and the size of the alkane ring to be oxidised.

2.3. EPR investigation

In order to understand the formation of dimers **10**, **14** and **19** during the oxidation of stereoisomeric cyclohexane and cyclopentane derivatives with polymer-microencapsulated MTO catalyst **IV**, an EPR investigation was performed on freshly prepared catalysts **I**–**V** at 25 °C. The EPR spectra of MTO and the uncharged resins were also recorded.

MTO has high thermal stability, since it decomposes only above 300 °C, however, it slowly decomposes by radical pathway under daylight and it is very sensitive to UV radiation. In particular, photolytic reactions lead to a homolytic cleavage of the carbon–rhenium bond, with the formation of CH_3• and •ReO_3 radicals.[22b] Since no EPR signals were observed on pure MTO, we assume that no significant catalyst decomposition takes place under our experimental conditions.

The EPR spectrum of poly(4-vinylpyridine) catalysts **I**–**III** showed a very broad isotropic signal (g=2.299, ΔH_{pp}~1450 G). The same signal was also observed in the pure polymer, and it is probably due to metal contaminants. Similarly, the EPR spectrum of pure polystyrene resin showed an isotropic sharp signal (g=1.978, ΔH_{pp}=11.3 G, Fig. 3 line a).

When MTO was encapsulated into PS resin (catalyst **IV**), the EPR spectrum showed the same signal observed in pure resin; in addition, four resonance lines not equally spaced and having different amplitudes and widths appeared at g~2.00 (Fig. 3, line b). The absence of symmetry about the centre of resonances indicates anisotropy of both g and A tensors.[23] Thus, the quartet was simulated by the spectrum of a CH_3• radical with axial anisotropy of both g and A tensors ($g\perp$=2.0028, $g\|$=2.0069, $A\perp$=10.4 G, A$\|$=11.7 G), linewidth $\Delta H\perp$=5.1 G and $\Delta H\|$=4.0 G (Fig. 3, line b′).

The literature reports the g and A tensor anisotropy for the CH_3• radical in Ar, Kr and CO matrices at liquid He temperatures,[23] attributing it to interaction with the hosts. In our case, the anisotropy of g tensor was higher (Δg=0.0041 against Δg=0.0005 of CH_3• in CO matrix[23]) and indicates

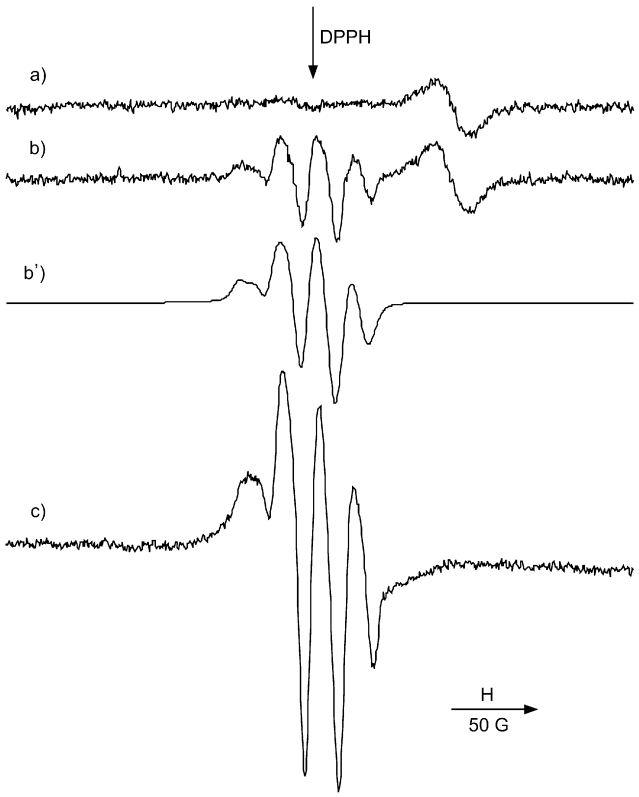


Figure 3. X-band EPR spectra, recorded at 298 K, of: PS resin (line a); PS/MTO (line b, experimental; line b′, simulated); PS/MTO after treatment with H_2O_2 (line c).

a significant interaction between methyl radical and PS resin; the much lower value of the hyperfine coupling constants with respect to the value reported for 'free' CH_3• (A=23 G),[24] confirms that such interaction strongly affects the electronic distribution on methyl radicals. The fact that MTO dispersed in polystyrene matrix interacts with the surroundings was also confirmed by the results of FTIR analyses previously performed in our laboratories;[11] in fact microencapsulated PS/MTO **IV** showed the lowest ν(ReO) stretching vibration frequencies (ν_s 953, ν_{as} 911 cm^{-1}) with respect to either polymer-supported MTO systems **I–III** (ν_s 963–964, ν_{as} 923–932 cm^{-1}) or pure MTO (ν_s=998, ν_{as} 959 cm^{-1}). As expected, polymer-supported MTO systems (**I–IV**) showed vibration frequency values lower than those for MTO, thus suggesting that the π-bonded hydrocarbon ligands cause the lowering of the Re–O bond order, probably due to their electron-donating ability. A similar correlation between the π-donor qualities of the ring ligand and the decreasing of the rhenium–oxygen bond order in the (η^5-C_5Me_5)ReO_3 half-sandwich complex, if compared with MTO, was already observed by *Herrmann* and coworkers.[25a]

Previously, methyl radicals formed by cleavage of carbon–rhenium bonds were observed, only in solution, after photolysis of organorhenium(VII) oxides[26] [R–ReO_3, with R=CH_3, C_2H_5, η^1-mesityl, C_6H_5, η^5-C_5H_5, η^5-$C_5H_4(CH_3)$ and η^5-$C_5(CH_3)_5$]. In those cases, methyl radicals were detected by using a spin trap molecule. To the best of our knowledge, PS/MTO shows the first example of stable methyl radicals from cleavage of the Re–CH_3 bond.

The signal of •ReO_3 centre was not observed in the EPR spectrum, probably due to the fast formation of perovskite ReO_3.[27] After treatment with H_2O_2, the EPR signals of the pure polymer disappeared, while the amount of CH_3• radicals increased from 1.2×10^{15} spin/g on PS/MTO to 1.3×10^{16} spin/g, corresponding to a molar ratio CH_3•/MTO= 0.1% (Fig. 3, line c). For what concerns this spectrum, the presence of small amounts of peroxo radicals[24] could explain the difference in the relative intensity of the four resonance lines with respect to that observed in untreated PS/MTO.

The signal of CH_3• radical was observed neither with PVP catalysts **I–III** nor with PS/MTO-L **V**. The absence of CH_3–Re cleavage in poly(4-vinylpyridine)-based systems is probably due to the stabilising effect of the nitrogen ligands on the metal–carbon bond. Analogous reasons concerning the stabilising role of the bidentate ligand 2-aminomethyl pyridine (L, in Fig. 2) on the behaviour of MTO, could be used to justify the absence of the radical pathway with catalyst **V**.

The identification of CH_3• radical in PS/MTO **IV**, associated to the increase of the radical amount after addition of the oxidant, can be reasonably correlated to the formation of dimers **10**, **14** and **19** by using the microencapsulated catalyst. The mechanism of the dimer formation was not further investigated. However, since the coupling of two CH_3• radicals is not favoured,[25b] it can be thought that the methyl radical in solution abstracts one hydrogen atom from the substrate, with formation of methane and a tertiary alkyl radical, directly available for the dimerisation process.

Finally, in the investigated reactions, the solvent (*t*-BuOH) probably plays a relevant role,[28] as it can be deduced from the fact that the oxidation of 1,2-dimethylcyclohexane catalysed by polymer-MTO catalysts **I–IV** gave the alcohol **5** as the only recovered product, in ionic liquids.[17]

3. Conclusions

MTO and polymer-supported MTO systems **I–V** are shown to be efficient catalysts for the oxidative functionalisation of cyclohexane and cyclopentane derivatives with H_2O_2 as oxygen atom donor. Different reaction pathways were observed depending on the nature of the polymeric support. In the case of catalysts **I–III**, obtained by heterogenation of MTO on poly(4-vinyl)pyridine and poly(4-vinylpyridine)-*N*-oxide resins, the reaction proceeded through a concerted oxygen insertion from the intermediate peroxo complexes **A** and **B**[5] into the very reactive tertiary C–H bonds, to give the corresponding cycloalkanol derivatives. Due to the multifunctional catalytic properties of MTO, elimination of water molecule, epoxidation of the resulting double bond, nucleophilic ring-opening reactions of the epoxide ring and oxidative C–C bond cleavage were also operative processes. The selectivity of the reactions was found to be correlated both to the structural properties of the poly(4-vinyl)pyridine support and to the stereochemical properties of the substrate. Noteworthy, a different reaction pathway was observed with microencapsulated catalyst **IV**, leading to the formation of a cycloalkane dimer, irrespective of the

nature of the substrate, in yields ranging from acceptable to good. Moreover, dimeric compounds were also recovered, although in low yields, by treating cycloalkanes with PS/MTO **IV** in the absence of H_2O_2, showing a direct role of microencapsulated MTO on the dimerisation process.

The EPR analysis showed that homolytic cleavage of the CH_3–Re bond selectively occurs for catalyst **IV**, leading to the formation of a PS-trapped methyl radical. On the basis of these data it is reasonable to suggest the intervention of a radical pathway in the formation of the cycloalkane dimers. The radical pathway observed with catalyst **IV** can be suppressed by modulating the chemical reactivity of microencapsulated MTO as in the case of catalyst **V** containing the Lewis adduct [MTO·2-aminomethyl pyridine]. Thus, a large panel of reaction products can be obtained during the oxidation of stereoisomeric cycloalkane derivatives with MTO-based heterogeneous catalysts, the selectivity of the transformation being tuned by different experimental parameters, such as the nature of the support, the reaction solvent and the stereochemical properties of the substrate. Further work is in progress in order to better evaluate the synthetic potentiality of the microencapsulated MTO catalyst **IV** for the oxidation of hydrocarbons and hydrocarbon derivatives with H_2O_2 in *t*-BuOH.

4. Experimental

4.1. General remarks

All commercial products were of the highest available grade and were used as such. NMR spectra were recorded on a Bruker (AC 200 MHz). When necessary, chromatographic purification was performed on columns packed with silica gel, 230–400 mesh, for flash technique. In order to evaluate the scaling-up of our catalytic procedure, the oxidation of *cis*-1,2-dimethylcyclohexane **1** with catalyst **I** (PVP-2/MTO) was repeated on the scale of 10 mmol of substrate, and working under the same experimental conditions: neither substantial changes in the reaction selectivity nor sensible variations of reaction yields were observed.

4.2. Preparation of supported catalysts I–IV[11a,12]

MTO (256 mg, 1.0 mmol) was added to a suspension of the appropriate resin (0.5 g, loading factor=2) in ethanol (4 mL). The mixture was allowed for stirring for 1 h. The solvent was removed by filtration, and the catalyst washed with ethyl acetate and finally dried under high vacuum.

FTIR (KBr), ν (Re–O) cm^{-1}: **I**: 963, 923; **II**: 964, 932; **III**: 924; **IV**: 953, 911.

4.3. Preparation of supported catalyst V

The preparation of [MTO·2-aminomethyl pyridine] adduct was performed according to a published method.[15a] Briefly, 0.5 mmol of 2-aminomethyl pyridine was added to 1.0 mmol of MTO in toluene (10 mL) at room temperature. A yellow precipitate was immediately formed. The reaction mixture was concentrated, cooled to −35 °C and the precipitate isolated by filtration. The microencapsulation on polystyrene of the so obtained adduct was performed analogously as previously published.[15a]

4.4. Typical oxidative reaction

One millimole of *cis*- and *trans*-1,2-dimethylcyclohexanes, **1** and **2**, respectively, dissolved in *t*-BuOH (2.0 mL) was added with MTO (2.4 mg, 2% w/w) or supported catalysts **I–V** (11.2 mg, 10% w/w) and H_2O_2 (4.0–6.0 equiv). The mixture was heated at 40 °C and allowed for stirring for 72 h. Catalysts were recovered by filtration at the end of the reaction, when the reaction was performed under heterogeneous conditions. A low amount of MnO_2 was added to decompose the excess of oxidant and the solvent was evaporated after filtration of the oxide. The reaction products were fully characterised by GC–MS, ^1H and ^{13}C NMR analyses and by comparison with authentic samples.[18]

4.4.1. 1,2-Dimethylcyclohexanol 5.[29] ^1H NMR ($CDCl_3$) δ 1.71–1.16 (m, 9H), 1.50 (s, 1H), 1.05 (s, 3H), 0.88 (d, J=6.9 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 73.05, 42.28, 41.35, 32.01, 25.28, 24.01, 20.69, 15.31. GC–MS *m/z* (%): 128 (20), 113 (25), 95 (25), 85 (60), 71 (100).

4.4.2. 1,6-Dimethyl-7-oxabicyclo[4.1.0]heptane 6.[30] ^1H NMR ($CDCl_3$) δ 2.10–1.28 (m, 8H), 1.22 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 62.25, 32.18, 22.13, 20.75. GC–MS *m/z* (%): 126 (20), 110 (25), 95 (73), 81 (60), 69 (100).

4.4.3. 2,3-Dimethylcyclohexanone 7.[31] ^1H NMR ($CDCl_3$) δ 2.6–1.5 (m, 8H), 0.98 (d, J=9 Hz, 3H), 0.85 (d, J=9 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 213.62, 48.75, 40.12, 36.62, 30.78, 22.85, 11.62, 11.51. GC–MS *m/z* (%): 126 (37), 111 (28), 98 (30), 83 (80), 55 (100).

4.4.4. 7-Hydroxyoctan-2-one 8. ^1H NMR ($CDCl_3$) δ 3.15 (br s, 1H), 3.42–3.34 (m, 1H), 2.45 (t, J=6.8 Hz, 2H), 2.14 (s, 3H), 1.58–1.25 (m, 6H), 1.20 (d, J=7 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 207.68, 65.25, 43.15, 42.98, 28.76, 25.33, 24.18, 23.12. GC–MS *m/z* (%): 101 (55), 83 (15), 59 (78), 43 (100).

4.4.5. 1,2-Dimethylcyclohexane-1,2-diol 9.[32] ^1H NMR ($CDCl_3$) δ 2.06 (br s, 2H), 1.70–1.25 (m, 8H), 1.22 (s, 6H), 1.15 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 74.32, 36.40, 23.20, 22.10. GC–MS *m/z* (%): 145 (4), 127 (30), 111 (28), 71 (55), 43 (100).

4.4.6. 1,1′,2,2′-Tetramethyl-1,1′-bi(cyclohexyl) 10. ^1H NMR ($CDCl_3$) δ 2.28–2.10 (m, 2H), 1.75–1.20 (m, 16H), 0.94 (s, 6H), 0.85 (m, 6H). ^{13}C NMR ($CDCl_3$) δ 38.65, 36.82, 33.24, 29.80, 23.62, 21.85, 17.40, 15.82. GC–MS *m/z* (%): 111 (75), 69 (100), 55 (20), 43 (50).

4.4.7. 1-Methylcyclohexanol 11. ^1H NMR ($CDCl_3$) δ 2.3 (br s, 1H), 1.65–1.30 (m, 10H), 1.20 (s, 3H). ^{13}C NMR ($CDCl_3$) δ 69.85, 39.45, 29.15, 24.35, 22.68. GC–MS *m/z* (%): 114 (9), 99 (28), 81 (25), 71 (100), 58 (25).

4.4.8. 2-Methylcyclohexanone 12.[33] ^1H NMR ($CDCl_3$) δ 2.40–2.08 (m, 5H), 1.80–1.65 (m, 3H), 1.33–1.38 (m, 1H), 1.05 (d, J=6.5 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 214.01, 45.81, 41.65, 35.98, 28.22, 25.67, 14.58. GC–MS *m/z* (%): 112 (35), 97 (25), 81 (54), 69 (100), 56 (50).

4.4.9. 7-Hydroxy-2-heptanone 13. ^{1}H NMR ($CDCl_3$) δ 1.33–1.40 (m, 2H), 1.54–1.62 (m, 4H), 2.14 (s, 3H), 2.19 (br, 1H), 2.45 (m, 2H), 3.63 (m, 2H). ^{13}C NMR ($CDCl_3$) δ 23.35, 25.20, 29.80, 32.29, 43.52, 62.35, 209.32. GC–MS *m*/*z* (%): 101 (60), 83 (16), 59 (84), 43 (100).

4.4.10. 1,1′-Dimethyl-1,1′-bi(cyclohexyl) 14. ^{1}H NMR ($CDCl_3$) δ 1.64–1.55 (m, 8H), 1.47–1.07 (m, 12H), 0.81 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 38.10, 30.34, 26.61, 20.34, 16.61. GC–MS *m*/*z* (%): 97 (100), 69 (20), 55 (75), 43 (25).

4.4.11. 1,2-Dimethylcyclopentanol 15.[29] ^{1}H NMR ($CDCl_3$) δ 1.98–1.50 (m, 6H), 1.87 (br s, 1H), 1.21–1.14 (m, 1H), 1.11 (s, 3H), 0.84 (d, J=7 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 81.00, 44.62, 39.98, 31.75, 22.78, 20.48, 15.36. GC–MS *m*/*z* (%): 114 (5), 99 (12), 85 (30), 71 (100), 43 (60).

4.4.12. 1,5-Dimethyl-6-oxabicyclo[3.1.0]hexane 16.[34] ^{1}H NMR ($CDCl_3$) δ 1.81–1.73 (m, 2H), 1.70–1.65 (m, 2H), 1.38–1.22 (m, 2H), 1.22 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 62.97, 35.41, 17.01, 16.84. GC–MS *m*/*z* (%): 112 (60), 97 (80), 71 (50), 69 (49), 43 (100).

4.4.13. 2,3-Dimethylcyclopentanone 17. ^{1}H NMR ($CDCl_3$) δ 2.23–1.75 (m, 5H), 1.38–1.29 (m, 1H), 0.93 (d, J=7.1 Hz, 3H), 0.90 (d, J=6.9 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 218.04, 47.05, 39.25, 35.38, 28.66, 16.74, 11.22. GC–MS *m*/*z* (%): 112 (50), 97 (22), 81 (75), 69 (100), 55 (82).

4.4.14. 6-Hydroxyheptan-2-one 18. ^{1}H NMR ($CDCl_3$) δ 3.87 (m, 1H), 3.11 (br s, 1H), 2.49 (t, J=6.8 Hz, 2H), 2.10 (s, 3H), 1.63 (m, 2H), 1.43 (m, 2H), 1.19 (d, J=6.7 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 207.98, 68.22, 43.68, 42.95, 29.12, 28.75, 19.22. GC–MS *m*/*z* (%): 101 (58), 83 (14), 59 (80), 43 (100).

4.4.15. 1,1′,2,2′-Tetramethyl-1,1′-bi(cyclopentyl) 19. ^{1}H NMR ($CDCl_3$) δ 1.83–1.72 (m, 2H), 1.65–1.45 (m, 8H), 1.38–1.26 (m, 2H), 1.10–0.99 (m, 2H), 0.92 (s, 6H), 0.89 (d, J=6.8 Hz, 3H). ^{13}C NMR ($CDCl_3$) δ 45.18, 38.42, 38.05, 36.22, 21.14, 15.28, 14.77. GC–MS *m*/*z* (%): 97 (100), 69 (22), 55 (73), 43 (58).

4.5. EPR analysis

The EPR spectra were recorded on samples in powdered form. Pure MTO and resins were studied as received. Heterogeneous catalysts **I–V** were prepared as previously described. The H_2O_2-treated samples were prepared by suspending the catalyst (1 g) in *t*-BuOH (30 mL), then H_2O_2 (5 equiv) was added and the suspension was maintained under stirring for 1 h. At the end, the catalyst was recovered by filtration and allowed to dry in air. For all samples, spectra were recorded at 25 °C on an X-band CW EPR Bruker EMX spectrometer. The g values were determined by standardisation with α,α′-diphenyl-β-picryl hydrazyl (DPPH), g=2.0036±0.0003. The spin concentration, expressed as spin/g of catalyst, was calculated with a ±10% accuracy by double integration of the resonance lines and referring the area under the absorption curve to that of the standard Bruker weak pitch (10^{13}±5% spin/cm); then the weight of sample filling 1 cm length of EPR cavity was determined. Care was taken in order to ensure that the sensitive part of the EPR cavity (1 cm length) was always full; no variations were observed in the density of samples. All the experimental spectra were fitted by the 6/9/91 DOS version of the SIM14S simulation program.

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