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Manganese 1,4,7-trimethyl-1,4,7-triazacyclononane complexes: Versatile catalysts for the oxidation of organic compounds with hydrogen peroxide

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Abstract

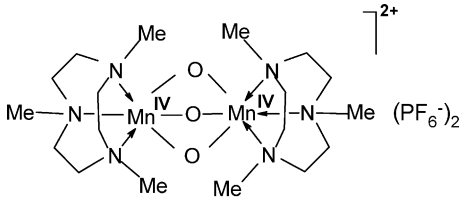
The oxidation of phenols, cinnamic acids and methyl aryl sulfides by hydrogen peroxide, using three catalyst systems, $[L_2Mn_2^{IV}(\mu\text{-}O)_3](PF_6)_2$, L = 1,4,7-trimethyl-1,4,7-triazacyclononane; $[LMn^{IV}(OMe)_3(PF_6)$; and $Mn^{II}/L/H_2O_2$, have been studied. The results from a combination of spectroscopic and kinetic studies, coupled with Hammett correlations and ^{18}O labelling experiments, suggest that with each system the active oxidant is an electrophilic, mononuclear oxo-manganese (V) species. The influence of additives that can act as co-ligands for the manganese species has been investigated, with a view to controlling the activity/selectivity of the active oxidant. The two-step, sulfide–sulfoxide–sulfone, oxidation shows an unusual switch in the philicity of the active oxidant from electrophilic in the first step to nucleophilic in the second. Mechanisms for the oxidations are proposed.

Keywords: Oxidation; Hydrogen peroxide; Catalysis; Manganese; 1,4,7-Trimethyl-1,4,7-triazacyclononane

1. Introduction

The traditional chlorine-based bleaching agents, chlorine and hypochlorite, used in aqueous systems can generate chlorinated by-products which are detrimental to the environment. Alternative approaches are of considerable interest both commercially and academically. Of these, the use of hydrogen peroxide has the advantages that the oxidant is cheap and clean; the by-products from its decomposition, water and dioxygen, are non-toxic [1,2]. However, unlike the chlorine-based compounds, hydrogen peroxide requires catalytic activation to be an effective oxidant at low temperatures (<80 °C) and to this end a large number of metal complexes have been designed, prepared and screened as catalysts.

Iron and manganese complexes, being less damaging to the environment than many other transition metal species, have been studied most thoroughly. Two manganese compounds, **1** and **2**, have shown significant potential and have been added to laundry detergents to activate the bleaching power of hydrogen peroxide [3,4]. The first, prepared originally as a model for some manganese enzymes, was added to Persil Power but was subsequently withdrawn when it was found to bring about colour fading and to attack cotton fabrics. The second is currently being tested in the laundry market in Asia.



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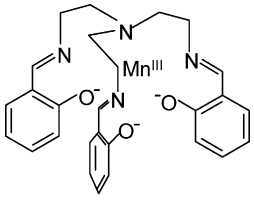

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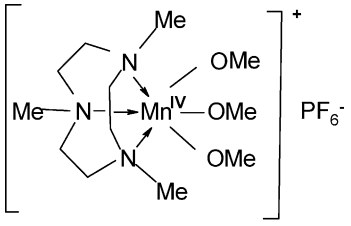
In parallel with the commercial aspects of developing catalysts for hydrogen peroxide activation, there has been much interest in exploring the potential of manganese complexes as catalysts for clean oxidations in organic synthesis. The dinuclear manganese(IV) TMTACN compound, **1** (TMTACN, 1,4,7-trimethyl-1,4,7-triazacyclononane), in particular, and the structurally related mononuclear complex **3** have been used to catalyse the oxidation of a wide range of organic functional groups by hydrogen peroxide. They are effective in alkene epoxidation [3] and dihydroxylation [5], alkane hydroxylation [6,7], and in the oxidation of benzyl alcohols [8], phenols [9,10] and sulfides [11–13].

A significant simplification of the catalytic systems, avoiding the need to prepare the complexes **1** and **3**, was reported by De Vos and Bein [14] who showed that a manganese(II) salt with TMTACN and H_2O_2 can be used to form the Mn(TMTACN) catalyst in situ. These Mn/TMTACN systems have proved very versatile; they can be used both in aqueous and organic solutions and they can be heterogenised [15–17]. Acetone is an excellent organic solvent for the oxidations as it is reported to minimise the unwanted and wasteful manganese-catalysed self-destruction of H_2O_2 to dioxygen and water [18].

A further refinement of the Mn/TMTACN systems has been the use of co-catalysts. De Vos et al. [19] showed that alkene epoxidations in acetonitrile are dramatically improved using oxalic acid/oxalate buffer and Berkessel and Sklorz [20] found ascorbic acid to be very effective. Feringa and co-workers [5] using complex **1** and methyl glyoxylate methyl hemiacetal in acetonitrile reported the first example of manganese-catalysed cis-dihydroxylation of alkenes.



(3)

The mechanisms of the oxidations described above are less well understood. It is considered likely that complexes **1** and **3** and the in situ system generate the same active oxidant and it is generally agreed, by analogy with the better characterised manganese porphyrin [21] and salen [22,23] systems, that the active oxidant in the reactions is a high valent manganese species and not a free radical, such as $HO^{\bullet}$. However, the precise nature of this species, as to whether it is an oxo-, peroxo-or hydroperoxo-manganese complex, and the role of the co-catalysts remain uncertain.

In this paper we use spectroscopic, kinetic and product studies, together with ^{18}O labelling experiments and Hammett correlations to show how the oxidation mechanisms with hydrogen peroxide catalysed by Mn/TMTACN systems depend on the structure of the substrate. For electron-rich phenols, cinnamic acids and sulfides, the results support the suggestion that the active oxidant, with catalysts **1** and **3** and the in situ system, is an electrophilic mononuclear oxo-manganese(V) species. With the phenols oxidation occurs by electron-transfer whereas with cinnamic acids and sulfides it involves oxygen-transfer. In marked contrast, in the oxidation of sulfoxides to sulfones, the mechanism involves nucleophilic attack by H_2O_2 on a manganese-sulfoxide complex.

2. Experimental

2.1. Materials

Unless otherwise stated, all chemicals were commercially available (Aldrich Chemical Co. Ltd., Sigma Chemical Co. Ltd., Lancaster Chemical Co. Ltd.) and were used without further purification. Deionised water was used in all experiments. All other solvents used were analytical grade. Hydrogen peroxide solution, 31%, w/w, (Fisons) was checked by iodometric titration. ^{18}O-labelled hydrogen peroxide (90 at.%), 2% w/w, and $H_2{}^{18}O$ (98 at.%) was obtained from Icon Isotopes. Manganese complex **1** was provided by C6 Solutions Ltd., 1,4,7-trimethyl-1,4,7-triazacyclononane (TMTACN) was from Unilever and C6 Solutions Ltd., naphthalene-1,8-diol was from Dr. J. Ragot and 3,3′,5,5′-tetra-*t*-butyl-2,2′-biphenol from Professor M. Nee.

Manganese complex **3** was prepared as described by Koek et al. [24]. 5,5′-Dichloro-2,2′-biphenol was obtained as reported previously [25].

2.2. Instrumentation

UV–vis spectra were obtained on Hewlett Packard 8452A and 8453 diode array spectrophotometers and analysed using a PC running Hewlett Packard A.02.05 UV–vis ChemStation software. Spectral deconvolution was carried out with Hewlett Packard Quant II software. Quartz cuvettes (1 cm pathlength) were used at all times. Electrospray mass spectra were recorded on an LCQ Finnigan MAT mass spectrometer. GC analyses used a Varian 3380 chromatograph with a flame ionisation detector and a Supelcowax 10 column (30 m × 0.25 mm, 0.25 μm film). HPLC analyses were carried out with isocratic elution (water/acetonitrile) using a Hewlett Packard Series II 1090 chromatograph, equipped with a UV–vis diode array detector and Phenomenex Spheroclone ODS2 column (15 cm × 4.6 mm, 5 μm).

2.3. Oxidation procedures

In the ESI-MS study of the oxidation of phenols, biphenols and aromatic diols, hydrogen peroxide (to give an initial concentration of 1×10^{-2} mol dm^{-3}) was added to a solution of the substrate (1×10^{-3} mol dm^{-3}) and manganese complex **1** (1×10^{-5} mol dm^{-3}) in aqueous borate buffer (pH 10.5):acetonitrile (9:1, v/v) at 60 °C. An aliquot of this reaction mixture was introduced into the mass spectrometer using a syringe pump.

The standard method for cinnamic acid epoxidations involved preparing a water:acetonitrile (1:1 v/v) solution containing, $MnSO_4{\cdot}4H_2O$ (3.13×10^{-5} mol dm^{-3}), TMTACN (9.38×10^{-5} mol dm^{-3}), additive (6.25×10^{-5} mol dm^{-3}) and

cinnamic acid (5×10^{-5} mol dm^{-3}). This was thermostatted at 25 °C and adjusted to a measured pH of 9.5 with aqueous sodium hydroxide. An aliquot (3 cm^3) was added to a cuvette and the reactions were initiated by the addition of H_2O_2, to give an initial concentration of 3.13×10^{-3} mol dm^{-3}, and followed by monitoring the disappearance of the absorbance of the cinnamic acid anion ($\lambda_{max} \sim 260$ nm).

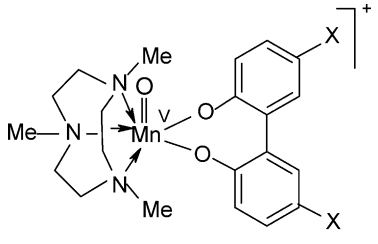
For ESI-MS analyses, aliquots were removed from the reaction mixtures at selected intervals and injected into the mass spectrometer.

The standard procedure used for sulfide and sulfoxide oxidations involved thermostatting (25 °C) a stirred solution of substrate (1.5×10^{-4} mol) and manganese complex **1** (3.7×10^{-7} mol) in acetone (5 cm^3) and adding hydrogen peroxide (2.2×10^{-3} mol, 31%, w/w) to initiate the reaction. Aliquots (0.18 cm^3) were removed at selected time intervals and diluted 386-fold with acetonitrile and analysed by UV–vis spectroscopy.

3. Results and discussion

3.1. Phenol oxidation

Our initial studies on oxidations with hydrogen peroxide, catalysed by Mn/TMTACN systems, used phenols, in aqueous base (pH 10.5) [9,10]. These substrates and conditions were selected to model the bleaching of natural phenolic stains in domestic laundry. The results showed that complex **1** catalyses the rapid one-electron oxidation of electron-rich phenols to phenoxyl radicals which couple to give bi-and poly-phenols and by further oxidation diphenoquinones (reactions (1) and (2)). EPR spectroscopy and positive ion ESI-MS were used to show that the dinuclear manganese(IV) complex, **1**, is reductively cleaved to give mononuclear species and the latter are the active components of the catalytic cycle. ESI-MS also revealed the presence of a mixed O = Mn^V/TMTACN/biphenol complex (**4**, X = OMe or OEt) in the oxidation of 4-methoxy-and 4-ethoxy-phenol. The same complex was also obtained when **1** was replaced by the mononuclear manganese(IV) compound, **3**, or by the in situ system [Mn(II)/TMTACN].



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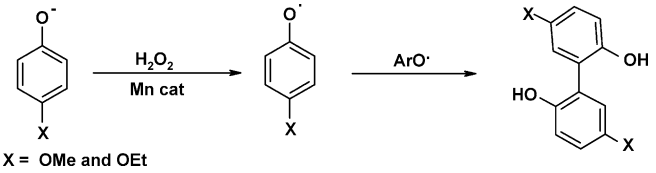

X = OMe and OEt

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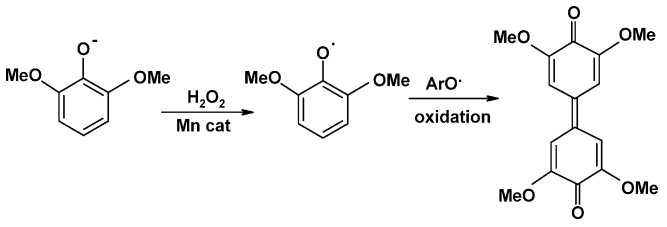

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It has been suggested that the effective co-catalyst oxalate, introduced first by De Vos et al. [19], functions by forming a manganese/oxalate chelate in a mixed Mn(TMTACN)(oxalate) complex [26]. The results with phenols above opened up the opportunity to test this hypothesis by preparing a range of O = Mn^V/TMTACN/co-ligand complexes to tune the reactivity/stability of the oxo-manganese(V) species. To this end we have used ESI-MS to screen the reactions of a selection of phenols, biphenols and aromatic diols with **1** and H_2O_2 (in aqueous base, pH 10.5), for the formation of Mn(TMTACN)(co-ligand) complexes. (It should be noted that the monophenols require oxidation to biphenols before they can participate as chelate ligands.) Apart from differences in the electronic properties of the substituents on the phenols, the substrates were chosen to give a range of chelate ring sizes with manganese; 5-membered (catechol), 6-membered (naphthalene-1,8-diol) and 7-membered with (2,2′-biphenols). The results are shown in Table 1.

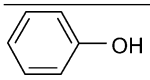
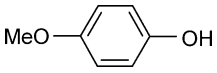
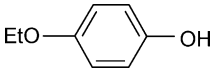
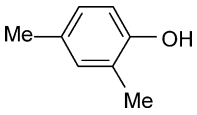
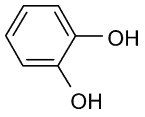
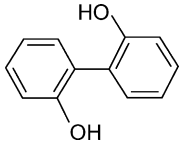
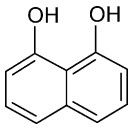
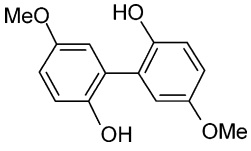
With all the substrates, except phenol which is presumably not oxidised to 2,2′-biphenol, ESI-MS analysis revealed the formation of a species with *m/z* corresponding to the expected manganese(III)(TMTACN)(chelate). However, only with the biphenols and the electron-rich phenols was the species with *m/z* corresponding to O = Mn^V(TMTACN)(chelate) observed. With biphenol a small peak with the expected *m/z* 410 was detected but this required higher concentrations of H_2O_2 than the other substrates. Clearly stabilisation of the high valent oxo-manganese species requires good electron donor ligands. Catechol readily forms the Mn^{III}(TMTACN)(catecholate) complex, and a species with *m/z* 271 (negative ion ESI-MS) which we assign to Mn^{III}(catecholate)$_2$, but its ease of oxidation appears to prevent the formation of O = Mn^V(TMTACN)(catecholate). Likewise naphthalene-1,8-diol is destroyed and no mixed ligand oxo-manganese(V) species was detected.

We conclude that biphenols and aromatic diols, capable of reductively cleaving the dinuclear manganese complex **1** and acting as chelate ligands, form mixed Mn^{III}(TMTACN)(chelate) species. These are oxidised by hydrogen peroxide to the corresponding O = Mn^V complex which can be detected by ESI-MS if the ligand is a good electron-donor and not too readily oxidised (Scheme 1).

3.2. Epoxidation of cinnamic acid

We decided to explore further the role of additives in oxidations catalysed by Mn/TMTACN systems, by investigating the epoxidation of cinnamic acids. For these reactions we employed the in situ system rather than catalyst **1** to circumvent the need to cleave the dinuclear manganese complex to generate the active

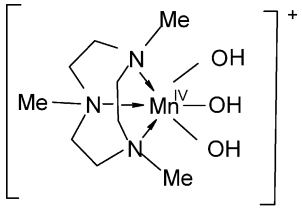
Table 1
Mn^{III}-and O = Mn^{V}(TMTACN)(co-ligand) complexes detected by positive ion ESI-MS in the reactions of phenols, diols and biphenols with H_2O_2 in the presence of **1**

Substrate	Mn^{III}(L)(co-ligand)	*m/z*	O = Mn^{V}(L)(co-ligand)	*m/z*
	×	–	×	–
	√	470	√	486
	√	498	√	514
	√	466	√	482
	√	334	×	–
	√	410	(√)	426
	√	384	×	–
	√	470	√	486

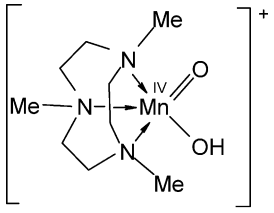
mononuclear species. The reactions were carried out at 25 °C in 50:50 v/v, aqueous acetonitrile (pH 9.5), using the catalyst, TMTACN and additive in the molar ratios 1:3:2 and were monitored by following the disappearance of the UV absorption of the cinnamic acid anion. The additives selected covered a range of compounds, all of which have the potential to act as chelating agents. To avoid possible problems from catalyst degradation complicating the kinetic study, the catalyst turnovers were kept low by using a substrate to catalyst ratio of 1.6:1. Virtually all the reactions followed excellent first-order kinetics, although a few showed an initial lag phase followed by a first-order reaction.

From their effect on the rate of cinnamic acid epoxidation, the additives can be divided into three groups (Fig. 1).

Positive ion ESI-MS studies detected a manganese/TMTACN/co-ligand species only in the reaction using biphenol as the co-ligand. This was the Mn^{III}(TMTACN)(biphenolate) species previously observed in the study described above. However, two ions with *m/z* 277 and 259 (assigned to complexes **5** and **6** [27]) were common to all the oxidation mixtures.



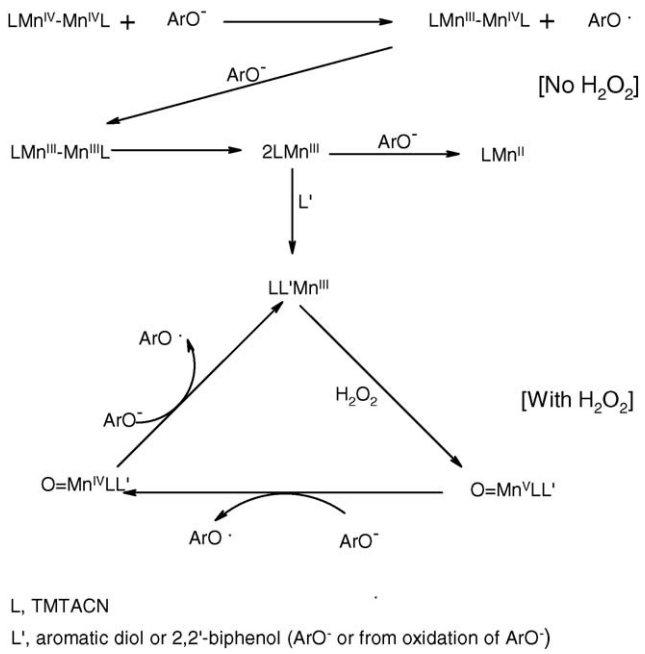
(**5**) *m/z* 277



(**6**) *m/z* 259

From the above results we conclude that:

(a) The rate-retarding additives reduce the rate of epoxidation either by stabilising the oxo-manganese(V) species as an



Scheme 1. The reaction of phenols with complex **1** and hydrogen peroxide in aqueous solution, pH 10.5.

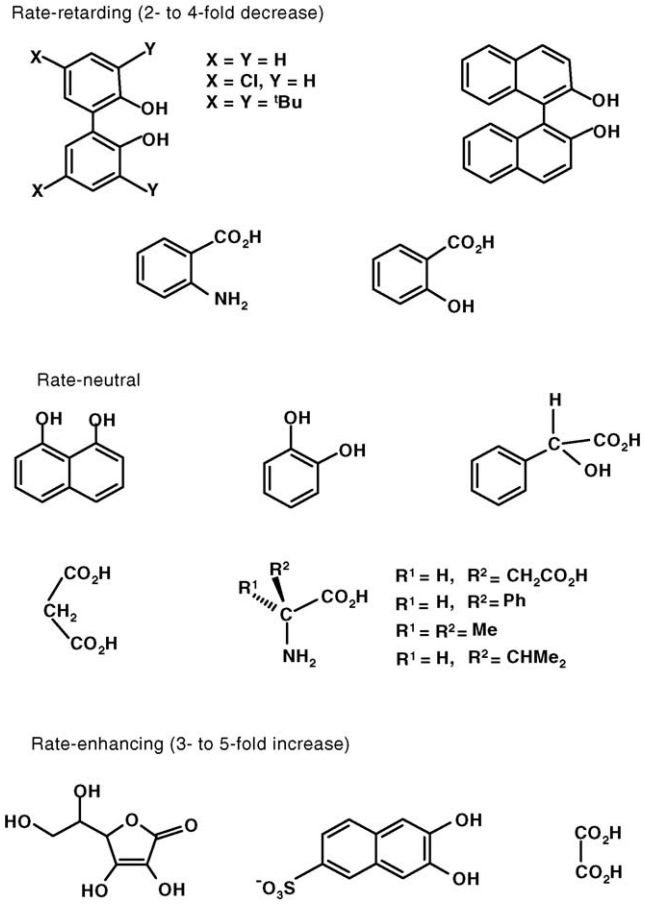
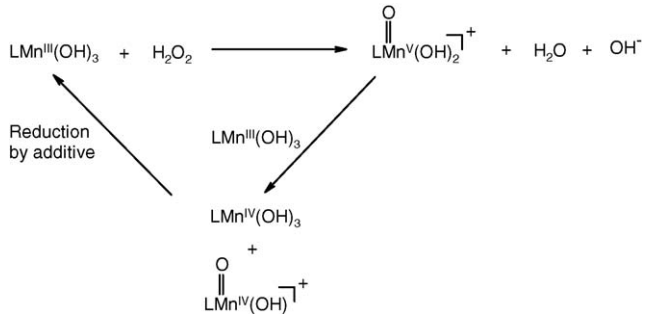


Fig. 1. Additives used in the epoxidation of cinnamic acid by hydrogen peroxide catalysed by $MnSO_4$ and TMACN in aqueous acetone, pH 9.5.



Scheme 2. Catalytic cycle involving the reduction of manganese(IV) species.

$O = Mn^V$(additive) complex which makes it a less effective oxidant and/or by acting as competitive substrates.

(b) The rate-neutral additives do not participate in the cinnamic acid epoxidations.

(c) The three rate-enhancing additives function either by complexing and activating the active oxidant or by reducing the relatively unreactive manganese(IV), formed by comproportionation between manganese(V) and manganese(III), to give manganese(III) species needed for the catalytic cycle (Scheme 2). Oxalate which has been reported previously to improve the oxidising efficiency of Mn/TMACN/H_2O_2 systems [19] was the most efficient additive (five-fold rate increase) and was used in all subsequent studies with cinnamic acids.

To obtain more information about the epoxidation mechanism we studied the influence of substituent electronic effects on the rate of epoxidation using cinnamic acid and six substituted derivatives. The rate data gave a good linear Hammett plot (correlation coefficient 0.979) against σ^- with a ρ-value of -0.63 ± 0.05. This confirms the expected electrophilic character of the oxidant and the value compares well with those reported for the epoxidation of styrenes using manganese(III) tetraphenylporphyrin ($\rho - 0.41$ [28]) and manganese(III) salen ($\rho - 0.3$ [29]) systems. Both the latter oxidations are believed to involve $O = Mn^V$ species as the active oxidant.

The ρ-value from the present study indicates that a small positive charge develops on the substrate in the epoxidation transition state. This is consistent with either an oxygen-or an electron-transfer mechanism. The latter alternative was eliminated using $H_2{}^{18}O_2$ (90 at.%) to investigate the origin of the oxygen in the epoxide. Negative ion ESI-MS showed that the epoxide contained 92.8% of the label. An electron-transfer mechanism

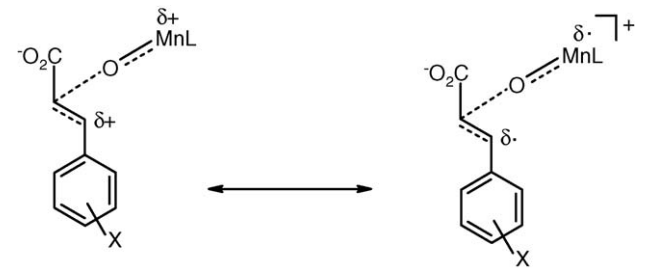
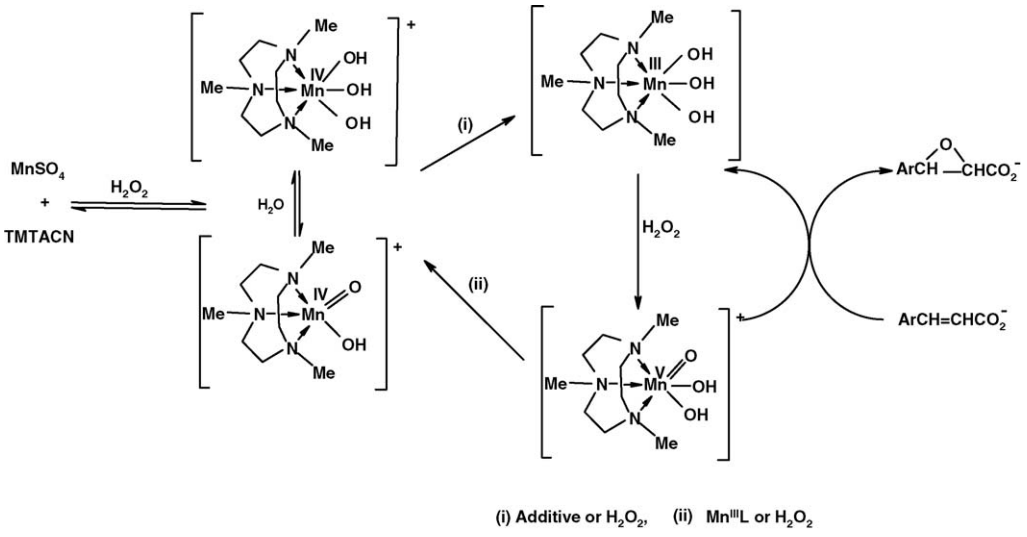


Fig. 2. Transition state for cinnamic acid epoxidation by $O = Mn^V$(TMTACN) species.



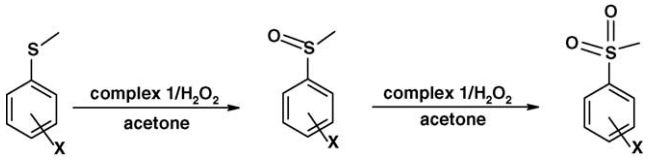
Scheme 3. Mechanism of cinnamic acid epoxidation by the in situ Mn^{II}/TMTACN/H_2O_2 system.

would generate an alkene radical cation that would be trapped by water and further oxidation of the resultant β-hydroxyalkyl radical would give unlabelled epoxide [30]. We propose oxygen-transfer between the $O=Mn^{V}$ species and cinnamic acid occurs either with an early transition state or one which has significant radical character (Fig. 2). The overall mechanism we propose for the in situ Mn/TMTACN/H_2O_2 system is shown in Scheme 3.

3.3. Sulfide oxidation

Sulfide oxidation is the normal synthetic route to sulfoxides and sulfones which have important industrial and biological applications [31]. Consequently there is much interest in developing catalytic methods to bring about these transformations, especially if these are clean and selective. There have been three previous brief reports of sulfide oxidation with hydrogen peroxide catalysed by Mn/TMTACN systems [11–13]. However, since none of these included mechanistic investigations we decided to include sulfide oxidation in the present study.

Initial investigations with five methyl 4-substituted phenyl sulfides showed that they are readily oxidised in acetone, by hydrogen peroxide catalysed by the dinuclear manganese complex **1**, to a mixture of aryl methyl sulfoxide and sulfone (Scheme 4). The reactions were followed by removing aliquots at regular time intervals, diluting them with acetonitrile and recording their UV–vis spectra (see for example Fig. 3). The spectra were readily deconvoluted to give reaction profiles showing the disappearance of sulfide and the formation of sulfoxide and sulfone, initial rate data and maximum yields of sulfoxides (see for example Fig. 4). The reactions of sulfoxides to give sulfones



Scheme 4. Oxidation of aryl methyl sulfides to sulfoxides and sulfones.

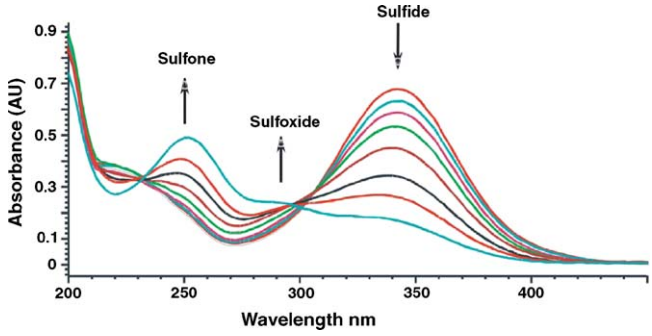


Fig. 3. Change of UV–vis spectrum of methyl 4-nitrophenyl sulfide reaction mixture with time.

were carried out under identical conditions and the spectra were followed and analysed in the same way.

Substituent electronic effects on the initial rates of sulfide and sulfoxide oxidation were analysed using the Hammett equation. For sulfides, the plot of log relative rate data against σ^+ gives a good linear correlation ($r=0.987$) and a negative ρ-value of -0.28 ± 0.01 (Fig. 5). However, a comparable anal-

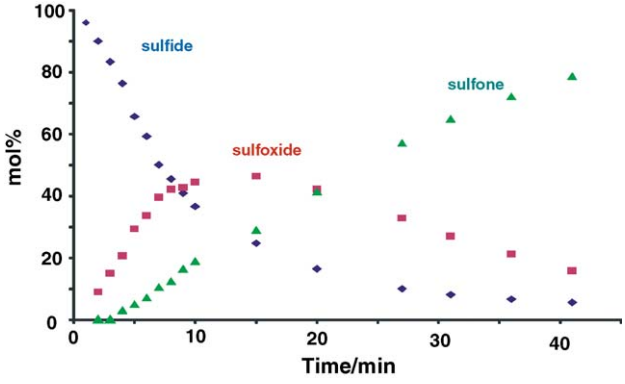


Fig. 4. Reaction profile for the oxidation of methyl 4-nitrophenyl sulfide using H_2O_2 (15 equiv.) and complex 1 (0.25 mol%) in acetone at 25 °C. ◆ sulfide, ■ sulfoxide, ▲ sulfone.

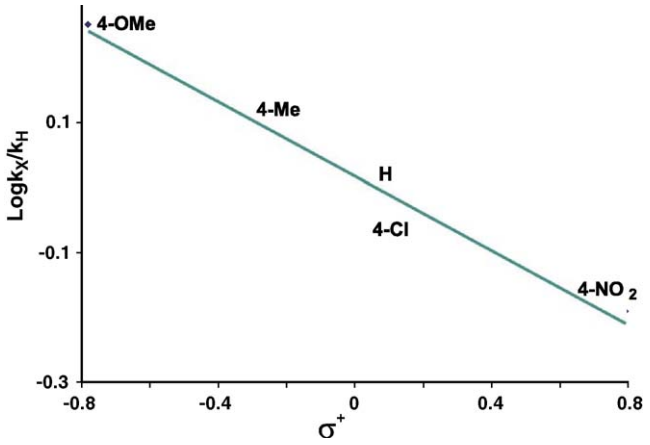


Fig. 5. Hammett plot for the oxidation of methyl 4-substituted phenyl sulfides using H_2O_2 (15 equiv.) and complex **1** (0.25 mol%) in acetone at 25 °C.

ysis of the data from the oxidation of sulfoxides to sulfones, performed under identical conditions, has a positive reaction constant ($\rho = 0.2 \pm 0.01$, $r = 0.990$) (Fig. 6). The change in the sign of the ρ-value indicates a change in the philicity of the active oxidant from electrophilic for the sulfides to nucleophilic for the sulfoxides. Huang and Espenson [32] noted, in their study on the oxidation of sulfines (thioketone *S*-oxides) with H_2O_2, catalysed by methyltrioxorhenium, that the active oxidant changed from being electrophilic for electron-rich to nucleophilic for electron-deficient sulfines. Bonchio et al. [33] found that sulfoxide oxidation, using Ti^{IV}-homochiral *C*3 symmetric trialkanolamine-hydroperoxo complexes, can occur by either electrophilic or nucleophilic mechanisms. In this study, however, the active oxidant is uniquely electrophilic for sulfides and nucleophilic for sulfoxides .

As a consequence of the change in the philicity of the oxidant, the selectivity for sulfoxide over sulfone in these reactions is lower than is observed when both steps occur by electrophilic attack, typically $k_{sulfide}/k_{sulfoxide} \approx 10^3$ [34]. Furthermore, the selectivity is greatest for electron-rich substrates and decreases as the substituent becomes more electron-withdrawing (Table 2).

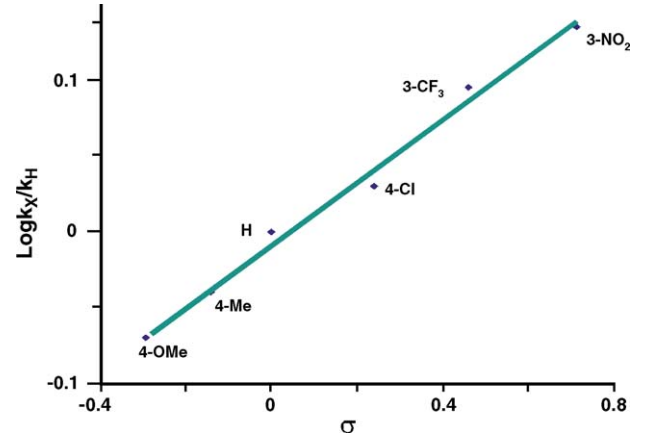
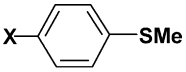


Fig. 6. Hammett plot for the oxidation of methyl 3-and 4-substituted phenyl sulfoxides using H_2O_2 (15 equiv.) and complex **1** (0.25 mol%) in acetone at 25 °C.

Table 2
Maximum yield of sulfoxide and yield of sulfone in the oxidation of methyl 4-substituted phenyl sulfides with H_2O_2 (5 equiv.) catalysed by complex **1** (0.25 mol%) in acetone at 25 °C

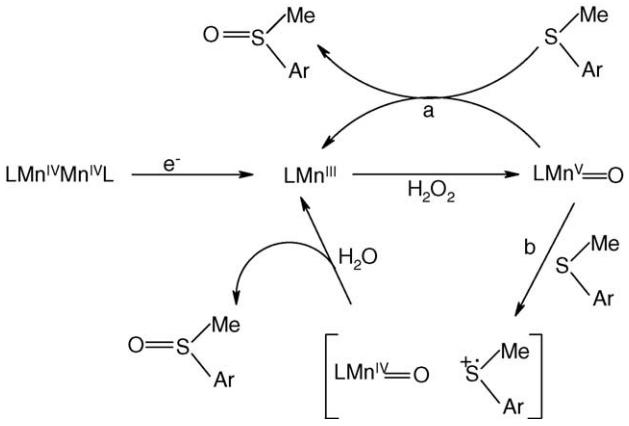


X =	Maximum sulfoxide yield (%)	Sulfone yield (%)	Sulfoxide/sulfone ratio
MeO	71	12	5.9
Me	69	13	5.3
H	67	13	5.2
Cl	62	15	4.3
NO_2	47	22	2.1

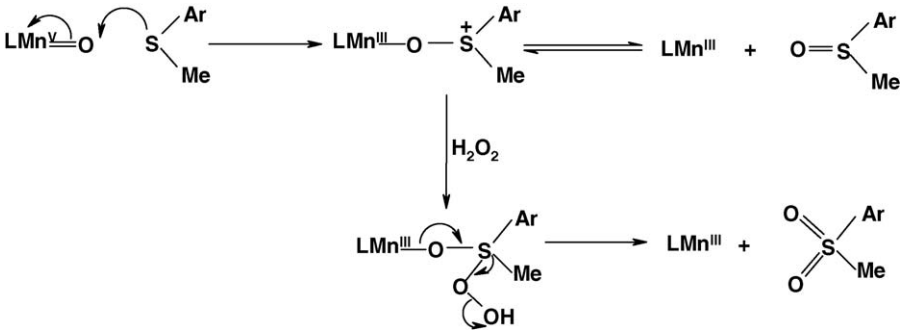
Positive ion ESI-MS studies on the sulfide oxidations showed that complex **1** is reductively cleaved, via the dinuclear manganese(III/IV) species (*m*/*z* 500) seen in phenol oxidations [10], to give the mononuclear manganese(IV) species (*m*/*z* 259 and 277) detected in the cinnamic acid oxidations above.

To determine the origin of the oxygens in the sulfoxide and sulfone, methyl phenyl sulfide was oxidised using $H_2{}^{18}O_2/H_2{}^{16}O$ and $H_2{}^{16}O_2/H_2{}^{18}O$. With labelled H_2O_2 (90 atom%) the isotopic incorporation in sulfoxide and sulfone was 96.5 and 89.2%, respectively, whereas with labelled water (98% enriched) it was 8.6 and 10.4%, respectively. These results show that the large majority of the oxygen in the products arises from hydrogen peroxide.

Two alternative mechanisms satisfy the ρ-value for the oxidation of sulfide by the oxo-manganese(V) species, oxygen-transfer [path (a)] and electron-transfer [path (b)] (Scheme 5). Based on the ^{18}O studies, we believe that the main (if not the only), oxidation route (see below) is oxygen-transfer, path (a), since, as noted above for cinnamic acid oxidations, electron-transfer would lead to unlabelled oxygen in the sulfoxide. This conclusion is supported by a competitive oxidations which showed that *t*-butyl methyl sulfide is >10-times more reactive than methyl phenyl sulfide. Two-electron oxygen-transfer is known to occur more rapidly with dialkyl sulfides whereas single electron-transfer is faster with aryl sulfides [35].



Scheme 5. Alternative pathways for the oxidation of sulfides to sulfoxides.



Scheme 6. Overall mechanism for the oxidation of aryl methyl sulfides to sulfoxides and sulfones with H_2O_2 catalysed by complex **1**.

Table 3
The effect of solvent and co-catalyst on the maximum yield of sulfoxide and yield of sulfone in the oxidation of methyl 4-nitrophenyl sulfide with H_2O_2 (5 equiv.) catalysed by complex **1** (0.25 mol%) at 25 °C

Solvent	Co-catalyst	Max sulfoxide yield (%)	Yield sulfone (%)	Sulfoxide/sulfone ratio
MeCOMe	–	47	22	2.1
MeCN	–	55	14	3.9
MeCN	$MeCO_2H$	60	11	5.5
MeCN	$MeCO_2^-Na^+$	70	8	8.8

The small amount of oxygen in the sulfoxide (ca. 10%) that originates from water could arise from a minor electron-transfer pathway (Scheme 5, path (b)) or from a small amount of oxygen exchange in the oxo-manganese(V) species. The latter reaction, which occurs by protropy with coordinated water, has been observed previously in oxidations with oxo-manganese(V) porphyrins [36,37] and salens [32].

We propose the mechanism in Scheme 6 to account for the switch in philicity of the active oxidant. Thus the manganese(III)TMTACN-sulfoxide complex formed in the first oxidation is in equilibrium with free sulfoxide. In the complexed form it is activated to nucleophilic attack by hydrogen peroxide. It is noteworthy that in the absence of catalyst no reaction occurs between the sulfoxide and hydrogen peroxide.

On the basis of the mechanistic rationale in Scheme 6, we explored the possibility of improving the selectivity for sulfoxidation in these oxidations by shifting the manganese(III)(TMACN)-sulfoxide equilibrium in favour of manganese(III)(TMTACN) and free sulfoxide. For this study we chose methyl 4-nitrophenyl sulfide with the lowest sulfoxide to sulfone ratio in Table 2 and the results are shown in Table 3.

Changing the reaction solvent from acetone to acetonitrile increased the maximum yield of sulfoxide from 47 to 55% and almost doubled the sulfoxide:sulfone ratio. We interpret this change in selectivity in terms of acetonitrile competing with the sulfoxide for the manganese-centre thereby discouraging the further oxidation of the sulfoxide.

The selectivity was further improved by the addition of acetic acid or sodium acetate as a co-catalyst giving a maximum yield of sulfoxide of 60 and 70%, respectively. We believe that the co-catalysts, by acting as oxidatively stable ligands for the manganese, compete with the sulfoxide and suppress sulfone formation. The greater efficiency of the latter co-catalyst may be attributed to Na^+ binding to the sulfoxide.

4. Conclusions

1. The manganese complexes, **1**, **2** and the in situ system (Mn^{II}/TMTACN/H_2O_2), are versatile catalysts for the oxidation of a wide range of organic functional groups by the clean oxidant H_2O_2.
2. The reactivity of the catalysts and the selectivity of the oxidations can be tuned by the use of additives which act as co-ligands for the manganese or reducing agents that regenerate manganese(III) from relatively unreactive manganese(IV).
3. Experimental evidence suggests that, with all three catalytic systems, the majority of substrates are oxidised by an electrophilic oxo-manganese(V) species, by electron-transfer, if the substrates oxidation potential is sufficiently low, or alternatively by oxygen-transfer.
4. With some substrates, such as sulfoxides, oxidation can proceed by nucleophilic attack by hydrogen peroxide on a manganese(III)(TMTACN)-substrate complex. Thus in the oxidation of sulfides to sulfones there is an unusual switch in philicity of the active oxidant from electrophilic in the first step to nucleophilic in the second.

Acknowledgements

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