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A mechanistic study of the epoxidation of cinnamic acid by hydrogen peroxide catalysed by manganese l,4,7-trimethyl-l,4,7-triazacyclononane complexes

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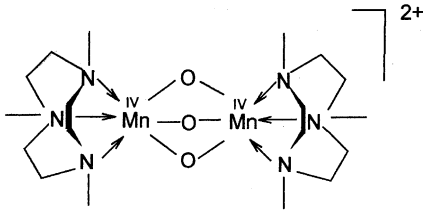
Abstract

l,4,7-Trimethyl-l,4,7-triazacyclononane (TMTACN), $MnSO_4$ and H_2O_2, in basic aqueous acetonitrile, is an effective system for the epoxidation of cinnamic acid. The influence of a selection of organic additives, potential co-ligands for the manganese species, on the reactions has been studied by UV–vis spectroscopy and ESI-MS. The mechanism of the most efficient system, with added oxalic acid, has been investigated in more detail using cinnamic acid and seven of its 3- or 4-substituted derivatives. A Hammett correlation of rate data shows that the active oxidant is electrophilic (ρ value −0.63). Oxygen (^{18}O) labelling experiments reveal that H_2O_2 and not H_2O is the source of the oxygen in the epoxide. Possible mechanisms for the reactions are discussed.

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

1. Introduction

The excellent bleach-enhancing properties reported for the dinuclear manganese 1,4,7-trimethyl-l,4,7-triazacyclononane (TMTACN) complex **1** in aqueous hydrogen peroxide solution [1] has led to considerable interest in the potential of manganese complexes of cyclic triamines as oxidation catalysts. This research has revealed that manganese TMTACN complexes are active catalysts in the oxidation of alkenes [1–7], alcohols [7,9], phenols [10–12], thioethers [13,14], alkanes and aralkanes [15–18], azo dyes [19] and other compounds [12,14,20]. Furthermore, the oxidations can be carried out in aqueous or organic solution with a preformed manganese complex or by generating the catalyst in situ from a manganese(II) salt, TMTACN and hydrogen peroxide. As a further elaboration the catalysts can be heterogenised by covalent binding to silica [6,21] or by encapsulation in a zeolite [22].



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Attempts to optimise the synthetic potential of these systems have concentrated on using the clean oxidant H_2O_2 and minimising the unwanted catalase activity of the manganese complexes. The best results have been obtained using sub-ambient temperatures with acetone as solvent or using acetonitrile in the presence of oxalate [5], ascorbic acid [7], squaric acid [7] or the methyl hemiacetal of methyl glyoxylate [8]. The role of the co-catalysts in these oxidations is unclear although their enhancing effect may arise from their reducing properties or from their ability to ligate to manganese [11,18].

Our work on the oxidation of phenols and azo dyes by hydrogen peroxide, in aqueous solution catalysed by **1**, suggests that the dinuclear manganese complex is converted into

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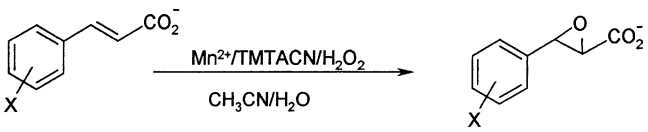
a catalytically active mono-nuclear manganese species; EPR spectroscopy, electrospray mass spectrometry (ESI-MS) and product studies support a single electron-transfer mechanism for these oxidations [10,11,19]. The ESI-MS identification of a mononuclear oxo-manganese(V) complex in the oxidation of electron-rich phenols [11] has led us to propose a catalytic cycle for phenol oxidation that is analogous to that of peroxidases [23]. However, for substrates such as alkenes and, in particular electron-deficient alkenes, that are not normally susceptible to electron-transfer oxidation an alternative oxidation pathway must be available.

In this paper we report our mechanistic studies on the epoxidation of cinnamic acids in basic aqueous acetonitrile solution with hydrogen peroxide and manganese/TMTACN complexes, generated in situ from $MnSO_4$/TMTACN/H_2O_2 (a catalytic system used previously by De Vos and Bein [2,3]) (Reaction 1). We also explore the effect of additives (potential co-ligands) on the performance of these systems. We propose that the epoxidations occur by oxygen-transfer from an electrophilic oxo-manganese(V) complex to the alkene.



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% enriched), 2% w/w, was obtained from Icon Isotopes. l,4,7-Trimethyl-l,4,7-triazacyclononane (TMTACN) was provided by R. Hager (Unilever, Holland), naphthalene-1,8-diol by Dr. J. Ragot and 3,3′,5,5′-tetra-*t*-butyl-2,2′-biphenol by Professor M. Nee.

5,5′-Dichloro-2,2′-biphenol was prepared by oxidative coupling of 4-chlorophenol using the methodology of Sartori et al. [24]. The phenol (50 mmol) in nitromethane (50 cm^3) was added to $AlCl_3$ (50 mmol) dissolved in the same solvent (50 cm^3) and the solution was stirred under nitrogen. After 30 min, $FeCl_3$ (50 mmol) in CH_3NO_2 (50 cm^3) was added to the reaction mixture and the stirring was continued for 5 h at room temperature before 2 M HCl (150 cm^3) was added and the biphenol was extracted with CH_2Cl_2 (3 × 150 cm^3). The organic phase was dried ($MgSO_4$), filtered, concentrated under vacuum and the residue was purified by flash chromatography (silica gel 60, ICN Biomedicals GmbH) using hexane/ethyl acetate as the eluant. ES-MS: *m*/*z* 254 (100) 256 (65) 258 (11). ^{1}H NMR (DMSO) 270 MHz: δ 7.20 (d, 2H, *J* 1.5 Hz, ArH), 7.16 (dd, 2H, *J* 8.5 and 1.5 Hz, ArH), 6.90 (d, 2H, *J* 8.5 Hz, ArH).

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. Quartz cuvettes (1 cm pathlength) were used at all times. Electrospray mass spectra were recorded on an LCQ Finnigan MAT mass spectrometer. ^{1}H NMR spectra were measured on a Jeol JNM-EX270 (270 MHz) spectrometer and were referenced against tetramethylsilane (TMS).

2.3. Oxidation procedure

The general method involved making up solutions, to give the following concentrations: $MnSO_4{\cdot}4H_2O$, 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} in H_2O and CH_3CN, 1:1 v/v. The solutions were thermostatted at 25 °C, adjusted to a measured pH of 9.5 with aqueous sodium hydroxide and a measured volume (3 cm^3) was added to a cuvette 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 (λ_{max} ∼260 nm).

The reaction conditions used in the ESI-MS experiments were the same as those above. The procedure involved taking aliquots of the reaction mixture at selected intervals and injecting them into the mass spectrometer. Positive ion ESI-MS was used to detect the manganese complexes, ligand and ligand oxidation products and negative ion ESI-MS to detect the substrates and their oxidation products.

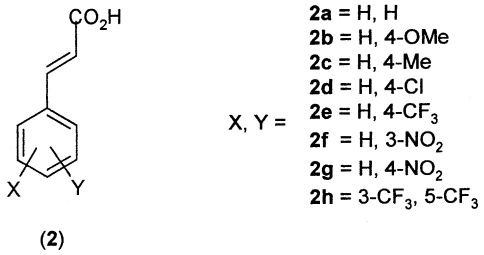
3. Results and discussion

3.1. The oxidation system and methods

Eight cinnamic acids (**2a**–**h**) were selected as substrates for this study on alkene epoxidation. These substrates are readily soluble in the basic reaction conditions and allow the possibility of studying the electronic effects, of substituents on the phenyl ring, on the rate of oxidation.

The course of the epoxidations was monitored by UV–vis spectroscopy and ESI-MS. Loss of the double bond through epoxidation leads to the disappearance of the band at −260 nm, providing a convenient method to follow the kinetics of the oxidation.

Negative ion ESI-mass spectra of aliquots removed from the reaction mixtures at selected times show that during the course of the reaction the peak corresponding to the



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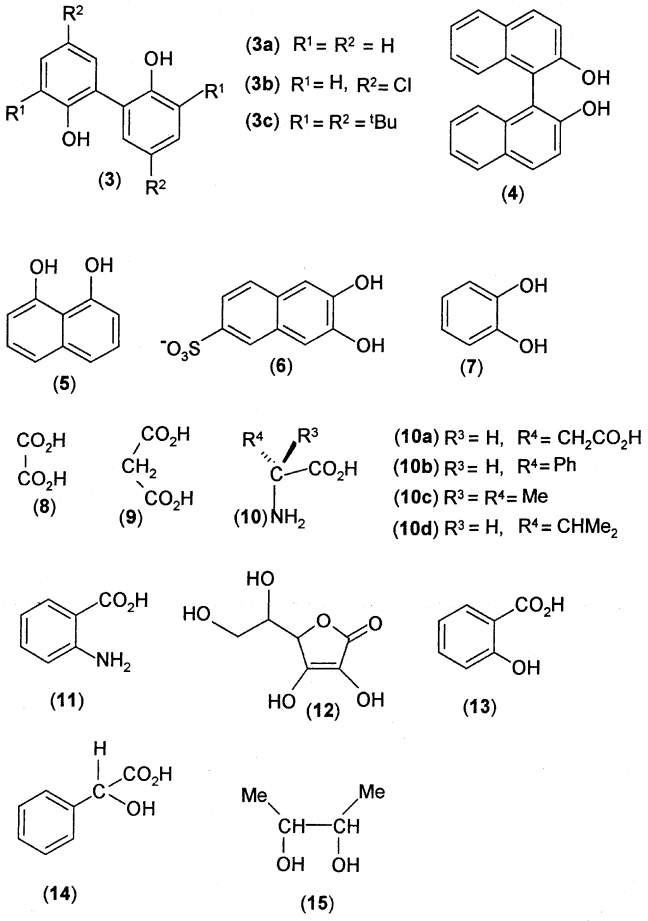
cinnamate anion decreases with concomitant formation of the epoxide as the sole product (for the parent compound, cinnamic acid, these ions have *m*/*z* 147 and 163, respectively).

The oxidations were carried out at 25 °C in aqueous acetonitrile (50:50, v/v). The reactions are catalytic in manganese; however, in this study the catalyst turnovers, based on cinnamic acid epoxidation, were intentionally kept low to simplify the kinetic analysis and to avoid any potential problems that might arise from catalyst degradation in a multiple turnover process. The reagent concentrations selected were: [$MnSO_4$], 3.13×10^{-5} mol dm^{-3}; [TMTACN], 9.38×10^{-5} mol dm^{-3}; [cinnamic acid], 5×10^{-5} mol dm^{-3}; and [H_2O_2], 3.13×10^{-3} mol dm^{-3} (giving a ratio of Mn:TMTACN:substrate:oxidant, 1:3:1.6:100). Initial studies showed that base was needed for the system to be active and NaOH was added to the reactions to give a measured pH of 9.5.

As part of this study, the epoxidation of cinnamic acid was also carried out in the presence of a selection of additives, **3**–**15** (6.25×10^{-5} mol dm^{-3}) most of which have the potential to act as chelating co-ligands for the manganese species. These include biphenols, dicarboxylic acids, amino acids, hydroxy acids and diols. In previous studies we have shown that $MnSO_4$/TMTACN/H_2O_2 in the presence of 5,5′-dimethoxy-2,2′-biphenol forms the relatively stable complex, O=Mn^V(TMTACN)(biphenol) [11,23]. We argued that by the correct choice of biphenol additive it might be possible to use substituents to control the activity of this high valent manganese species. The naphthalene diols and catechol, whose oxidations we have also studied [23], were included in this study for comparison with the biphenols. Oxalic acid (**8**) has been shown by De Vos et al. [5] to be a potent epoxidation activator for the Mn/TMTACN/H_2O_2 system, although the origin of this effect remains unresolved. Malonic acid was also included for comparison. Berkessel and Sklorz [7] have explored the use of chiral amino acids with the Mn/TMTACN/H_2O_2 system in asymmetric epoxidations, and additives **10a**–**d** and **11** were included in this study as potential nitrogen/oxygen ligands. Ascorbic acid (**12**) is a known enhancer of epoxidation by the Mn/ATMTACN/H_2O_2 system [7]; hydroxy acids **13** and **14** and diol **15** were included for comparison with the dicarboxylic and amino acids.



3.2. Kinetic studies on epoxidation of cinnamic acid

Control experiments using H_2O_2 with either $MnSO_4$ or TMTACN or any of the additives showed that none of these systems oxidises cinnamic acid. Furthermore, $MnSO_4$ with oxalic acid and H_2O_2, in the absence of TMTACN, is also inactive. However, the complete system, H_2O_2 with $MnSO_4$ and TMTACN, brings about the rapid epoxidation of cinnamic acid and a typical UV–vis profile is shown in Fig. 1.

The absorbance time plots (λ 260 nm) from the above epoxidation system and from those including additives **3**–**15** were recorded. The large majority of these followed excellent pseudo-first-order kinetics (see, for example, Fig. 2). With a few of the additives, the reactions showed an initial lag phase that was followed by a first order decay of the cinnamic acid absorbance: this behaviour is similar to that observed in the oxidation of azo dyes by hydrogen peroxide catalysed by the manganese TMTACN complex **1** [19].

Based on their effect on the rate of cinnamic acid epoxide, the additives can be divided into three groups. First, the biphenols, salicylic and anthranilic acid led to a decrease (two- to four-fold) in oxidation rate compared with the con-

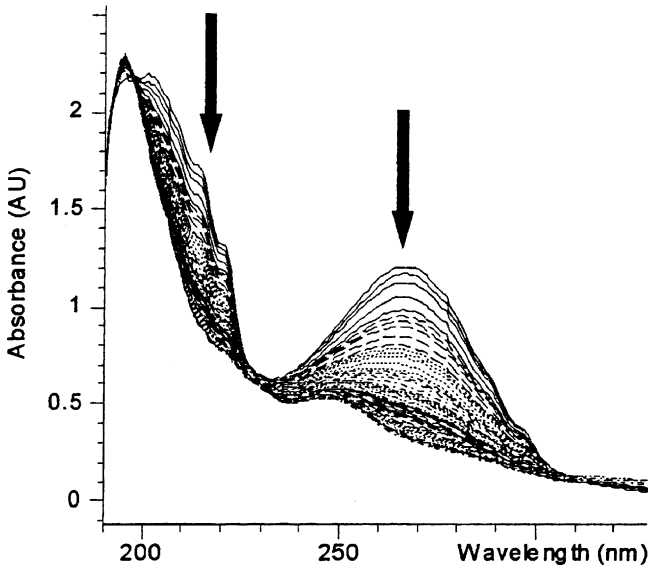
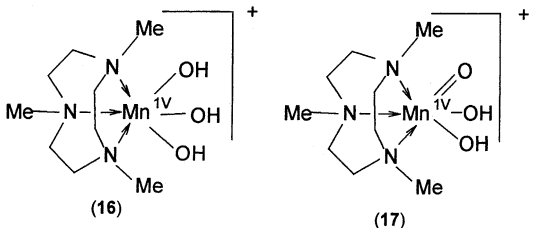


Fig. 1. UV–vis spectra, taken at 30-s intervals, during the oxidation of cinnamic acid with H_2O_2 and Mn/TMTACN complexes in H_2O:CH_3CN (1:1) at pH 9.5 and 25 °C.

trol reaction with no additive present. Secondly, the diols (except naphthalene-2,3-diol-6-sulfonate), aliphatic amino acids and malonic and mandelic acid had a negligible effect on the reaction. Thirdly, oxalic acid, ascorbic acid and naphthalene-2,3-diol-6-sulfonate gave a three- to five-fold increase in the rate of epoxidation, with oxalic acid being the most effective additive.

3.3. ESI-MS studies on the manganese species formed during the cinnamic acid epoxidations

To obtain further information about the oxidation mechanism, the build-up and decay of manganese species in the reaction mixtures over a typical reaction period of 30 min were investigated by positive ion ESI-MS. These analyses of the oxidation mixtures in the absence of additives showed the build-up of species with *m*/*z* 277 and 259 in the first few minutes of the reaction which then decayed and finally disappeared after 30 min. Other ions with *m*/*z* 142, 156, 170 and 186 also increased in intensity as the reaction progressed. A very similar pattern of ions was detected by ESI-MS in our previous study of the oxidation of azo dyes with H_2O_2, in aqueous solution, pH 10, catalysed by the dinuclear manganese complex **1** [19]. The species with *m*/*z* 277 and 259 are assigned to the mononuclear manganese(IV) ions $Mn^{IV}(TMTACN)(OH)_3^+$ (**16**) and $O{=}Mn^{IV}(TMTACN)(OH)_2^+$ (**17**), respectively. It seems likely that, with the present system in acetonitrile/water, the same species are formed by complexation of manganese(II) by TMTACN followed by oxidation to manganese(IV) by hydrogen peroxide as observed in the breakdown of complex **1**. In our earlier study the ions with *m*/*z* 156, 170 and 186 were shown to be TMTACN degradation products arising from both single electron transfer oxidation and oxygen transfer [19].



When the reactions were repeated in the presence of the additives, very similar patterns of ions were observed by positive ion ESI-MS. However, although manganese(III) mixed ligand complexes, $Mn^{III}(TMTACN)(L)^+$, were detected (ESI-MS) in the reactions of hydrogen peroxide and the dinuclear manganese complex 1 with 2,2′-biphenol, catechol and naphthalene-1,8-diol [23], in the present study only in the reactions with 2,2′-biphenol was such a complex detected. The oxidation with 2,2′-biphenol also gave

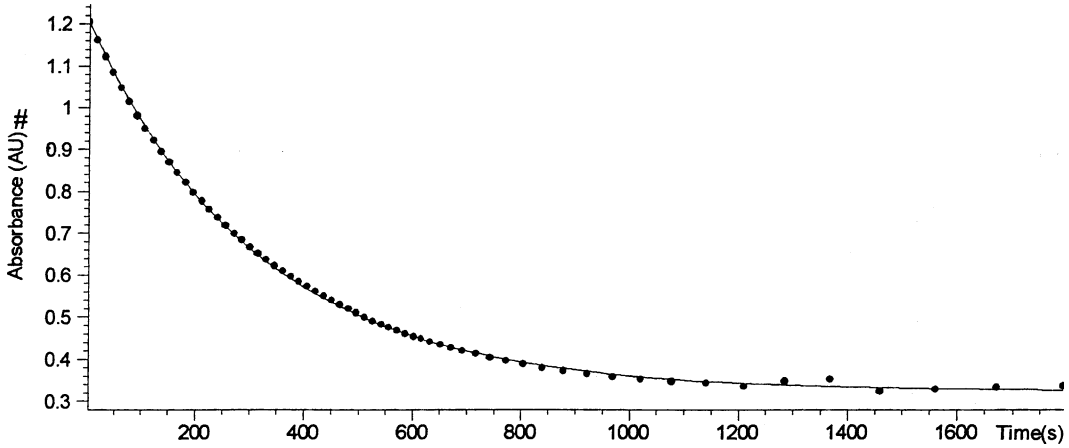
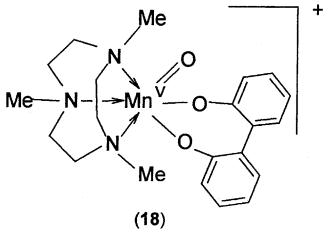


Fig. 2. Plot of absorbance (λ 266 nm) vs. time for cinnamic acid epoxidation by the Mn/TMTACN/oxalic acid/H_2O_2 system. The points show the experimental results and the curve is a non-linear first order fit.

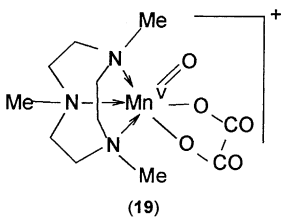
the $O{=}Mn^{V}$(TMTACN)(biphenol)$^{+}$ complex (**18**) with *m*/*z* 426 [11,23].



(18)

We conclude from the ESI-MS studies that:

(a) For most of the reactions, manganese/additive complexes are either not formed or break down during MS analysis or are ESI-MS silent.
(b) Although biphenols can form mixed-ligand complexes, $O{=}Mn^{V}$(TMTACN)(biphenol)$^{+}$ [11,23], when added to the cinnamic acid oxidations they lead to lower rates of epoxidation. We suggest that these complexes, when formed, stabilise the $O{=}Mn^{V}$ species (e.g. **18**) [23] making it a less effective oxidant for cinnamic acid. This, coupled with the competitive oxidation of the phenols to polyphenols and quinones [10,11], results in a poor epoxidation system.
(c) It is likely that the amino acids, mandelic acid, malonic acid, catechol, naphthalene-1,8-diol and butane-2,3-diol which have a negligible effect on the reaction rate do not participate in the cinnamic acid epoxidations. This is consistent with the failure to induce asymmetric epoxidation of alkenes by Mn/TMTACN/H_2O_2 in the presence of chiral amino acids reported by Berkessel and Sklorz [7]: oxidants based on manganese amino acid complexes might have been expected to show significant enantioselectivity.
(d) Since ESI-MS provided no evidence for complexation between manganese and the three best additives, oxalic acid, ascorbic acid and naphthalene-2,3-diol-6-sulfonate, the attractive suggestion of Bennur et al. [18] for the participation of mixed ligand species such as **19** in oxidations by this system remains unproven. An alternative possibility is that these three additives function as redox co-catalysts which regenerate low valent manganese from relatively inert manganese(IV) species (see below).



(19)

3.4. Peroxyacids as potential active species in the epoxidation of cinnamic acid with H_2O_2 and Mn/TMTACN complexes

Carboxylic acids and hydrogen peroxide in aqueous solution are known to form equilibrium mixtures with the corresponding peroxyacids and it was argued that, in the oxidation systems, this equilibrium could give peroxycinnamic or peroxyoxalic acid and these might be the active species or generate it by reaction with a manganese complex.

The possible role of peroxyacids in these systems was investigated using methyl cinnamate in place of cinnamic acid as the substrate. The Mn/TMTACN/H_2O_2 system, in the absence of oxalic acid, led to the epoxyester, although the initial rate of reaction was five-fold lower than that of the corresponding reaction with cinnamic acid. ESI-MS analysis showed that the ester was neither hydrolysed to the acid nor perhydrolysed to the peroxyacid. The lower activity of the ester is attributed to electronic effects, since COOMe is a more electron-withdrawing group than COO^{-}. This conclusion was supported by using methyl 4-methoxycinnamate as the substrate both with and without added oxalic acid: the more electron-rich substrate gave the expected increase in rate of epoxidation.

To confirm that peroxyacids are not involved in these epoxidations, a further set of experiments using peroxyacetic acid as the oxidant instead of hydrogen peroxide was performed. In a reaction catalysed by Mn/TMTACN/oxalic acid, replacing the 100-fold excess of H_2O_2 with an equivalent amount of peroxyacetic acid gave a small lag phase (∼100 s) and a lower rate of epoxide formation. The results from the experiments described above effectively rule out peroxyacids or manganese peroxyacid complexes as key intermediates/oxidants in the reactions with H_2O_2.

To obtain further mechanistic information on these reactions, the electronic effects of substituents on the epoxidation were investigated. For this study and all subsequent studies oxalic acid, the most effective additive, was included in the oxidation system.

3.5. The electronic effects of substituents on the epoxidation of cinnamic acids with H_2O_2 and the Mn/TMTACN/oxalic acid system

The electronic effects of substituents on the epoxidation have been studied using cinnamic acid and seven of its 3- or 4-substituted derivatives. The initial rates of the oxidations of the eight substrates were compared by monitoring the disappearance of the long wave absorption of each substrate anion under the standard conditions. The reactions were investigated at least in triplicate to confirm the reproducibility of the method and the logs of the initial rates (Table 1) were plotted against their Hammett substituent constants σ [25]. This gave a ρ value of -0.73 ± 0.10 (correlation coefficient 0.948) with the point for 4-nitrocinnamic acid lying significantly off the linear plot. Replotting the data using the

Table 1
Hammett σ and σ^- values [25] and initial rates of epoxidation of substituted cinnamic acids by the Mn/TMTACN/oxalic acid/H_2O_2 system in water/acetonitrile (1:1, v/v) at 25 °C, pH 9.5

Substituent	σ	σ^-	Initial rate/10^{-8} mol dm^{-3} s^{-1}	Log(initial rate)
4-OMe	−0.27	−0.27	28.0 ± 0.6	−6.55
4-Me	−0.17	−0.17	21.7 ± 3.7	−6.66
H	0	0	21.5 ± 2.4	−6.67
4-Cl	0.23	0.23	11.4 ± 0.7	−6.94
4-CF_3	0.54	0.54	15.9 ± 2.2	−6.80
3-NO_2	0.71	0.71	6.2 ± 0.7	−7.21
4-NO_2	0.78	1.24	3.2 ± 5.3	−7.49
3,5-diCF_3	0.86	0.86	4.56 ± 1.2	−7.34

σ^- value [25] for the 4-nitro-substituent led to an improved correlation involving all the substrates, with a ρ of −0.63 ± 0.05 (correlation coefficient 0.979) (Fig. 3). The negative ρ values indicate that the active oxidant is electrophilic. This result is consistent with oxo-manganese(V) rather than a hydroperoxo-manganese(III) species being the epoxidising agent. Based on studies with manganese [26] and iron porphyrin [27] systems, the latter species would be expected to be nucleophilic which would result in a positive ρ value from the Hammett plots.

The related epoxidation of alkenes catalysed by manganese(III) salens and tetra-arylporphyrins have been very thoroughly studied and the active oxidant in each is generally accepted to be an electrophilic O=Mn^V species. Furthermore, two Hammett correlations on the epoxidation of substituted styrenes, catalysed by manganese(III) tetraphenylporphyrin [28] and by manganese(III) 5,5′-dinitrosalen [29], have been reported. These have negative ρ values −0.41 and −0.3, respectively. We conclude that the epoxidising agent generated by the Mn^{II}/TMTACN/oxalic acid system is also an oxo-manganese(V) species.

Oxygen-transfer from the active oxidant to the alkene with an early transition state in the rate determining step, suggested by Bortolini and Meunier for epoxidation by oxo-manganese(V) tetraphenylporphyrin [28], is a possible mechanism that would fit the data. Alternatively the oxygen-transfer step may have some radical character [29]. Both would be expected to show a small negative ρ value. The better correlation using σ^- for the 4-nitro group can be interpreted in terms of significant resonance stabilisation of the reactant by the substituent influencing the activation energy. It is probable that the oxygen transfer to cinnamic acid, unlike alkene epoxidations with peroxyacids, is not concerted and involves the formation of an intermediate, similar to those proposed for epoxidations by the oxo-manganese(V) porphyrin and salen complexes. Further work is needed to resolve this matter.

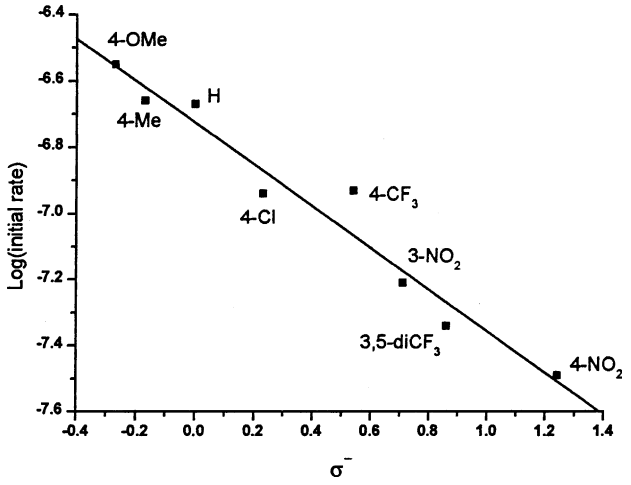


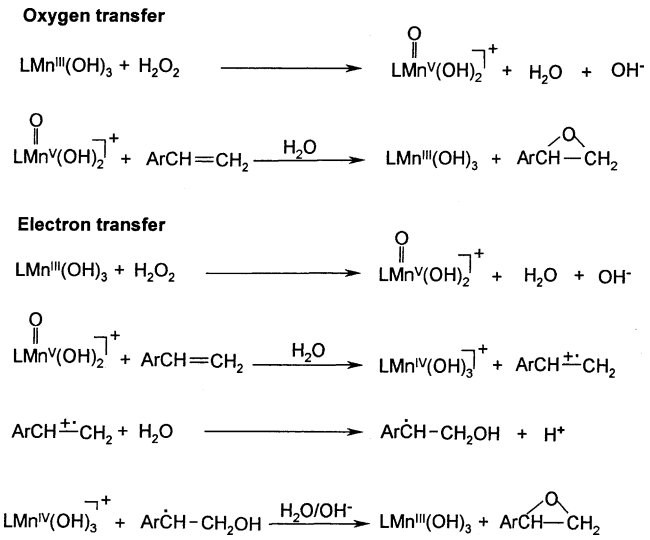
Fig. 3. Plot of log(initial rate) vs. σ^- for the epoxidation of substituted cinnamic acids by the Mn/TMTACN/oxalic acid/H_2O_2 system at 25 °C, pH 9.5.

3.6. The origin of the oxygen in cinnamic acid epoxide

In our earlier EPR spin-trapping studies on the oxidation of azo dyes with hydrogen peroxide catalysed by manganese/TMTACN complexes [19,30], we concluded that a high valent manganese species, and not $^{\bullet}OH$ or $^{\bullet}O_2H$, is the active oxidant in these systems. The present study with cinnamic acid provided an opportunity to determine the origin of the oxygen in the product.

Cinnamic acid was oxidised with $H_2{}^{18}O_2$ (90% enriched) in the Mn/TMTACN/oxalic acid system. Negative ion ESI-MS showed the product epoxide to contain 83.5 ± 3.5% ^{18}O label (92.8% incorporation), confirming H_2O_2 and not H_2O as the oxygen source of the epoxide. This supports an oxygen-transfer rather than an electron-transfer oxidation. Although both mechanisms would be expected to show negative Hammett ρ values, the latter mechanism, proposed previously for the copper(II)/persulfate oxidation of alkenes [31], would require water to be the source of the epoxide oxygen (Scheme 1).

Interestingly oxo-manganese(V) porphyrins [32] and salens [29] can show oxygen exchange by prototropy with



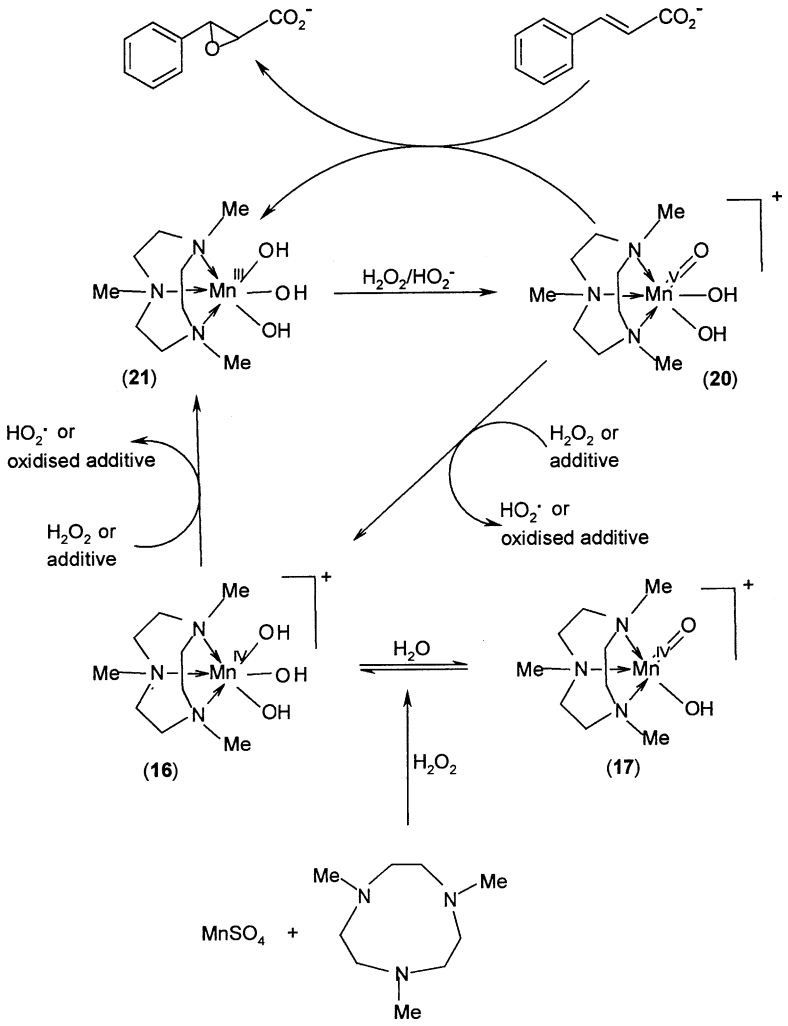
Scheme 1.

coordinated water; consequently, unless ^{18}O-transfer to the alkene is fast compared with the exchange with $H_2{}^{16}O$, only a portion of the labelled oxygen in the oxidant will be observed in the epoxide. Groves et al. [33] reported a rate of exchange of $\sim 10^3\ s^{-1}$ for the water soluble oxo-manganese(V) tetra(4-*N*-methylpyridiniumyl)porphyrin. In the present study, assuming the active oxidant is an $O{=}Mn^V$ species, oxygen transfer to the alkene must be fast by comparison with oxygen exchange with water.

3.7. Mechanistic conclusions

Manganese sulfate, in the presence of TMTACN, catalyses the epoxidation of cinnamic acid by hydrogen peroxide in basic aqueous acetonitrile. Of a selection of potential co-ligands, only ascorbic acid, naphthalene-2,3-diol-6-sulfonate and oxalic acid increase the rate of epoxidation. With the most effective additive, oxalic acid, substituent effects (Hammett correlations) show that the oxidant is electrophilic and ^{18}O-labelling experiments reveal that the oxygen in the epoxide is derived from H_2O_2. ESI-MS analyses detect the formation of mono-nuclear MnTMTACN species in the reaction mixtures but provide little evidence for mixed ligand complexes, [Mn(TMTACN)(L)]. Based on these studies and the mechanism we proposed recently for azo dye oxidation with H_2O_2 catalysed by MnTMTACN complexes [19], a suggested oxidation cycle for cinnamic acid with the Mn/TMTACN/H_2O_2 system is shown in Scheme 2.s

Initial complexation of manganese(II) by TMTACN and oxidation by H_2O_2 leads to the manganese(IV) species **16** and **17** (detected by ESI-MS) [19], which undergo one-electron reduction to the ESI-MS silent manganese(III) complex, **21**, by either H_2O_2 or the additive. Subsequent oxidation by H_2O_2 gives $O{=}Mn^V(TMTACN)(OH)_2{}^+$, **20**, which we propose to be the active oxidant in the Mn/TMTACN/oxalic acid system rather than the manganese(IV) species **16** and **17**. Support for this conclusion comes from a comparison of previous work on alkene epoxidation catalysed by manganese porphyrins [34,35] with that catalysed by the Mn/TMTACN/oxalic acid system [5]. Thus, the epoxidation of alkenes with hydrogen peroxide



Scheme 2.

catalysed by the latter system is effective and stereospecific whereas in the absence of oxalic acid the reaction is less effective and leads to a significant loss of stereochemistry [2,3]. These observations bear a striking parallel with alkene epoxidation catalysed by manganese porphyrins in which $O{=}Mn^{V}$porphyrins are reported to be efficient stereospecific epoxidising agents but by contrast the analogous $O{=}Mn^{IV}$ species are less reactive and lead to loss of stereochemistry [33,34]. We conclude that oxalic acid, either by ligation or by reductively removing manganese(IV), favours the formation of the $O{=}Mn^{V}$ active oxidant **20** over **16** or **17** with the Mn/TMTACN/H_2O_2 system. In its absence the less reactive manganese(IV) complexes become the dominant species.

We are currently investigating the generality of the mechanisms, proposed in this and our previous papers, in a programme of research into the oxidation of a range of other functional groups with hydrogen peroxide catalysed by manganese/TMTACN complexes.

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