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# Oxidation of aromatic compounds by hydrogen peroxide catalyzed by mononuclear iron(III) complexes

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## Highlights

- Iron(III) complexes were studied as catalysts in aromatic hydrocarbons oxidation

- Toluene was oxidized in yields up to 30%, forming cresols as major products

- The reactivity against hydrogen peroxide was followed by UV-Vis and ESI-MS

- Iron-hydroperoxide intermediate was proposed as the active catalytic species

- o-cresol and p-cresol interacts with the intermediate forming a yellow chromophore

Graphical abstract fx1

<sup>§</sup> in memoriam

## Abstract

In the present work, four mononuclear iron(III) complexes containing BMPA (BMPA = bis-(2-pyridylmethyl)amine) and derivative ligands, have been studied as catalyst in toluene oxidation, at 25 °C and 50 °C, using hydrogen peroxide as oxidant and acetonitrile as solvent. All catalysts were able to oxidize toluene with satisfactory yields, producing *o*-, *m*-, *p*-cresols, benzaldehyde and benzyl alcohol, as main product, and traces of 2-methylbenzoquinone and benzoic acid. The catalyst [Fe(BMPA)Cl<sub>3</sub>] presented the most promising results, reaching yields up to 30.2 % at 50 °C after 24 hours. Furthermore, [Fe(BMPA)Cl<sub>3</sub>] was applied in the oxidation of other aromatic compounds as benzene, ethylbenzene, cumene, *n*-propylbenzene, *p*-xylene and anisole. The reaction with H<sub>2</sub>O<sub>2</sub> was monitored by electronic UV-Vis spectroscopy in the presence and absence of toluene and its oxidation products, as well as by ESI-(+)-MS/Q-TOF mass spectrometry, in order to provide some information about the reaction mechanism.

Keywords: toluene oxidation, iron(III) complexes, hydrogen peroxide, iron-peroxo intermediate

## 1. Introduction

The selective functionalization of aromatic hydrocarbons is an important task for the industry, nevertheless the cleavage of C-H bond in large scale is still a challenge, judging by the high temperature and pressure required in the actual industrial processes [1-3]. From the environmental and economic perspective, the development of cleaner synthetic routes to provide industry feedstocks through a green chemistry approach, involves the design of efficient catalysts [4,5]. Oxygenated hydrocarbons are important intermediates for chemicals, agrochemicals, fragrances, pharmaceuticals and polymers manufacture. The industrial processes usually employ homogeneous catalysts as Cr(VI), Mn(VII) or Os(VII) complexes, with the inconvenient formation of toxic metallic side products. In this way, cleaner catalytic systems that can operate at mild conditions are desirable [6].

Non-heme iron(III) complexes inspired in enzymes as methane monooxygenase [7-13] and toluene 4-monooxygenase [14-16] have been studied as catalysts in the selective hydrocarbon oxidation, nevertheless, there are still a few reports on the selective oxidation of aromatic compounds. The iron(III) center in these synthetic models are usually coordinated to polydentade ligands carrying nitrogen and oxygen donor atoms [17]. Molecular oxygen, hydrogen peroxide and *tert*-butyl hydroperoxide have been used as oxidant, however, due to the lower yield usually obtained with the former, peroxides have been more extensively employed [18-20]. Besides the higher yields obtained with H<sub>2</sub>O<sub>2</sub>, its side product H<sub>2</sub>O is environmental friendly compared to classical strong oxidants, as chromium compounds.

In the context of biomimetic models for selective hydrocarbon oxidation, we have reported the application of iron(III) complexes, coordinated to the ligand BMPA (BMPA =

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bis-(2-pyridylmethyl)amine) and its derivates, as catalysts in the cyclohexane oxidation using H<sub>2</sub>O<sub>2</sub>, in acetonitrile, and satisfactory yields were achieved [21]. In this work, the catalysts [Fe(BMPA)Cl<sub>3</sub>] (1), [Fe(MPBMPA)Cl<sub>3</sub>] (2),[Fe(PBMPA)Cl<sub>2</sub>] (3) and  $[Fe(PABMPA)Cl_2](ClO_4)$  (4) (where: MPBMPA = N-methylpropanoate-N,N-bis-(2pyridylmethyl)amine), PBMPA = N-propanoate-N,N-bis-(2-pyridylmethyl)amine and PABMPA = N-propanamide-N,N-bis-(2-pyridylmethyl)amine)) were investigated in the oxidation of toluene and other aromatic compounds, such as ethylbenzene, cumene, npropylbenzene, p-xylene and anisole. The reaction of the catalysts with H<sub>2</sub>O<sub>2</sub> was monitored by electronic UV-Vis spectroscopy in presence and absence of toluene and its oxidation products, as well as by ESI-(+)-MS/Q-TOF mass spectrometry, in order to provide information about the reaction mechanism.

## 2. Experimental

## 2.1. Materials

Toluene, ethylbenzene, *n*-propylbenzene, *p*-xylene and anisole (>98% of purity) were used as received. Cumene was purified by distillation before handling. Commercial 30% aqueous  $H_2O_2$  solution was titrated by the iodometric method before use and the determined concentration was 10.30 mol L<sup>-1</sup>. Acetonitrile was used as solvent. The catalysts [Fe(BMPA)Cl<sub>3</sub>] (1), [Fe(MPBMPA)Cl<sub>3</sub>] (2), [Fe(PBMPA)Cl<sub>2</sub>] (3) and [Fe(PABMPA)Cl<sub>2</sub>](ClO<sub>4</sub>) (4) were synthesized according to the literature [22,23].

## 2.2. Analytic methods

The oxidation products were analyzed in a Varian 3800 gas chromatographer with FID detector and DB-1 column. The analysis conditions were:  $T_{inlet} = 220$  °C,  $T_{detector} = 250$ °C. For toluene reaction analysis the temperature was raised from 50 °C to 55 °C at rate = 1.5 °C/min, then from 55 °C to 82 °C at rate = 10 °C/min, isothermal at 82 °C for 5 min, and then from 82 to 200 °C at rate = 20 °C/min. For ethylbenzene reaction analysis the temperature was raised from 50 °C to 70 °C at rate = 1.5 °C/min, then from 70 to 100 °C at rate = 10 °C/min, and from 100 to 200 °C at rate = 20 °C/min. The analysis of the other aromatic compundss started at 50 °C to 55 °C at rate = 1.5 °C/min, then from 55 °C to 100 °C at rate = 10 °C/min, and from 100 to 200 °C at rate = 20 °C/min. External calibration technique was carried out for quantification, where calibration curves for all substrates and products were used to determine the respective response factor. For a reliable quantification of the alkyl hydroperoxides, the samples were analyzed before and after addition of an excess of solid PPh<sub>3</sub>, which reduces of the hydroperoxide to the corresponding alcohol, since this product can be partially decomposed in the detector. This method allows the calculation of the real yield of hydroperoxide [24]. Typical chromatogram is shown in Figures S1-S2. The products were confirmed by GC/MS analyses, carried out in a Shimadzu GCMS-QP2010S with electron impact ionization of 70 eV and DB-5 column.

UV-Vis spectra were recorded on a Shimadzu 1601PC UV-Vis spectrophotometer using a quartz cuvette in acetonitrile solution. ESI-(+)-MS/Q-TOF mass spectrometry experiments were carried out in a MicrOTOF-Q II equipment from Bruker Daltonics, at capillary voltage of 4.0 kV in positive ion polarity, in acetonitrile solution.

#### 2.3. Oxidation reactions

Initially, the catalytic efficiency of the complexes was investigated towards toluene oxidation at 25 °C or at 50 °C, in acetonitrile, and the best condition was applied to the other substrates. A typical reaction was carried out in a 25 mL round-bottomed flask, where 7.7  $\mu$ mol of catalyst; 7.7 mmol of substrate; 7.7 mmol of H<sub>2</sub>O<sub>2</sub> and CH<sub>3</sub>CN to complete 10 mL of volume, were sequentially mixed and stirred under argon atmosphere, under a thermostated bath. The reaction was transferred to a separatory funnel and quenched by adding 20 mL of aqueous 0.4 mol L<sup>-1</sup> Na<sub>2</sub>SO<sub>4</sub> solution, followed by extraction with 10 mL of diethyl ether. The ether layer was dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and analyzed by GC-FID. The progress of the reaction over time was followed in a reaction volume of 35 mL, where aliquots of 5 mL were taken at 1 h intervals during the first 5 h and one last sample after 24 h, and quenched as described above.

The reactions were also followed by UV-Vis spectroscopy employing an acetonitrile solution containing the catalysts at concentration of  $1.0 \times 10^{-4}$  mol L<sup>-1</sup> or  $1.0 \times 10^{-3}$  mol L<sup>-1</sup>. For the reactions with H<sub>2</sub>O<sub>2</sub>, 100 equivalents of H<sub>2</sub>O<sub>2</sub> were added. For the reactions in presence of toluene or the oxidized products (*o*-cresol, *p*-cresol, benzaldeyde, benzyl alcohol, benzyl acid, 2-methylbenzoquinone) 100 equivalents of the respective product were added.

For ESI-(+)-MS/Q-TOF studies, the following amounts of reactants were used: [Fe(BMPA)Cl<sub>3</sub>]  $1.0\times10^{-3}$  mol L<sup>-1</sup>, H<sub>2</sub>O<sub>2</sub>  $1.0\times10^{-2}$  mol L<sup>-1</sup>, *o*-cresol  $1.0\times10^{-2}$  mol L<sup>-1</sup> in CH<sub>3</sub>CN/H<sub>2</sub>O.

## 3. Results and discussion

## 3.1 Oxidation reactions

The catalysts [Fe(BMPA)Cl<sub>3</sub>] (**1**), [Fe(MPBMPA)Cl<sub>3</sub>] (**2**), [Fe(PBMPA)Cl<sub>2</sub>] (**3**) and [Fe(PABMPA)Cl<sub>2</sub>](ClO<sub>4</sub>) (**4**), represented in **Figure 1**, were tested in toluene oxidation, resulting in the products shown in **Scheme 1**. Benzaldehyde, benzyl alcohol, 2-methylbenzoquinone, cresols, benzyl hydroperoxide and benzoic acid, were identified in the reaction. The catalytic activity of the complexes was investigated at 25 °C and 50 °C, and higher yields were achieved at 50 °C for all the catalysts. The results for 24 hours are summarized in **Table 1**.



Figure 1. Representation of the catalysts 1-4.



Scheme 1. Toluene oxidation reaction promoted by the catalysts 1-4.

The reactions at 25 °C were more selective to cresols, in special to *o*-cresol which accounts for 30% of all products, followed by benzaldehyde (12%) and 2-methylbenzoquinone (2%). 2-methylbenzoquinone is formed from oxidation of *o*-cresol [26], and its formation is favored at lower temperatures [27]. Traces of benzoic acid were also detected as product.

Cresols production can be associated with the presence of hydroxyl radicals, which can be formed via a radicalar mechanism through autoxidation process [25] or to a highly electrophilic oxo-metal transient reacting with the arene  $\pi$ -system [16]. Interestingly, the reactions at 50 °C were more selective to benzaldehyde and presented only traces of 2methylbenzoquinone and benzoic acid. The decrease in the amount of benzyl hydroperoxide and benzyl alcohol with concomitant increase of benzaldehyde, in relation to the reaction at 25 °C, suggested that benzaldehyde was formed from the oxidation of these products. The increase of benzaldehyde selectivity with temperature has been observed by other authors, nevertheless in higher temperatures benzaldehyde was further oxidized to benzoic acid [19,28].

Cat	T (°C)	Yield (%)/Selectivity (%) <sup>a</sup>										
		Dongoldohudo	Benzyl	2-Methyl	Benzoic	Benzyl		Total	TON			
		Benzaiuenyue	alcohol	benzoquinone	Acid	Hydroperoxide	o-cresol	<i>m</i> -cresol + <i>p</i> -cresol	Total	IUN		
<b>1</b> <sup>b</sup>	25	3.3 / 14	1.1 / 5	2.5 / 10	0.5/2	1.5 / 6	7.9/33	7.3/30	24.1	240		
<b>1</b> <sup>b</sup>	50	9.6 / 31	3.3 / 11	0.1 / 0.3	-	1.3 / 4	8.5 / 27	8.3 / 27	31.1	310		
<b>1</b> °	50	6.9 / 24	3.3 / 12	-	-	0.1 / 0.3	9.5 / 33	8.6/30	28.4	284		
<b>1</b> <sup>d</sup>	50	3.5 / 13	3.1 / 11	-	-	-	10.9 / 40	9.7 / 36	27.2	273		
<b>1</b> <sup>e</sup>	50	0.3/8	0.1/3	-	-	-	1.6/44	1.6/44	3.6	36		
<b>2</b> <sup>b</sup>	25	2.1 / 12	0.7/4	1.4 / 8	0.2/1	2.3/13	5.9/33	5.3/30	17.9	179		
<b>2</b> <sup>b</sup>	50	10.5 / 36	3.9 / 13	0.2 / 0.7	0.4 / 1.5	0.4 / 1.5	7.7 / 26	6.1 / 21	29.2	291		
<b>2</b> °	50	9.9 / 33	4.3 / 14	0.2 / 0.7	-	0.6 / 2	8.2 / 28	6.6/22	29.8	297		
<b>3</b> <sup>b</sup>	25	1.4 / 11	0.4/3	1.1 / 8	0.1 / 0.8	2.3/17	4.1/31	3.8/29	13.2	131		
<b>3</b> <sup>b</sup>	50	9.1 / 38	3.3 / 14	0.3 / 1	0.7/3	0.0 / 0.0	5.2 / 22	5.1/21	23.7	237		
<b>3</b> °	50	4.9 / 22	2.8 / 13	-	-	0.2 / 0.9	7.6/34	6.7 / 30	22.2	222		
<b>4</b> <sup>b</sup>	25	3.1 / 13	0.9/4	2.6/11	0.5/2	2.8/12	7.3/31	6.3 / 27	23.5	234		
<b>4</b> <sup>b</sup>	50	9.3 / 39	3.2 / 13	0.3 / 1	0.2 / 0.8	0.5 / 2	5.5 / 23	4.9/21	23.9	239		
<b>4</b> <sup>c</sup>	50	6.1 / 29	2.4 / 12	-	-	-	6.9/33	5.4/26	20.8	208		

Table 1. Results for toluene oxidation promoted by catalysts 1-4 H<sub>2</sub>O<sub>2</sub> in CH<sub>3</sub>CN after 24 h.

<sup>a</sup> Yields are based on toluene. No product was identified in the blank tests performed in absence of catalyst.

<sup>b</sup> Reaction condition: toluene 0.77 mol L<sup>-1</sup>, catalyst  $7.7 \times 10^{-3}$  mol L<sup>-1</sup>, H<sub>2</sub>O<sub>2</sub> 0.77 mol L<sup>-1</sup>, acetonitrile, argon athosphere, 24 h.

<sup>c</sup> Addition of another aliquot of  $H_2O_2$  at 4 h (catalyst 1, 3 and 4) or 24 h (catalyst 2).

<sup>d</sup> Addition of 2 equivalents of  $H_2O_2$  in relation to toluene.

<sup>e</sup> Addition of 3 equivalents of H<sub>2</sub>O<sub>2</sub> in relation to toluene.

<sup>f</sup> TON =  $(n_{\text{products}}/n_{\text{catalyst}}) \times 100$ .

**Figure 2** shows the reaction progress over time for catalyst **1** at 50 °C (data at 25 °C and for catalysts **2-4** are shown in **Figures S3-S9**). **Figure 3** compares the total yield progress

over time for all catalysts at 50 °C. After 5 hours the catalysts 1, 2 and 3 achieved similar

values, around 23 %, while 4 reached 9%, but at 25 °C (Figure S10) the total yield was 20,

10, 6 and 1.5%, for 1, 4, 3 and 2, respectively. The corresponding initial reaction rates W<sub>0</sub>

are presented in **Table S1**, all catalysts presented higher W<sub>0</sub> at 50 °C. The catalytic activity order in the beginning of the reaction was 1 > 4 > 2 > 3 at 25 °C and 1 > 3 > 4 > 2 at 50 °C. Similar trend was observed for these catalysts in the oxidation of cyclohexane at 25 °C [21]. In an attempt to increase the total yield, a new batch of H<sub>2</sub>O<sub>2</sub> was added after 4 hours (catalyst 1, 3 and 4) or 24 hours (catalyst 2) of reaction and no significant improvement was observed, what can indicate the deactivation or decomposition of the catalysts.

For catalyst **1**, reactions employing 2 or 3 equivalents of  $H_2O_2$  in relation to toluene were carried out, as shown in **Table 1**. The better condition was obtained with 1 equivalent of oxidant and a change in color was observed, from yellow to orange. The yield was considerably reduced with higher amounts of  $H_2O_2$ , in this case the color was changed from yellow to colorless, probably due to the faster decomposition of the catalyst with peroxide excess. Besides that, these complexes usually present catalase-like activity [25], which is accelerated by higher amounts of  $H_2O_2$ , leading to faster peroxide and catalyst decomposition.



**Figure 2.** Reaction progress for toluene oxidation with the catalyst [Fe(BMPA)Cl<sub>3</sub>] (1),  $H_2O_2$ , in CH<sub>3</sub>CN, catalyst :  $H_2O_2$  : substrate = 1:1000:1000, at 50 °C.



**Figure 3.** Total yield progress for toluene oxidation with  $H_2O_2$ , in CH<sub>3</sub>CN, catalyst :  $H_2O_2$  : substrate = 1:1000:1000, at 50 °C.

In order to quantify properly the hydroperoxides, GC analyses were carried out before and after treatment with PPh<sub>3</sub> [24]. Comparison of the chromatograms showed the disappearance of the peak corresponding to the hydroperoxide, with the increase of the peak of the corresponding alcohol after addition of PPh<sub>3</sub>, indicating that all the hydroperoxide was reduced. The presence of benzyl hydroperoxide suggested a side-chain oxidation mechanism, where the hydroxyl and/or hydroperoxyl radicals were responsible to abstract the hydrogen atoms from alkanes [18].

The catalytic activity of complex **1**, which showed the most promising results at 50  $^{\circ}$ C, was also evaluated toward other aromatic compounds as benzene, ethylbenzene, cumene, *p*-xylene, *n*-propylbenzene and anisole (**Table 2**).

**Table 2.** Results for the aromatic hydrocarbon oxidation with complex 1, with  $H_2O_2$ , in

Entry	Substrate	Products (%)/ Selectivity(%) <sup>b</sup>								Others Products	Total yield (%)
1		0H 29.7 / 100								-	29.7
2	Ś	Р	0 H		HO	С	OH	ОН	HOO	0.9	30.0
		0.4 / 1	1.3 / 4	7.0/23	9.3 / 31	1.7 / 6	2.5 / 8	2.8/9	4.1 / 14		
3	$\bigcirc$		Í	ОН			и он	$\sim$		1.5	20.2
		2.0/10		1.7/8	2.5/12	6.6/33	2.3/	11	3.6/18		
4		O H			[	OH	ОН			-	16.0
-		0.4 / 2		6.7 / 42	3	3.5 / 22	1.3 / 8		4.1 / 26		
5	K	OH		EH C		Сон				0.6	31.7
	•	10.3 / 32	4.1 / 13	3.7 / 12	5.4 / 17	2.2 / 7	4.1 / 13	0.5 / 1	0.8/2		
6	o-		OH		ĺ	он		O'		-	7.6
			2.6/34		4	1.5 / 59		0.5/7			

CH<sub>3</sub>CN, at 50 °C, after 24 h.<sup>a</sup>

<sup>a</sup> Reaction condition: substrate 0.77 mol L<sup>-1</sup>, catalyst 7.7×10<sup>-3</sup> mol L<sup>-1</sup>, H<sub>2</sub>O<sub>2</sub> 0.77 mol L<sup>-1</sup>, acetonitrile, argon atmosphere, 24 h.

<sup>b</sup> Yields are based on substrate. No product was identified in the blank tests performed in absence of catalyst.

The benzene produced only phenol as product, reaching a yield of 29.7% (entry 1).

Other authors have also described similar selectivity [29].

Acetophenone, 1-phenylethanol, 1-phenylethylhydroperoxide and traces of benzaldehyde, phenylacetaldehyde and *ortho-, metha-* and *para-*ethylphenol, were obtained from the oxidation of ethylbenzene, with 30% of total yield (entry 2). The same product profile was already described in the literature [29].

*n*-Propylbenzene oxidation furnished 20.2 % of yield, where *o*-propylphenol was the main product, followed by 1-phenylpropan-1-one, 1-phenylpropan-1-ol, *p*-propylphenol, 1-phenylpropan-2-one and 1-phenylpropan-2-ol (entry 3). *p*-Xylene oxidation reached 16.0 % of total yield (entry 4) and its main product was 2,5-dimethyl-2,5-cyclohexen-1,4-dione, probably obtained from 2,5-xylenol oxidation. 4-Methylbenzaldehyde was formed from 4-methylbenzyl alcohol oxidation and *p*-cresol was formed from *ipso*-attack in the hydroxylation of *p*-xylene. Anisole oxidation furnished the lowest yields, only 7.6 % (entry 6), with phenol being obtained from anisole demethylation and the other products from ring hydroxylations. In cumene oxidation, cumyl hydroperoxide, phenol and acetophenone were formed, with traces of 2-phenyl-2-propanol, 2-phenylpropanal, 2-phenyl-1-propanol and *ortho-, metha-* and *para*-cumenol (entry 5).

The formation of hydroperoxides in the reaction of ethylbenzene and cumene suggests a radicalar mechanism. When *n*-propylbenzene, *p*-xylene and anisole were oxidized, no hydroperoxide was observed. All reactions suggest a competition between ring hydroxylation (mainly, to *ortho* and *para* positions) and benzylic oxidation [29]. In ethylbenzene, cumene and *n*-propylbenzene oxidations, the major products were those obtained from benzylic oxidation, with only 23, 20 and 44 % of selectivity to ring hydroxylation products, respectively. Nevertheless, in *p*-xylene and anisole oxidations, the ring hydroxylation products were obtained preferentially with selectivity of 76 and 66 %, respectively. In general, the pathway leading to ring hydroxylation was more favored than that to benzylic oxidation, judging by the high yields obtained for the *ortho, meta* and *para* products.

The high yields obtained in the oxidation of benzene can be associated to its six positions suitable for hydroxylation. Ethylbenzene has 5 positions for ring hydroxylation

beyond the  $\alpha$ -carbon suitable for oxidation. Similarly, cumene possesses positions available for ring and benzylic oxidation, and a variety of products is obtained because the ramified chain stabilizes the radicals formed, especially in the  $\alpha$ -position [29]. The side chain radical stabilization is less favored in *n*-propylbenzene because the linear chain decreases its reactivity. The ring hydroxylation in *p*-xylene oxidation is less favorable because it has only four C-H bonds available for oxidation. The anisole oxidation furnished the lowest yields, which may be due to the electron withdrawing effect of the methoxy group. The order of substrate reactivity was: benzene  $\geq$  cumene  $\geq$  ethylbenzene > n-propylbenzene > p-xylene >anisole.

## 3.2. Reactivity of the complexes toward $H_2O_2$ followed by electronic UV-Vis spectroscopy

It was possible to observe a color change during the oxidation reactions from yellow to orange, probably due to the formation of an oxygenated intermediate species, such as  $Fe^{III}(OOH)$  or  $Fe^{IV}(O)$ , or from coordination of an oxidized product to the iron center, either to the free complex or to the oxygenated intermediate. To address this question, the reaction of the complexes with H<sub>2</sub>O<sub>2</sub> in CH<sub>3</sub>CN, at 25 °C, was followed bt UV-Vis spectroscopy, in absence as well as in presence of toluene and some representative oxidation products.

Catalyst **1** spectrum (**Figure 4**-solid line) presents a band at 253 nm attributed to pyridine intraligand CT transition  $\pi \rightarrow \pi^*$ , and two other bands at 290 and 379 nm attributed to LMCT [23]. After addition of 100 equivalents of H<sub>2</sub>O<sub>2</sub> to **1**, the band at 379 nm was blue-shifted to 359 nm and bands at 312 and 269 were formed (**Figure 4**-dashed blue line). The spectra presented two isosbestic points at ~430 and ~370 nm, indicating the presence of two coexisting species. When the experiments were carried out employing a higher comcentration of the catalyst (**Figure 4**-inlet) it was possible to observe a new band at  $\lambda_{max} = 570$  nm. It has

been described that intermediates possessing the Fe<sup>III</sup>(OOH) core present a signature band in the region of 530-590 nm and were proposed as the active species in the oxidation of hydrocarbons catalyzed by iron complexes, in some cases competing with a radical mechanism [33-38]. The Fe<sup>IV</sup>(O) signature band usually appears in the region of 650-800 nm, which is absence in our case, supporting the formation of a Fe<sup>III</sup>(OOH) intermediate [37]. The time trace at 570 nm shows a growth region with maximum around 34 minutes, which can be fit to a single exponential function, with  $k_{growth} = 3.4 \times 10^{-3} \text{ s}^{-1}$  (**Figure S11**), indicating a first order process. A decay is observed after 34 minutes and can also be fit to a single exponential function, with  $k_{decay} = 2.9 \times 10^{-3} \text{ s}^{-1}$  (**Figure S12**). Que and coworkers have shown that (TPA)Fe<sup>III</sup>(OOH) formed at 540 nm from [Fe<sup>II</sup>(TPA)(NCCH<sub>3</sub>)<sub>2</sub>]<sup>2+</sup> and H<sub>2</sub>O<sub>2</sub> in CH<sub>3</sub>CN at -40 °C and decays,  $k_{decay} = 2.4(3) \times 10^{-3} \text{ s}^{-1}$ , in presence of water to form Fe<sup>V</sup>(O)(OH), which is responsible for 1-octene oxidation [39]. Isolated [(L<sub>5</sub><sup>2</sup>)Fe(OOH)](PF<sub>6</sub>)<sub>2</sub> complex with a amine/pyridine ligand also degraded in acetonitrile solution at 7 °C in a first-order decay,  $k_{decay} = 5.3 \times 10^{-3} \text{ s}^{-1}$  at 519 nm, due to the oxidation of CH<sub>3</sub>CN to -CH<sub>2</sub>CN radical, which by its turn consume the Fe<sup>III</sup>(OOH) species [40].



**Figure 4.** Reaction between [Fe(BMPA)Cl<sub>3</sub>] (1) and H<sub>2</sub>O<sub>2</sub> followed by UV-Vis spectra in CH<sub>3</sub>CN, at [complex] =  $1.0 \times 10^{-4}$  mol L<sup>-1</sup> and [H<sub>2</sub>O<sub>2</sub>] =  $1.0 \times 10^{-2}$  mol L<sup>-1</sup>. Inlet: spectra at complex and H<sub>2</sub>O<sub>2</sub> concentration  $10 \times$  higher and time trace of the absorption spectra at  $\lambda_{max}$  = 570 nm.

A titration experiment (**Figure S13**) was carried out in an attempt to determine the molar ratio of  $H_2O_2$  per complex molecule, however, spectral changes were only observed after addition of 10 equivalents of  $H_2O_2$ . With 20 equivalents of  $H_2O_2$  the complete disappearance of the band at 379 nm and the formation of the band at 359 nm were observed.

The reaction of **2** and **3** with H<sub>2</sub>O<sub>2</sub> (**Figures S17-18**) showed no spectral change in the region of 500-700 nm, while the appearance of a band at 530 nm was observed for **4** (**Figure S19-20**). The time trace (**Figure S21**) presented first-order growth and decay, with  $k_{\text{growth}} = 7.4 \times 10^{-4} \text{ s}^{-1}$  and  $k_{\text{decay}} = 9.6 \times 10^{-4} \text{ s}^{-1}$  (**Figures S22**), one order of magnitude smaller

than those obtained for **1** and  $H_2O_2$ . This result is in accordance with the initial reaction rate  $W_0$  obtained in toluene oxidation (**Table S1**), where  $W_0$  for catalyst **1** was one order of magnitude higher than **4** at 25 °C. Complexes **2** and **3** presented the lowest  $W_0$  and no intermediate was observed from their reaction.

The reaction in presence of toluene (**Figure S25**) showed similar spectral changes as those observed for **1** and H<sub>2</sub>O<sub>2</sub>, indicating no influence on the Fe(OOH) intermediate formation. The same behavior was observed for the oxidation products benzoic acid (**Figure S36**) and 2-methylbenzoquinone (**Figure S48**) due to their low coordination ability. Similar results were described for the system [(bpmen)<sub>2</sub>Fe<sub>2</sub>O( $\mu$ -O)( $\mu$ -OH)](ClO<sub>4</sub>)<sub>3</sub>, benzene and H<sub>2</sub>O<sub>2</sub> (bpmen = *N*,*N*'-dimethyl-*N*,*N*'-bis(2-pyridylmethyl)-1,2-diaminoethane), where the formation of the intermediate iron(III)-phenolate was independent of the initial substrate concentration [16]. However, when the reaction of **1** and H<sub>2</sub>O<sub>2</sub> was carried out in presence of benzyl alcohol or benzaldehyde (**Figure 5**) the bands of the catalyst showed a blue shift compared to the reaction of **1** and H<sub>2</sub>O<sub>2</sub> right after the reaction started, indicating the coordination of these products to the Fe(OOH) intermediate. In the course of the reaction, new bands appeared as the solution color changed from yellow to bright yellow, due to the displacement of the bands from visible to the ultraviolet range, but the signature band of Fe(OOH) was not observed.

Control experiments without  $H_2O_2$  showed that the coordination of the oxidized products to the pure complex can be neglected, judging by the lack of changes in the electronic spectrum after 60 min (Figures S28, 34, 38, 41, 46) except for sodium benzoate (Figure S50) and benzaldehyde (Figure S31) which showed subtle spectral changes, the latter after easy oxidation to benzoate under air. No further oxidation of the products were

observed in absence of the complex (Figures S24, 29, 35, 39, 42, 47, 51), except for benzaldehyde as mentioned (Figure S32).



**Figure 5.** Reaction between [Fe(BMPA)Cl<sub>3</sub>] (1)  $(1.0 \times 10^{-4} \text{ mol } \text{L}^{-1})$  and H<sub>2</sub>O<sub>2</sub>  $(1.0 \times 10^{-1} \text{ mol } \text{L}^{-1})$ , in presence of benzyl alcohol or benzaldehyde, followed by UV-Vis spectroscopy, in CH<sub>3</sub>CN, during 60 minutes,.

In the reaction of **1**, H<sub>2</sub>O<sub>2</sub> and *o*-cresol or *p*-cresol, immediate formation of a redorange chromophore was observed at  $\lambda_{max} = 388$  nm and 360 nm, respectively, which are responsible for the color change during the toluene oxidation reaction. In presence of *o*-cresol (**Figure 6(a)**) the complex absorption at 379 nm was red-shifted to 388 nm, as the intensity has also increased. A new band at  $\lambda_{max} = 570$  nm attributed to the Fe(OOH) species emerged, and the time trace was fitted to a first-order growth (**Figure S40**),  $k_{growth} = 3.9 \times 10^{-4} \text{ s}^{-1}$ . The reaction in presence of *p*-cresol (**Figure 6(b**)) presented a similar behavior, however a blue shift to 360 nm was observed, with a less intense absorption. The band at  $\lambda_{max} = 570$  nm

increased in the beginning of the reaction and then decreased after 40 min (**Figure 6(b)**inlet), the time trace was fit with a first-order growth,  $k_{\text{growth}} = 2.0 \times 10^{-4} \text{ s}^{-1}$ , and decay,  $k_{\text{decay}} = 1.5 \times 10^{-3} \text{ s}^{-1}$  (**Figures S44-45**). Both  $k_{\text{growth}}$  values are one order of magnitude smaller than that for **1** and H<sub>2</sub>O<sub>2</sub>, indicating that the buildup of the Fe(OOH) intermediate is slower when *ortho* or *para* cresol is bound. However, the  $k_{\text{decay}}$  observed for *p*-cresol is higher and indicates that the intermediate consumption is accelerated in presence of *p*-cresol. Moreover, *o*-cresol inhibited the intermediate decay.





**Figure 6.** Reaction between [Fe(BMPA)Cl<sub>3</sub>] (1)  $(1.0 \times 10^{-4} \text{ mol } \text{L}^{-1})$  and H<sub>2</sub>O<sub>2</sub>  $(1.0 \times 10^{-2} \text{ mol } \text{L}^{-1})$  followed by UV-Vis spectroscopy, in CH<sub>3</sub>CN, during 100 minutes. (a) in presence of *o*-cresol  $1.0 \times 10^{-2}$  mol L<sup>-1</sup> or (b) *p*-cresol  $1.0 \times 10^{-2}$  mol L<sup>-1</sup>. Inlet: time trace at  $\lambda_{\text{max}} = 570$  nm.

# 3.3. Reactivity of $[Fe(BMPA)Cl_3]$ toward $H_2O_2$ followed by ESI-(+)-MS/Q-TOF mass spectrometry

To confirm the formation of the intermediates proposed by UV-Vis, we followed the reaction of **1**, H<sub>2</sub>O<sub>2</sub>, and *o*-cresol by ESI-(+)-MS/Q-TOF mass spectrometry, as shown in **Figure 7**. The spectrum of the pure complex in CH<sub>3</sub>CN (**Figure 7a**) presented signals from mononuclear species at m/z 325.0 and m/z 289.0, assigned to [Fe<sup>III</sup>(BMPA)Cl<sub>2</sub>]<sup>+</sup> and [Fe<sup>III</sup>(BMPA – H<sup>+</sup>)Cl]<sup>+</sup>, respectively. Besides, binuclear species such as [Fe<sup>III</sup><sub>2</sub>( $\mu$ -Cl)(BMPA)(BMPA – H<sup>+</sup>)Cl<sub>3</sub>]<sup>+</sup> and [Fe<sup>III</sup><sub>2</sub>( $\mu$ -Cl)(BMPA)<sub>2</sub>Cl<sub>4</sub>]<sup>+</sup> were also observed at m/z

651.0 and m/z 686.9, respectively. The assignments were confirmed by concordance between the experimental and simulated isotopic pattern (**Figures 53-56**).

The spectrum after reaction of **1** and H<sub>2</sub>O<sub>2</sub> (**Figure 7b**) showed new signals attributed to Fe(OOH) species, at m/z 288.0 and m/z 323.0. The first peak is a combination of three different species, as confirmed by the isotopic pattern simulation (**Figure 7d**): [Fe<sup>III</sup>(BMPA – H<sup>+</sup>)(OOH)]<sup>+</sup>, [Fe<sup>II</sup>(BMPA)(OOH)]<sup>+</sup> and [Fe<sup>III</sup>(BMPA – H<sup>+</sup>)Cl]<sup>+</sup>. The second peak is a combination of two species: [Fe<sup>III</sup>(BMPA)Cl(OOH)]<sup>+</sup> and [Fe<sup>III</sup>(BMPA)Cl<sub>2</sub>]<sup>+</sup> (**Figure 7e**). A third peak at m/z 510.1 is attributed to a combination of two binuclear species: [Fe<sup>III,II</sup><sub>2</sub>( $\mu$ -O)(BMPA)(BMPA – PyCH<sub>2</sub>)(CH<sub>3</sub>CN)(OOH)]<sup>+</sup> and [Fe<sup>III,III</sup><sub>2</sub>( $\mu$ -O)(BMPA)(BMPA – PyCH)(OH)<sub>2</sub>(CH<sub>3</sub>CN)]<sup>+</sup> (**Figure S57**). Similar Fe(OOH) intermediate was detected by ESI-MS from the reaction of [Fe<sup>II</sup>(bpmen)(CH<sub>3</sub>CN)<sub>2</sub>][ClO<sub>4</sub>]<sub>2</sub> (bpmen = N,N'-dimethyl-N,N'bis(2-pyridylmethyl)ethane-1,2-diamine) and H<sub>2</sub>O<sub>2</sub>: [Fe(bpmen)(OOH) + Na<sup>+</sup> + ClO<sub>4</sub>] [41].

The reaction of **1**, H<sub>2</sub>O<sub>2</sub> and *o*-cresol (**Figure 7c**) presented signals corresponding to the species formed from **1** and H<sub>2</sub>O<sub>2</sub>. Besides that, new peaks were observed at m/z 318.1, 389.1 and 660.2, which were assigned to a species containing *o*-cresol coordinated to the iron center. The first peak is due to the species [Fe<sup>IV</sup>(BMPA – PyCH)(OOH)(3-(O<sup>-</sup>)-*o*cresolate)]<sup>+</sup>, which presents a iron-peroxo units and an anionic form of the 3-hydroxy-*o*cresol (**Figure S58**). The peak at m/z 389.1 corresponds to [Fe<sup>IV</sup>(BMPA – Py – H<sup>+</sup>)(*o*-cresol – H<sup>+</sup>)<sub>2</sub>]<sup>+</sup>, a species containing two molecules of *o*-cresol coordinated to the iron center (**Figure 7f**). Finally, a binuclear species at m/z 600.2 is assigned to [Fe<sup>III,II</sup><sub>2</sub>( $\mu$ -O)(BMPA)(BMPA – PyCH)(OH)(CH<sub>3</sub>CN)(*o*-cresol – H<sup>+</sup>)]<sup>+</sup> (**Figure S59**). Similar intermediate with phenolate-bound iron(III) species was observed for the reaction of the

 $[(bpmen)_2Fe_2O(\mu-O)(\mu-OH)](ClO_4)_3$ , benzene and  $H_2O_2$ , which exhibited a peak assigned to  $[(bpmen)Fe^{III}(OPh)(MeCN) + H^+]$  [16].



**Figure 7.** ESI-(+)-MS/Q-TOF mass spectra of: (a) [Fe(BMPA)Cl<sub>3</sub>]  $(1.0\times10^{-3} \text{ mol } \text{L}^{-1} \text{ in } \text{CH}_3\text{CN})$ ; (b) after 30 minutes of H<sub>2</sub>O<sub>2</sub>  $(1.0\times10^{-2} \text{ mol } \text{L}^{-1})$  addition; (c) after 60 minutes of *p*-cresol  $(1.0\times10^{-2} \text{ mol } \text{L}^{-1})$  addition. Experimental and isotopic pattern simulation for the ions: (d) *m/z* 288.0 of spectrum (b); (e) *m/z* 323.0 of spectrum (b); (f) *m/z* 389.1 of spectrum (c).

## 4. Conclusions

The iron(III) complexes studied were able of oxidize toluene in presence of  $H_2O_2$ , furnishing satisfactory results. The higher yields were obtained at 50 °C, with the complex [Fe(BMPA)Cl<sub>3</sub>] (1), reaching up to 31%. The reactions at 25 °C were more selective to *o*-

cresol while the reactions at 50 °C were more selective to benzaldehyde. In the oxidation of benzene, phenol was obtained with 100% of selectivity and 30 % of yield, representing a very promising result. In the ethylbenzene and cumene oxidation, a higher selectivity was obtained to the benzylic chain products in relation to the ring hydroxylation products. In *n*-propylbenzene, *p*-xylene and anisole oxidation, the ring hydroxylation was more favoured. The reaction of [Fe(BMPA)Cl<sub>3</sub>] and H<sub>2</sub>O<sub>2</sub> was followed by electronic UV-Vis spectroscopy and ESI-(+)-MS/Q-TOF mass spectrometry. The data supported the formation of a intermediate Fe(OOH). In presence of *o*-cresol and *p*-cresol a chromophore was observed due to coordination to Fe(OOH) as phenolate.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version.

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