



Article

Catalytic Performance of Fe(II)-Scorpionate Complexes towards Cyclohexane Oxidation in Organic, Ionic Liquid and/or Supercritical CO₂ Media: A Comparative Study

Ana P. C. Ribeiro ¹, Luísa M. D. R. S. Martins ^{1,2,*} , Elisabete C. B. A. Alegria ^{1,2} ,
Inês A. S. Matias ¹, Tiago A. G. Duarte ¹ and Armando J. L. Pombeiro ¹

¹ Centro de Química Estrutural, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal; ana.paula.ribeiro@ist.utl.pt (A.P.C.R.); ebastos@deq.isel.ipl.pt (E.C.B.A.A.); ines_matias_6@hotmail.com (I.A.S.M.); tiago.gomes.duarte@tecnico.ulisboa.pt (T.A.G.D.); pombeiro@tecnico.ulisboa.pt (A.J.L.P.)

² Chemical Engineering Department, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, R. Conselheiro Emídio Navarro, 1959-007 Lisboa, Portugal

* Correspondence: lmartins@deq.isel.ipl.pt; Tel.: +351-218-317-226

Received: 27 June 2017; Accepted: 26 July 2017; Published: 2 August 2017

Abstract: The catalytic activity of the iron(II) C-scorpionate complexes [FeCl₂{HC(pz)₃}] **1** (pz = pyrazol-1-yl) and [FeCl₂{HOCH₂C(pz)₃}] **2**, and of their precursor FeCl₂·2H₂O **3**, towards cyclohexane oxidation with *tert*-butyl hydroperoxide was evaluated and compared in different media: acetonitrile, ionic liquids (1-butyl-3-methylimidazolium hexafluorophosphate, [bmim][PF₆], and 1-butyl-3-methylimidazolium tris(pentafluoroethyl)trifluorophosphate, [bmim][FAP]), supercritical carbon dioxide (scCO₂), and scCO₂/[bmim][X] (X = PF₆ or FAP) mixtures. The use of such alternative solvents led to efficient and selective protocols for the oxidation of cyclohexane. Moreover, tuning the alcohol/ketone selectivity was possible by choosing the suitable solvent.

Keywords: ionic liquid; supercritical carbon dioxide; cyclohexane; oxidation; C-scorpionate; catalyst

1. Introduction

The efficient application of a catalyst, instead of a stoichiometric conversion, as well as the use of supercritical fluids (e.g., carbon dioxide, scCO₂) or ionic liquids (IL) as safer solvents for chemical reactions are very important principles of green chemistry [1]. The combination of both is, therefore, a promising way to design more sustainable chemical conversions.

Currently, supercritical fluids (SCFs) have not only proven their environmental benefits, but also have offered substantial advantages in several features of catalytic processes [2]. Oxidation reactions have been investigated in supercritical carbon dioxide, mostly those of ethanol [3] and toluene [4,5]. Selective aerobic oxidation of cyclohexane in scCO₂ has also been attempted [6–8], relying on the oxidative stability of carbon dioxide and the miscibility of dioxygen above the critical point to drive free radical chemistry in scCO₂. Temperature and pressure have been shown to affect the reaction rate and conversion of cyclohexane [6], providing tunability of reactions in SCFs. Despite these encouraging results, homogeneous catalytic oxidations remain relatively unexplored in scCO₂ [9–11].

It is also known that the use of room temperature ionic liquids (ILs) in organic synthesis provides a good alternative to conventional volatile organic solvents [2]. Moreover, ILs not only present advantages regarding easier workups and catalyst recycling, but also tune the outcome of catalytic reactions, where, depending on the nature of ionic liquid used, different products can be obtained [12–18]. However, the IL medium is still underexplored as a solvent for oxidative catalysis [12,13,19–21].

Within our interest on the oxidation of alkanes catalyzed by C-scorpionate complexes [22–24], the main objective of the present study was to evaluate the suitability of the above alternative greener media as solvents for such reactions. The low environmental impact and the chemical inertness of scCO_2 and ILs under most catalytic process conditions are expected to promote safer reactions in these media. Moreover, IL- scCO_2 systems address separation problems, facilitating the recycling and re-use of catalysts.

Cyclohexane was chosen as a substrate model in view of the industrial relevance of its oxidation products (cyclohexanol and cyclohexanone) [25–27]. In addition, the environmentally acceptable oxidant *tert*-butyl hydroperoxide (TBHP) was used along with a known efficient C-scorpionate Fe(II) catalyst [28], $[\text{FeCl}_2\{\text{HC}(\text{pz})_3\}]$ **1** (pz = pyrazol-1-yl) and its alcohol derivative $[\text{FeCl}_2\{\text{HOCH}_2\text{C}(\text{pz})_3\}]$ **2** [29] (very recently prepared, but with catalytic activity unknown) for the partial oxidation of cyclohexane in acetonitrile. ILs 1-butyl-3-methylimidazolium hexafluorophosphate, $[\text{bmim}][\text{PF}_6]$, and 1-butyl-3-methylimidazolium tris(pentafluoroethyl)trifluorophosphate, $[\text{bmim}][\text{FAP}]$, (Figure 1a,b, respectively) were selected due to their ability to dissolve large quantities of scCO_2 , while they themselves are insoluble in scCO_2 , in accordance with their almost non-existing vapor pressure [30,31].

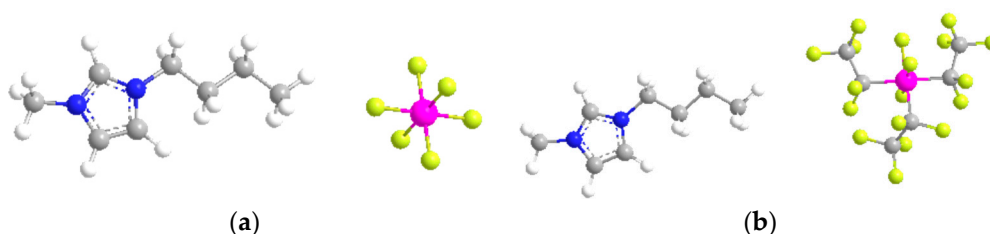


Figure 1. Schematic structure representation of (a) 1-butyl-3-methylimidazolium hexafluorophosphate, $[\text{bmim}][\text{PF}_6]$, and (b) 1-butyl-3-methylimidazolium tris(pentafluoroethyl) trifluorophosphate, $[\text{bmim}][\text{FAP}]$.

To our knowledge, this is the first time that the successful use of scCO_2 or scCO_2 -IL as solvents for the oxidation of alkanes catalyzed by a C-scorpionate complex is reported.

2. Results and Discussion

Compounds $[\text{FeCl}_2\{\text{HC}(\text{pz})_3\}]$ **1** (pz = pyrazol-1-yl) and $[\text{FeCl}_2\{\text{HOCH}_2\text{C}(\text{pz})_3\}]$ **2** (Figure 2), as well as their precursor $\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ **3**, were used as catalysts for the oxidation of cyclohexane to cyclohexanol and cyclohexanone, with *tert*-butyl hydroperoxide (TBHP, 70% aq. solution), at 70 °C, in different media, i.e., in a conventional solvent (CH_3CN), in IL (1-butyl-3-methylimidazolium hexafluorophosphate, $[\text{bmim}][\text{PF}_6]$, and 1-butyl-3-methylimidazolium tris(pentafluoroethyl)trifluorophosphate, $[\text{bmim}][\text{FAP}]$) medium, in scCO_2 , or in $\text{scCO}_2/[\text{bmim}][\text{X}]$ ($\text{X} = \text{PF}_6$ or FAP) mixtures (Scheme 1). When scCO_2 was used, the experiments were undertaken at 90 bar of CO_2 .

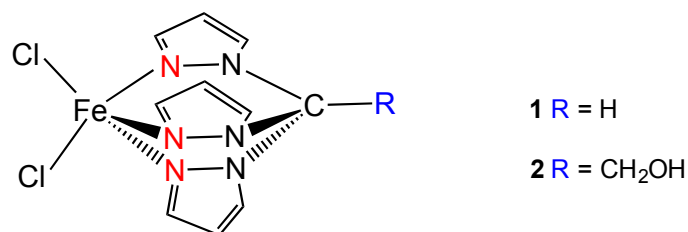
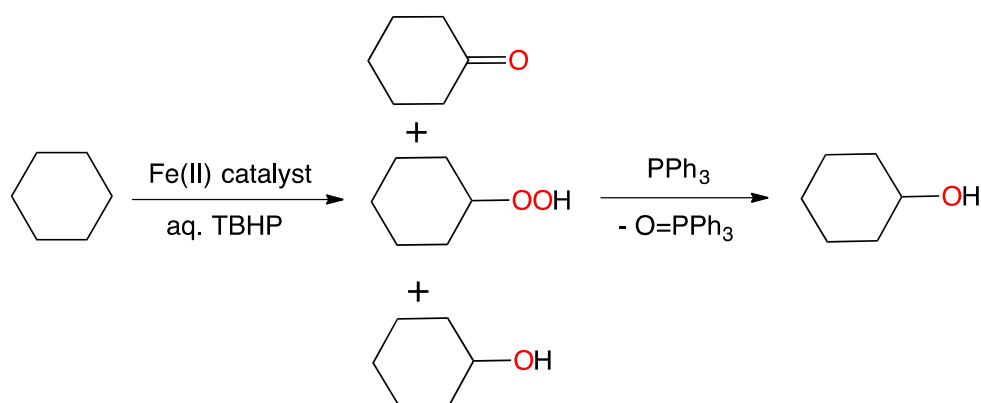


Figure 2. Schematic structure representation of C-scorpionate complexes $[\text{FeCl}_2\{\text{HC}(\text{pz})_3\}]$ **1** (pz = pyrazol-1-yl) and $[\text{FeCl}_2\{\text{HOCH}_2\text{C}(\text{pz})_3\}]$ **2**.



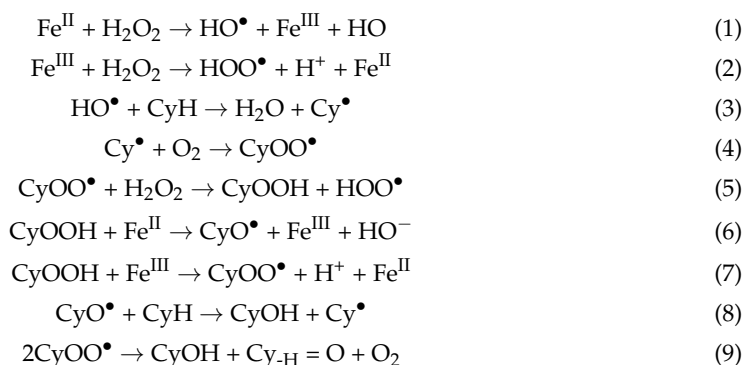
Scheme 1. Peroxidative oxidation of cyclohexane catalyzed by 1–3.

The catalytic performances of the C-scorpionate complexes [FeCl₂{RC(pz)₃}] (R = H, **1** or CH₂OH, **2**) were compared in terms of products yield, turnover number (TON) or frequency (TOF, h^{−1}), and selectivity as a function of reaction time and solvent media (Tables 1–3).

Cyclohexanol and cyclohexanone were the only products detected by gas chromatography-mass spectrometry (GC-MS) analysis, revealing the high selectivity of the oxidation systems under the chosen conditions, which was confirmed by the molar balance between the converted substrate and those products.

Complex **1** led to the highest yield and TON values in all tested media (Tables 1 and 3). The yield values achieved in acetonitrile were comparable to those previously obtained at room temperature [28] without any added promotor. Higher yields were reported in very different reaction conditions, such as when **1** was supported on carbon nanotubes or zeolites (total yield up to 38%) [32,33] or using microwave (MW) assistance (total yield of 33%) [12,34], always in the presence of pyrazinecarboxylic acid (Hpca) [32–35]. However, for the present study, to compare the catalysts' performances in different media, promotor-free conditions were preferred.

The FeCl₂·2H₂O **3** salt exhibited significant lower catalytic activity (Table S1, Supplementary Materials) than complexes **1** and **2** in all media, suggesting the favorable involvement of the scorpionate ligands in the metal-assisted steps [23] of this catalytic oxidation reaction. Moreover, the known radical trap 2,2,6,6-tetramethylpiperidyl-1-oxyl radical (TEMPO) was used in the different media and in all cases a marked decrease (between 80% and 93%) in the products yield was observed, suggesting the involvement of a radical mechanism as proposed in Scheme 2 [36]. The involvement of iron (III) species was also suggested by the Fe 2p XPS spectrum of **1** after the fourth recycling run (see below) in [bmim][PF₆] IL.



Scheme 2. Proposed mechanism for the oxidation of cyclohexane catalyzed by 1–3.

The cyclohexanol and cyclohexanone yields obtained in this work (under promotor-free conditions) were considerably higher than those provided by the current industrial process that uses a homogeneous cobalt species as a catalyst, dioxygen as an oxidant, needs a considerably high temperature (150 °C), and is only able to generate 5–12% yields to assure a selectivity of ca. 80–85% [26].

Table 1. Selected data ^a for the cyclohexane oxidation with TBHP using [FeCl₂{HC(pz)₃}] **1** as a catalyst.

Entry	Time	Yield (%) ^b			Total TON ^c	Total TOF ^d	Selectivity towards Cyclo-Hexanone ^e (%)
	(h)	Cyclo-Hexanol	Cyclo-Hexanone	Total		(h ⁻¹)	
CH ₃ CN							
1	1	1.5	1.6	3.1	15.5	15.5	52
2	3	2.3	2.8	5.1	25.5	8.5	55
3	6	2.9	3.2	6.1	30.5	5.1	52
[bmim][PF ₆]							
4	1	4.3	8.4	12.7	63.5	63.5	66
5	3	5.9	11.9	17.8	89.0	29.7	67
6	6	8.3	12.6	20.9	104.5	17.4	60
[bmim][FAP]							
7	1	2.9	6.3	9.2	46.0	230.0	68
8	3	3.9	9.2	13.1	65.5	21.8	70
9	6	4.1	12.8	16.9	84.5	14.1	76
scCO ₂ ^f							
10	1	2.3	2.5	4.8	24.0	120.0	52
11	3	4.8	6.3	11.1	55.5	18.5	57
12	6	6.1	8.2	14.3	71.5	11.9	57

^a Reaction conditions, unless stated otherwise: MeCN (3.0 mL), CyH (5.0 mmol), TBHP (10.0 mmol), **1** (10.0 μmol, 0.2 mol % vs. CyH), 70 °C. ^b Based on gas chromatographic (GC) analysis, after treatment with PPh₃; total yields in moles of cyclohexanol + cyclohexanone per 100 moles of cyclohexane. ^c TON = Total turnover number (moles of cyclohexanol + cyclohexanone per mol of catalyst). ^d TOF (h^{−1}) = TON/time (h). ^e Moles of cyclohexanone per 100 moles of cyclohexanol + cyclohexanone. ^f p (CO₂) = 90 bar.

Table 2. Selected data ^a for the cyclohexane oxidation with TBHP using [FeCl₂{HOCH₂C(pz)₃}] **2** as a catalyst.

Entry	Time	Yield (%) ^b			Total TON ^c	Total TOF ^d	Selectivity towards Cyclo-Hexanone ^e (%)
	(h)	Cyclo-Hexanol	Cyclo-Hexanone	Total		(h ⁻¹)	
CH ₃ CN							
1	1	0.8	1.2	2.0	10.0	10	60
2	3	1.1	1.5	2.6	13.0	4.3	58
3	6	1.3	2.1	3.4	17.0	2.8	62
[bmim][PF ₆]							
4	1	3.3	5.7	9.0	45.0	45	63
5	3	6.5	8.3	14.8	74.0	24.7	56
6	6	7.5	9.4	16.9	84.5	14.1	56
[bmim][FAP]							
7	1	1.4	3.4	4.8	24.0	24	71
8	3	1.9	5.1	7.0	35.0	11.7	73
9	6	2.5	8.6	11.1	55.5	9.3	77
scCO ₂ ^f							
10	1	3.4	4.9	8.3	41.5	41.5	59
11	3	4.5	5.1	9.6	48.0	16.0	53
12	6	5.3	7.5	12.8	64.0	10.7	59

^a Reaction conditions, unless stated otherwise: MeCN (3.0 mL), CyH (5.0 mmol), TBHP (10.0 mmol), **2** (10.0 μmol, 0.2 mol % vs. CyH), 70 °C. ^b Based on GC analysis, after treatment with PPh₃; total yields in moles of cyclohexanol + cyclohexanone per 100 moles of cyclohexane. ^c Total turnover number (moles of cyclohexanol + cyclohexanone per mol of catalyst). ^d TOF (h^{−1}) = TON/time (h). ^e Moles of cyclohexanone per 100 moles of cyclohexanol + cyclohexanone. ^f p (CO₂) = 90 bar.

Complexes **1** and **2** exhibited the same catalytic trend in the different tested pure solvents. The use of [bmim][PF₆] achieved the maximum yields (20.9% for **1** and 16.9% for **2**, Table 1, entry 6 and Table 2, entry 6, respectively) whereas the lowest yields were obtained in acetonitrile (6.1% for **1** and 3.4% for

2, Table 1, entry 6 and Table 2, entry 6, respectively). The viscosity of [bmim][PF₆] [37] is three times higher than that of [bmim][FAP] [38] and, as expected, mass transfer is higher in the less viscous IL, promoting a higher yield of cyclohexane oxidation products.

The following order is observed for the activity of the above C-scorpionate Fe(II) catalysts under promoter-free conditions in the solvents used:



scCO₂-IL (IL = [bmim][PF₆] or [bmim][FAP]) 2:1 molar mixtures were also tested as a reaction medium for **1** and **2** (Table 3), and were found to improve the solubility of the scorpionate complexes.

Table 3. Selected data ^a for the cyclohexane oxidation with TBHP in scCO₂-IL medium.

Entry	Catalyst	Yield (%) ^b			Total TON ^c	Total TOF ^d (h ^{−1})	Selectivity towards Cyclo-Hexanone ^e (%)
		Cyclo-Hexanone	Cyclo-Hexanol	Total			
scCO ₂ -[bmim][PF ₆]							
1	1	17.6	1.3	18.9	95	94.5	93
2	2	15.9	0.7	16.6	83	41.5	96
scCO ₂ -[bmim][FAP]							
3	1	19.5	3.2	22.7	114	113.5	86
4	2	16.7	2.5	19.2	96	48.0	87

^a Reaction conditions, unless stated otherwise: IL (3.0 mL), CyH (5.0 mmol), TBHP (10.0 mmol), 10.0 μmol of catalyst (0.2 mol % vs. CyH), 70 °C and *p* (CO₂) = 90 bar. ^b Based on GC analysis, after treatment with PPh₃; total yields in moles of cyclohexanol + cyclohexanone per 100 moles of cyclohexane. ^c Total turnover number (moles of cyclohexanol + cyclohexanone per mol of catalyst). ^d TOF (h^{−1}) = TON/time (h). ^e Moles of cyclohexanone per 100 moles of cyclohexanol + cyclohexanone.

A significant increase in the products yield was found in the scCO₂-[bmim][FAP] mixture, for both catalysts, relative to the values obtained in [bmim][FAP] or scCO₂ (compare e.g., entry 3 of Table 3 with entries 9 and 12 of Table 1). The dissolution of CO₂ in the IL reduces its viscosity and enhances the mass transfer of the IL, promoting higher yields. Moreover, in scCO₂-IL systems, oxygenates were separated without contamination of catalyst or solvents, making them good candidates for a continuous flow strategy able to further improve the efficiency and industrial potential of these systems.

Cyclohexanone was the main product of the cyclohexane oxidation in all tested media. Regarding pure solvents, the highest selectivity towards cyclohexanone was achieved in [bmim][FAP]. The possibility of tuning the selectivity towards alcohol or ketone formation by choosing the appropriate IL was previously found [12] for **1** in [bmim][N(CN)₂] and [bmim][BF₄] and was now extended to the media of the present study.

In scCO₂-IL, the selectivity towards cyclohexanone increased significantly (up to 96% in scCO₂-[bmim][PF₆] for **2**, Table 3, entry 2) when compared with that obtained in pure solvents (maximum of 77% in [bmim][FAP], Table 2, entry 9). Such a feature can be of applied relevance. In fact, the current production process of polyamide 6 involves the conversion of cyclohexanol and cyclohexanone mixture obtained from cyclohexane oxidation to pure cyclohexanone (at high pressure, 250 °C, in the presence of copper and chromium oxides), which is then used to form caprolactam, the monomer of polyamide 6 [26,27].

The influence of scCO₂ density on the selectivity for oxygenated products from the oxidation of cyclohexane has been reported previously [37]. A higher density leads to a higher selectivity, since the formed oxygenates are believed to be removed more easily from the catalyst surface without being totally oxidized due to the higher solvent power of the denser CO₂ in the supercritical phase [39].

The attempts to recycle catalysts **1** or **2** in acetonitrile or scCO₂ were not successful. However, recycling of these catalysts was performed up to five cycles in each pure ionic liquid medium or scCO₂-IL mixed solvents (Figure 3).

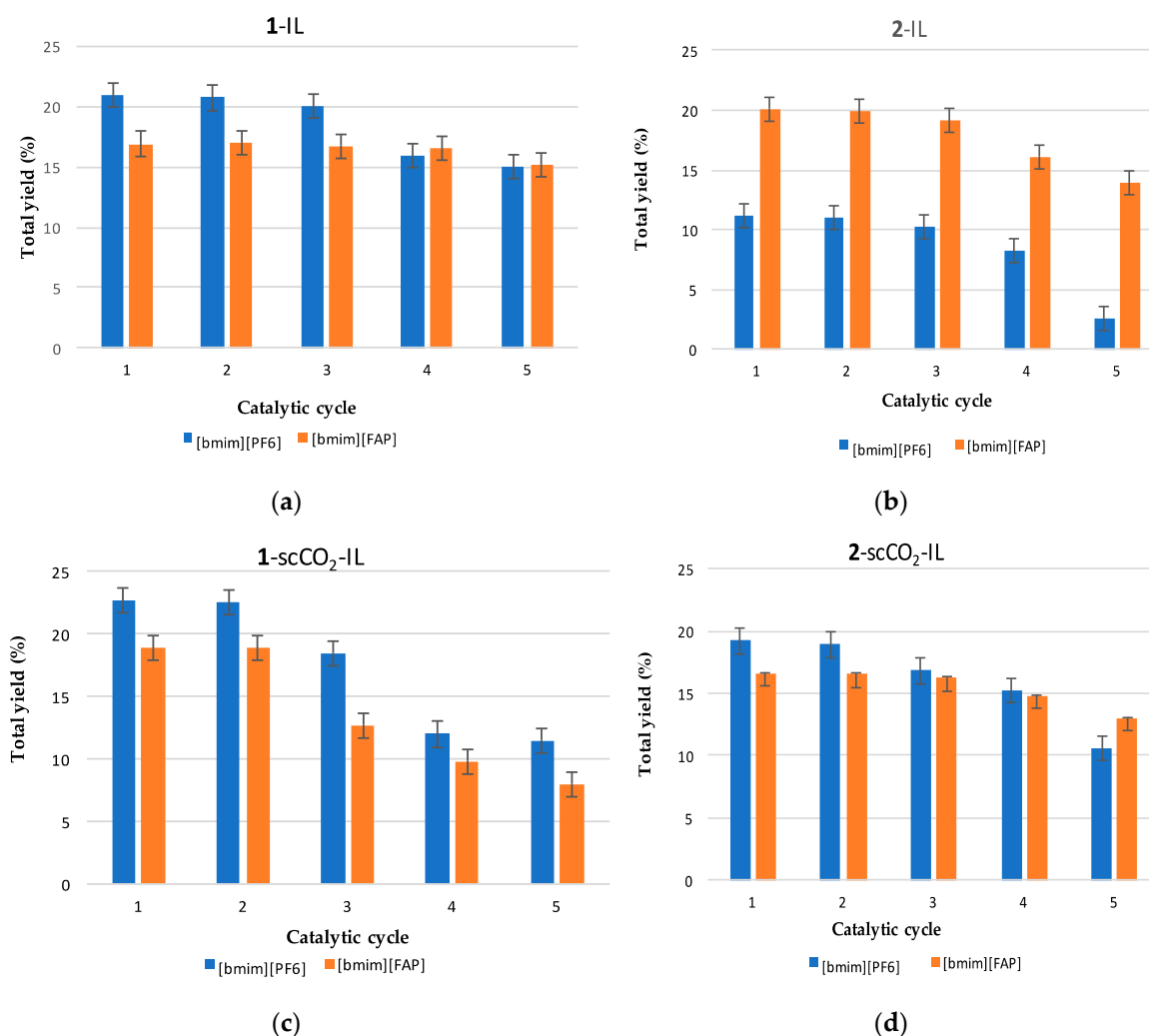


Figure 3. Products yield upon catalyst recycling in (a) ionic liquid (IL) for catalyst **1** (reaction time: 6 h), (b) IL for catalyst **2** (reaction time: 6 h), (c) scCO₂-IL for catalyst **1** ($p(\text{CO}_2) = 90$ bar and 6 h of reaction time) and (d) scCO₂-IL for catalyst **2** ($p(\text{CO}_2) = 90$ bar and 6 h of reaction time).

While the catalytic activity of compound **2** is well preserved in all (pure or mixture) tested solvents at least for the first three consecutive cycles (compare Figure 3b–d), catalyst **1** is better preserved in pure ILs than in the scCO₂-IL mixed solvents (compare Figure 3a–c). The decrease in the catalyst activity after the third cycle is probably associated to its decomposition or deactivation. A deeper understanding of how the ILs and SCFs properties can affect the performance of the catalytic systems, in particular their recyclability, will be addressed in future studies.

3. Materials and Methods

All the reagents and solvents were purchased from Sigma-Aldrich, Munich, Germany, and used as received. The scorpionate complexes **1** [28] and **2** [29] were synthesized and characterized according to methods described in the literature. Liquid CO₂, purity of 99.995%, in a cylinder with a dip tube was supplied by Air Liquid and used without further purification. [bmim][PF₆] was synthesized according to a published procedure [40], dried and degassed under vacuum at 70 °C for 48 h prior to use. [bmim][FAP] was kindly given by Merck Chemicals and no further treatment was performed.

3.1. Procedure for the Catalytic Oxidations Using a Molecular or an Ionic Liquid Solvent

The cyclohexane oxidation using [bmim][X] ($X = PF_6$ or FAP) or CH_3CN as a solvent (up to 5 mL total volume) was carried out in air, in a round bottom flask, with vigorous stirring. The catalyst was added to the solvent as a solid or in the form of a stock solution in the reaction medium. Cyclohexane (5 mmol) was then introduced, and the reaction started when TBHP (10 mmol) was added in one portion. The reaction was stopped after the desired time and 5 mL of diethyl ether were added for the extraction of the organic products.

The reaction mixtures were analyzed by gas chromatography (GC) upon the addition of an excess of triphenylphosphine to reduce cyclohexyl hydroperoxide to cyclohexanol, following a method developed by Shul'pin [41]. Nitromethane (0.05 mL) was used as an internal standard. Chromatographic measurements were performed in a Fisons Instruments GC 8000 series gas chromatograph with a BP20/SGE (30 m \times 0.22 mm \times 0.25 mm) capillary column (flame ionization detector (FID) detector) and Jasco-Borwin v.1.50 software (Jasco, Toquio, Japan) using helium as a carrier gas. All products formed were identified and their retention times confirmed with those of commercially available samples. A Perkin-Elmer Clarus 600 gas chromatograph, equipped with two capillary columns (SGE BPX5; 30 m \times 0.32 mm \times 25 mm), one with an electron impact-mass spectrometry EI-MS detector and the other one with an FID detector, was also used for analyzing the reaction mixtures. Helium was used as the carrier gas. Blank experiments in CH_3CN and ILs were performed and it was confirmed that no cyclohexane oxidation products (or only traces, below 1%) were obtained in the absence of the iron catalyst.

3.2. Procedure for the Catalytic Oxidations in $scCO_2$ or in $scCO_2$ -IL

The oxidation reaction was carried out in batch mode using a supercritical fluid apparatus as previously described [42], placed inside a fume hood for safety reasons.

Oxidation reactions were carried out in batch mode using a stainless steel reactor (16 mL, 316 stainless steel hollow cylinder, custom-fabricated with a mechanic stirrer). The reactor was charged with the catalyst, cyclohexane, and the oxidant. The system was then brought up to the desired CO_2 pressure and temperature. The supercritical temperature and pressure were measured with a platinum resistance thermometer and a digital pressure transducer, respectively. The reaction mixtures were stirred for 1–10 h at 70 °C and at CO_2 pressure up to 90 bar. Products were collected by trapping the reaction in cold ethyl ether and carefully vented to the atmospheric pressure through a cold trap cooled with liquid nitrogen. Products were analyzed by GC upon the addition of an excess of triphenylphosphine (see above) [41]. Blank experiments in $scCO_2$ were performed and it was confirmed that no cyclohexane oxidation products (or only traces, below 1%) were obtained in the absence of the iron catalyst.

3.3. Catalyst Recycling

Catalyst recyclability was investigated in all media, but only the ILs and $scCO_2$ -IL media led to successful results. Each new cycle was initiated after the preceding one upon the addition of new typical (see above) portions of all other reagents. After the completion of each run, the ionic liquid with the catalyst was recovered by drying in vacuum overnight at 80 °C and the products were analyzed as previously described.

4. Conclusions

The catalytic performance of the two C-scorpionate iron(II) complexes **1** and **2** in the tested media towards the oxidation of cyclohexane with TBHP follows the same trend: (i) the activity order [bmim][PF_6] > [bmim][FAP] > $scCO_2$ > CH_3CN can be established; and (ii) in each medium, **1** leads to higher yield and TON values than **2**. Thus, the highest oxygenates yield (21%) is achieved with **1** in [bmim][PF_6]. In comparison, the organic molecular solvent CH_3CN leads to much lower yields

(up to 6%) and selectivity towards cyclohexanone. Moreover, in this organic solvent, **1** and **2** cannot be recovered and recycled. In the scCO₂-IL (IL = bmim)[PF₆] or [bmim][FAP]) mixed solvents, complexes **1** and **2** show a remarkably high selectivity towards cyclohexanone formation and the products yield is also enhanced relative to the pure solvents. The catalysts can be recycled in those media, preserving their activity up to three consecutive cycles.

This study has initiated the exploration of the catalytic properties of C-scorpionate Fe(II) complexes for alkane oxidations in IL and scCO₂ (pure and mixed) solvents, and the promising results encourage further extension of the investigation to other alkanes and catalysts.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4344/7/8/230/s1, Table S1: Selected data for the cyclohexane oxidation using FeCl₂·2H₂O as catalyst.

Acknowledgments: Financial support from the Fundação para a Ciência e a Tecnologia (FCT), Portugal, for fellowship SFRH/BPD/90883/2012 to A.P.C.R. and for the UID/QUI/00100/2013, PTDC/QEQ-ERQ/1648/2014 and PTDC/QEQ-QIN/3967/2014 projects are gratefully acknowledged. The authors also acknowledge the Portuguese NMR Network (IST-UL Centre) for access to the NMR facility.

Author Contributions: A.P.C.R. and L.M.D.R.S.M. conceived and designed the catalytic experiments; T.A.G.D., E.C.B.A.A. and I.A.S.M. prepared and characterized the catalysts. A.P.C.R. performed the catalytic experiments; A.P.C.R. and L.M.D.R.S.M. analyzed the data and wrote the paper; L.M.D.R.S.M. and A.J.L.P. provided the means needed for the realization of this work. All authors read and approved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Anastas, P.; Warner, J.C. *Green Chemistry—Theory and Practice*, 1st ed.; Oxford University Press: New York, NY, USA, 1998; p. 30.
2. Muldoon, M. Chapter 4—Catalysis in ionic liquid-supercritical CO₂. In *Catalysis in Ionic Liquids: From Catalyst Synthesis to Application*, 1st ed.; Hardacre, C., Pârvulescu, V., Eds.; Royal Society of Chemistry: London, UK, 2014; Volume 15, pp. 309–344.
3. Zhou, L.; Akgerman, A. Catalytic oxidation of ethanol and acetaldehyde in supercritical carbon dioxide. *Ind. Eng. Chem. Res.* **1995**, *34*, 1588–1595. [[CrossRef](#)]
4. Zhou, L.; Erkey, C.; Akgerman, A. Catalytic oxidation of toluene and tetralin in supercritical carbon dioxide. *AIChE J.* **1995**, *41*, 2122–2130. [[CrossRef](#)]
5. Dooley, K.M.; Knopf, F.C. Oxidation catalysis in a supercritical fluid medium. *Ind. Eng. Chem. Res.* **1987**, *26*, 1910–1916. [[CrossRef](#)]
6. Srinivas, P.; Mukhopadhyay, M. Oxidation of cyclohexane in supercritical carbon dioxide medium. *Ind. Eng. Chem. Res.* **1994**, *33*, 3118–3124. [[CrossRef](#)]
7. Mukhopadhyay, M.; Srinivas, P. Multicomponent solubilities of reactants and products of cyclohexane oxidation in supercritical carbon dioxide. *Ind. Eng. Chem. Res.* **1996**, *35*, 4713–4717. [[CrossRef](#)]
8. Srinivas, P.; Mukhopadhyay, M. Influence of the thermodynamic state on cyclohexane oxidation kinetics in carbon dioxide medium. *Ind. Eng. Chem. Res.* **1997**, *36*, 2066–2074. [[CrossRef](#)]
9. Hou, Z.; Han, B.; Gao, L.; Liu, Z.; Yang, G. Selective oxidation of cyclohexane in compressed CO₂ and in liquid solvents over MnAPO-5 molecular sieve. *Green Chem.* **2002**, *4*, 426–430. [[CrossRef](#)]
10. Medina-Gonzalez, Y.; Camy, S.; Condoret, J.S. ScCO₂/green solvents: Biphasic promising systems for cleaner chemicals manufacturing. *ACS Sustain. Chem. Eng.* **2014**, *2*, 2623–2636. [[CrossRef](#)]
11. Sahle-Demessie, E.; Gonzalez, M.A.; Enriquez, J.; Zhao, Q. Selective oxidation in supercritical carbon dioxide using clean oxidants. *Ind. Eng. Chem. Res.* **2000**, *39*, 4858–4864. [[CrossRef](#)]
12. Ribeiro, A.P.C.; Martins, L.M.D.R.S.; Kuznetsov, M.L.; Pombeiro, A.J.L. Tuning Cyclohexane Oxidation: Combination of microwave irradiation and ionic liquid with the C-scorpionate [FeCl₂(Tpm)] catalyst. *Organomet* **2017**, *36*, 192–198. [[CrossRef](#)]
13. Ribeiro, A.P.C.; Martins, L.M.D.R.S.; Hazra, S.; Pombeiro, A.J.L. Catalytic oxidation of cyclohexane with hydrogen peroxide and a tetracopper(II) complex in an ionic liquid. *C. R. Chim.* **2015**, *18*, 758–765. [[CrossRef](#)]

14. Freire, M.G.; Cláudio, A.F.M.; Araújo, J.M.M.; Coutinho, J.A.P.; Marrucho, I.M.; Canongia Lopes, J.N.; Rebelo, L.P.N. Aqueous biphasic systems: A boost brought about by using ionic liquids. *Chem. Soc. Rev.* **2012**, *41*, 4966–4995. [[CrossRef](#)] [[PubMed](#)]
15. Pârvulescu, V.I.; Hardacre, C. Catalysis in ionic liquids. *Chem. Rev.* **2007**, *107*, 2615–2665. [[CrossRef](#)] [[PubMed](#)]
16. Hallett, J.P.; Welton, T. Room-temperature ionic liquids: Solvents for synthesis and catalysis. *Chem. Rev.* **2011**, *111*, 3508–3576. [[CrossRef](#)] [[PubMed](#)]
17. Giernoth, R. Homogeneous Catalysis in Ionic Liquids. In *Topics Current Chemistry*, 1st ed.; Bargon, J., Ed.; Springer: Berlin, Germany, 2007; Volume 276, pp. 1–23.
18. Ribeiro, A.P.C.; Karabach, Y.Y.; Martins, L.M.D.R.S.; Gamal, A.; da Silva, M.F.C.G.; Pombeiro, A.J.L. Nickel (II)-2-amino-4-alkoxy-1, 3, 5-triazapentadienate complexes as catalysts for Heck and Henry reactions. *RSC Adv.* **2016**, *6*, 29159–29163. [[CrossRef](#)]
19. Martins, L.M.D.R.S.; Ribeiro, A.P.C.; Pombeiro, A.J.L. Highly selective cyclohexane oxidation catalyzed by ferrocene in ionic liquid medium. *Lett. Org. Chem.* **2017**, *14*. [[CrossRef](#)]
20. Tiago, G.A.O.; Ribeiro, A.; Mahmudov, K.T.; da Silva, M.F.C.G.; Branco, L.C.; Pombeiro, A.J.L. Mononuclear copper(II) complexes of arylhydrazones of 1H-Indene-1,3(2H)-dione as catalysts for the oxidation of 1-phenylethanol in ionic liquid medium. *RSC Adv.* **2016**, *6*, 83412–83420. [[CrossRef](#)]
21. Hazra, S.; Ribeiro, A.P.C.; da Silva, M.F.C.G.; de Castro, C.A.N.; Pombeiro, A.J.L. Syntheses and crystal structures of benzene-sulfonate and -carboxylate copper polymers and their application to oxidation of cyclohexane in ionic liquid under mild conditions. *Dalton Trans.* **2016**, *45*, 13957–13968. [[CrossRef](#)] [[PubMed](#)]
22. Martins, L.M.D.R.S.; Pombeiro, A.J.L. Water-soluble C-scorpionate complexes: Catalytic and biological applications. *Eur. J. Inorg. Chem.* **2016**, *15–16*, 2236–2252. [[CrossRef](#)]
23. Martins, L.M.D.R.S.; Pombeiro, A.J.L. Tris(pyrazol-1yl)methane metal complexes for catalytic mild oxidative functionalizations of alkanes, alkenes and ketones. *Coord. Chem. Rev.* **2014**, *265*, 74–88. [[CrossRef](#)]
24. Martins, L.M.D.R.S. C-homoscorpionate oxidation catalysts—Electrochemical and catalytic activity. *Catalysts* **2017**, *7*, 12. [[CrossRef](#)]
25. Kirk-Othmer. *Kirk-Othmer Encyclopedia of Chemical Technology*; John Wiley & Sons: New York, NY, USA, 2014.
26. Elvers, B. *Ullmann's Encyclopedia of Industrial Chemistry*, 6th ed.; Ullmann, F., Hawkins, S., Schula, G., Gerhartz, W., Russey, W.E., Elvers, B., Eds.; Wiley-VCH: Weinheim, Germany, 1999–2016; Volume 11, pp. 41–49.
27. Clerici, M.G.; Ricci, M.; Strukul, G. *Metal-Catalysis in Industrial Organic Processes*; Chiusoli, G.P., Maitlis, P.M., Eds.; Royal Society of Chemistry: Cambridge, UK, 2006.
28. Silva, T.F.S.; Alegria, E.C.B.A.; Martins, L.M.D.R.S.; Pombeiro, A.J.L. Scorpionate vanadium, iron and copper complexes as selective catalysts for the peroxydative oxidation of cyclohexane under mild conditions. *Adv. Synth. Catal.* **2008**, *350*, 706–716. [[CrossRef](#)]
29. Ribeiro, A.P.C.; Alegria, E.C.B.A.; Martins, L.M.D.R.S.; Duarte, T.A.G.; Pombeiro, A.J.L. C-scorpionate iron(II) complexes as highly selective catalysts for the hydrocarboxylation of cyclohexane. *Adv. Synth. Catal.* **2017**, under review.
30. Hou, Z.; Han, B.; Gao, L.; Jiang, T.; Liu, Z.; Chang, Y.; Zhang, X.; He, J. Wacker oxidation of 1-hexene in 1-*n*-butyl-3-methylimidazolium hexafluorophosphate ([bmim][PF₆]), supercritical (SC) CO₂, and SC CO₂/[bmim][PF₆] mixed solvent. *New J. Chem.* **2002**, *26*, 1246–1248. [[CrossRef](#)]
31. Blanchard, L.A.; Hancu, D.; Beckman, E.J.; Brennecke, J.F. Green processing using ionic liquids and CO₂. *Nature* **1999**, *399*, 28–29. [[CrossRef](#)]
32. Martins, L.M.D.R.S.; Martins, A.; Alegria, E.C.B.A.; Carvalho, A.P.; Pombeiro, A.J.L. Efficient cyclohexane oxidation with hydrogen peroxide catalysed by a C-scorpionate iron(II) complex immobilized on desilicated MOR zeolite. *Appl. Catal. A Gen.* **2013**, *464–465*, 43–50. [[CrossRef](#)]
33. Martins, L.M.D.R.S.; de Peixoto Almeida, M.; Carabineiro, S.A.C.; Figueiredo, J.L.; Pombeiro, A.J.L. Heterogenisation of a C-scorpionate Fe(II) complex in carbon materials for cyclohexane oxidation with hydrogen peroxide. *ChemCatChem* **2013**, *5*, 3847–3856. [[CrossRef](#)]
34. Pombeiro, A.J.L.; Martins, L.M.D.R.S.; Ribeiro, A.P. Process for the Microwave-assisted Conversion of Cycloalkanes to the Corresponding Alcohol-Ketone Mixtures, with Hydrogen Peroxide, and Using a Scorpionate Chloro-Complex of Iron(II) as Catalyst. PT 107797, 25 July 2014.
35. Pombeiro, A.J.L.; Martins, L.M.D.R.S.; Alegria, E.C.B.A.; Silva, T.F.S. Scorpionate Chloro-Complexes of Iron and Vanadium and their Application as Catalysts for the Partial Oxidation, under Mild and Environmentally Tolerable Conditions, of Cyclohexane to Cyclohexanol and Cyclohexanone. PT 104153, 4 July 2008.

36. Pombeiro, A.J.L. (Ed.) Toward functionalization of alkanes under environmentally benign conditions. In *Advances in Organometallic Chemistry and Catalysis*; John Wiley & Sons: Hoboken, NJ, USA, 2013; Chapter 2; pp. 15–25.
37. Kerler, B.; Martin, A.; Jans, A.; Baerns, M. Partial oxidation of propane in compressed carbon dioxide using $\text{CoO}_x/\text{SiO}_2$ catalysts. *Appl. Catal. A Gen.* **2001**, *220*, 243–252. [[CrossRef](#)]
38. *Ionic Liquids Product Range for Your Innovations*; Merck Catalog; Merck KGaA: Darmstadt, Germany, 2014.
39. Olsen, M.H.N.; Salomao, G.C.; Drago, V.; Femandes, C.; Horn, A.; Cardozo, L.; Antunes, O.A.C. Oxidation of cyclohexane in supercritical carbon dioxide catalyzed by iron tetraphenylporphyrin. *J. Supercrit. Fluids* **2005**, *34*, 119–124. [[CrossRef](#)]
40. Huddleston, J.G.; Willauer, H.D.; Swatloski, R.P.; Visser, A.E.; Rogers, R.D. Room temperature ionic liquids as novel media for ‘clean’ liquid–liquid extraction. *Chem. Commun.* **1998**, 1765–1766. [[CrossRef](#)]
41. Shul’pin, G.B.; Kozlov, Y.N.; Nizova, G.V.; Süß-Fink, G.; Stanislas, S.; Kitaygorodskiy, A.; Kulikova, V.S. Oxidations by the reagent “ $\text{O}_2\text{--H}_2\text{O}_2\text{--vanadium derivative--pyrazine-2-carboxylic acid}$ ”. Part 12.1 Main features, kinetics and mechanism of alkane hydroperoxidation. *J. Chem. Soc. Perkin Trans.* **2001**, *2*, 1351–1371. [[CrossRef](#)]
42. Fernandes, R.R.; Lasri, J.; da Silva, M.F.C.G.; Palavra, A.M.F.; da Silva, J.A.L.; da Silva, J.J.R.F.; Pombeiro, A.J.L. Oxadiazoline and Ketoimine Palladium(II) complexes as highly efficient catalysts for Suzuki–Miyaura cross-coupling reactions in supercritical carbon dioxide. *Adv. Synth. Catal.* **2011**, *353*, 1153–1160. [[CrossRef](#)]



© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).