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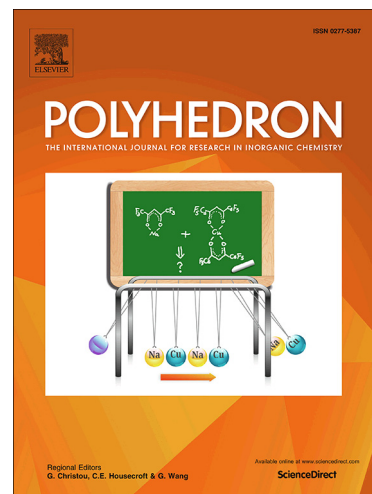
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***An eco-friendly approach to the cyclohexane oxidation catalyzed by manganese porphyrins:
green and solvent-free systems***

Adriano Silva Guimarães, Bernardo Schmitberger, Alexandre Moreira Meireles, Dayse Carvalho da Silva Martins, and Gilson DeFreitas-Silva[*]

*gilsonufmg@ufmg.br

Departamento de Química, Instituto de Ciências Exatas, Universidade Federal de Minas Gerais, 31270-901, Belo Horizonte, MG, Brazil.

* Corresponding author:

Prof. Gilson de Freitas Silva (G. DeFreitas-Silva)
Departamento de Química – Instituto de Ciências Exatas – Universidade Federal de Minas Gerais
Belo Horizonte, MG, 31270-901, BRAZIL
Tel.: +55 31 3409 5762.
E-mail address: gilsonufmg@ufmg.br

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Abstract

The selective cyclohexane oxidation to cyclohexanone and cyclohexanol based on a green strategy has been a challenge. A new manganese porphyrin [Mn[III](T2,4,5TMPP)Cl] was prepared and its activity and selectivity as a catalyst were studied together with the classical manganese porphyrin [Mn[III](TPP)Cl] using green solvents (dimethyl carbonate or ethyl acetate) and solvent-free systems. The effects of the solvent (or its absence), oxidant, and co-catalyst were investigated. Under the studied conditions, the new catalyst showed a higher selectivity for cyclohexanol (above 78%) in solvent-free systems compared to the [Mn[III](TPP)Cl]. The highest total yield of the products (89%) was observed in ethyl acetate/PhIO/water system.

Keywords

Introduction

Cyclohexane oxidation under mild temperature and pressure conditions has been a challenge for the scientific community due to the high thermodynamic stability of the C-H bonds (95.5 kcal mol^{-1}) [1]. Moreover, its industrial process has assumed a new dimension [2], and the development of new oxidation routes displays a great economic interest because of the importance of its intermediates cyclohexanol and cyclohexanone to the synthesis of many polymers [3, 4].

The search for more efficient processes also presents an increasing concern for the environment. Thus, researchers have been attempting to develop systems that meet the tenets of green chemistry established by Anastas e Warner [5], such as the use of catalysis and safer solvents or auxiliaries. Therefore, sustainable routes to the cyclohexane oxidation become an interesting target which may be explored by employing green solvents and catalysts.

Among the different catalysts used in the cyclohexane oxidation, the metalloporphyrins, especially the manganese porphyrins (MnP) [6-8], are highlighted because these compounds mimetize the P450 cytochrome and catalyze the oxidation of different compounds at room temperature and pressure. The first MnP catalytic system was described by Hill and Schardt in 1980 [9] in which cyclohexane was oxidized by PhIO (iodosylbenzene) using dichloromethane as solvent. Since then, aiming at more selective systems or higher yields, a variety of manganese porphyrins have been synthesized and employed as catalysts. However, the chlorinated solvents, which are toxic and environmentally detrimental, prevail as the mean to perform the reaction in the majority of these systems, leading to unsustainable practices [10-16]. To the best of our knowledge, the development of catalytic systems for cyclohexane oxidation based on MnP employing green solvents or in the absence of solvents are scarcely reported in the literature [17].

This work aims to evaluate the cyclohexane oxidation by PhIO and PhI(OAc)$_2$ (iodobenzene diacetate) in the presence of green solvents (dimethyl carbonate or ethyl acetate) and in solvent-free

systems. Two MnP {clorido-5,10,15,20-(tetraphenylporphyrinato)manganese(III) – [Mn^{III}(TPP)Cl]) – and the new compound clorido-5,10,15-20-(2,4,5-trimethoxyphenylporphyrinato)manganese(III) – [Mn^{III}(T2,4,5TMPP)Cl]} were employed as catalysts (Figure 1), and the use of water or imidazole as additives was also evaluated in order to achieve more efficient systems.
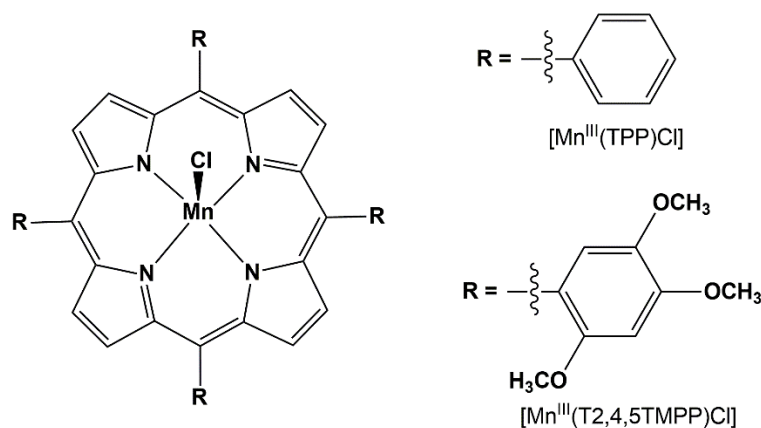
Figure 1. Structure of the manganese porphyrin catalysts.

Experimental

General Information

The pyrrole was obtained from Fluka and distilled under reduced pressure immediately before use. Dichloromethane (CH$_2$Cl$_2$) and methanol (CH$_3$OH) were obtained from Vetec and submitted to distillation before use. Iodosylbenzene (PhIO) was prepared following the procedure proposed by Saltzman e Sharefkin [18], stored at –20 ^{o}C in a freezer and periodically tested by iodometric titration. The catalyst clorido-5,10,15,20-(tetraphenylporphyrinato)manganese(III) – [Mn^{III}(TPP)Cl] – was obtained as described in the literature [19]. 2,4,5-trimethoxybenzaldehyde, nitrobenzene, propionic acid, iodobenzene diacetate {PhI(OAc)$_2$}, dimethyl carbonate {(CH$_3$O)$_2$CO} and ethyl acetate (CH$_3$COOC$_2$H$_5$) were obtained from Sigma-Aldrich with analytical degree and used without further purification.

Absorption spectra in the UV-vis region (190-1100 nm) were recorded on an HP-8453A diode-array spectrophotometer. Infrared (IR) spectra were recorded on a Perkin Elmer BXFTIR spectrometer with samples prepared in KBr pellets. Hydrogen nuclear magnetic resonance (^{1}H NMR) spectra were obtained in CDCl$_3$ at room temperature (25 ^{o}C) on a Bruker DPX-200 Advance spectrometer operating at 200 MHz with tetramethylsilane (TMS) as the internal standard. The ESI-MS analyzes were conducted on a Bruker micrOTOF-Q II mass spectrometer equipped with electrospray ionization (ESI) source operating in the positive ion mode and using acetonitrile as the solvent. The oxidation products were analyzed on a gas chromatographer (Shimadzu GC-17A) with flame ionization detector equipped with an Altech Econo-Cap capillary (30.0 m in length, 0.32 mm in diameter and 0.25 μm film thickness) with Carbowax® stationary phase. A mixture of synthetic air and hydrogen was used for the flame and

hydrogen was employed as the carrier gas. The ultrasound equipment Unique® MaxiClean 1400 (40 kHz) was also used in the experiments.

Obtaining of the new metalloporphyrin catalyst

5,10,15-20-(2,4,5-trimethoxyphenylporphyrin) – $H_2T2,4,5TMPP$

H$_2$T2,4,5TMPP was obtained by reacting 2,4,5-trimethoxybenzaldehyde (3.8910 g, 19.831 mmol) and pyrrole (1.40 mL, 20.1 mmol) in 50 mL of a mixture of propionic acid:nitrobenzene (7:3) (adaptation of the method described by Gonsalves et. al.) [20] The solution was kept under reflux and magnetic stirring for 1 hour. After cooling, the addition of 50 mL of methanol led to the precipitation of the porphyrin. The product was purified by column chromatography using neutral alumina (column height = 30 cm; column diameter = 2.50 cm) and CH$_2$Cl$_2$ as eluent. The yield of H$_2$T2,4,5TMPP was 15.4% (745.6 mg, 0.7646 mmol). UV-Vis (CH$_2$Cl$_2$), λ_{max}, nm (log ε): 424 (4.36); 516 (3.24); 553 (2.84); 592 (2.74); 652 (2.58). IR in KBr pellets (cm^{-1}): (3316) νN-H$_{pyrrole}$; (1346) νC=N$_{pyrrole}$; (1229) $\delta_{"breathing"}$ of porphyrin skeleton; (1210) $\delta_{assymetric}$ C-O-C$_{ether}$; (1015) $\delta_{symetric}$ C-O-C$_{ether}$; (978) δ N-H$_{pyrrole}$. ESI-MS in acetonitrile: [H$_2$T2,4,5MPP + H]$^+$ *m/z* 975.37. ^{1}H NMR (CDCl$_3$) δ ppm: -2.60 (s, 2H), 3.52 (m, 12H, -OCH$_3$, *para*), 3.91 (m, 12H, -OCH$_3$, *meta*), 4.20 (m, 12H, -OCH$_3$, *ortho*), 6.98 (m, 4H, ^{6}H *ortho aryl*), 7.57 (m, 4H, ^{5}H *meta aryl*), 8.81 (m, 8H β-pyrrole). Elemental analysis (%): H$_2$T2,4,5MPP (C$_{56}$H$_{54}$N$_4$O$_{12}$). Calculated: C (68.98), H (5.58), N (5.75). Experimental: C (68.45), H (4.20), N (6.06).

clorido-5,10,15-20-(2,4,5-trimethoxyphenylporphyrinato)manganese(III) – [Mn^{III}(T2,4,5TMPP)Cl]

The catalyst [Mn^{III}(T2,4,5TMPP)Cl] was obtained from the metallation of H$_2$T2,4,5TMPP (100 mg, 0,102 mmol) with MnCl$_2$.4H$_2$O (200.0 mg, 1.025 mmol) in 15 mL of *N,N*-dimethylformamide (DMF) (adaptation of the method described by Adler et al.) [21]. The reaction mixture was kept under reflux and magnetic stirring for 24 hours. The reaction was monitored by absorption spectroscopy in the UV-vis region until the porphyrin precursor was absent. The product was purified by neutral alumina column chromatography (column height = 15 cm; column diameter = 2.50 cm) using CH$_2$Cl$_2$ as eluent and then a mixture of CH$_2$Cl$_2$:CH$_3$OH (10:1) to collect the green fractions related to the complex. The yield of [Mn^{III}(T2,4,5TMPP)Cl] was 91% (97.0 mg, 0.0912 mmol). UV–Vis (CH$_2$Cl$_2$), λ_{max}, nm (log ε): 376 (4.66); 482 (4.93); 585 (3.98); 622 (4.00). IR in KBr pellets (cm^{-1}): (1349) νC=N$_{pyrrole}$; (1230) $\delta_{"breathing"}$ of porphyrin skeleton; (1208) $\delta_{assymetric}$ C-O-C$_{ether}$; (1013) $\delta_{symetric}$ C-O-C$_{ether}$; (1007) δ Mn-N$_{pyrrole}$. ESI-MS in acetonitrile: [Mn^{III}(T2,4,5TMPP)]$^+$ *m/z* 1027.29. Elemental analysis (%): [Mn^{III}(T2,4,5TMPP)Cl].0.5CH$_2$Cl$_2$ (C$_{56}$H$_{52}$N$_4$O$_{12}$MnCl.0.5CH$_2$Cl$_2$). Calculated: C(61.36), H(4.83), N(5.07). Experimental: C(62.01), H(4.00), N(5.75).

Cyclohexane oxidation

The cyclohexane oxidation in the presence of the solvent was performed according to the methodology described by Da Silva et al. [22]. In the case of solvent-free reactions, the employed methodology was the one described by Tôrres et al. [17]. The effect of imidazole was studied only for systems with solvents (by adding a 20 μL aliquot of a 1.0×10^{-2} mol L^{-1} imidazole solution prepared in the appropriate solvent) since this additive is insoluble in cyclohexane. The effect of H$_2$O was studied by adding an aliquot of 0.5 μL to the reaction medium.

Results and Discussion

Obtaining of the metalloporphyrin catalyst

H$_2$T2,4,5TMPP was initially characterized by absorption spectroscopy in the UV-Vis region (Figure 2) with a characteristic spectrum of a free base porphyrin [19]. [Mn^{III}(T2,4,5TMPP)Cl] (Figure 1) was obtained and confirmed by the loss of fluorescence (red) under ultraviolet light [23], characteristic of H$_2$T2,4,5TMPP. The UV-vis spectrum of the catalyst [Mn^{III}(T2,4,5TMPP)Cl], when compared to the free base porphyrin, revealed a bathochromic shift of the Soret band and a decrease in the number of bands [19]. The Mn(III) porphyrin spectrum is very peculiar because of the bands resulting from the ligand-metal charge transfer due to the interaction of Mn^{3+} ion orbitals with the porphyrin π system [24].
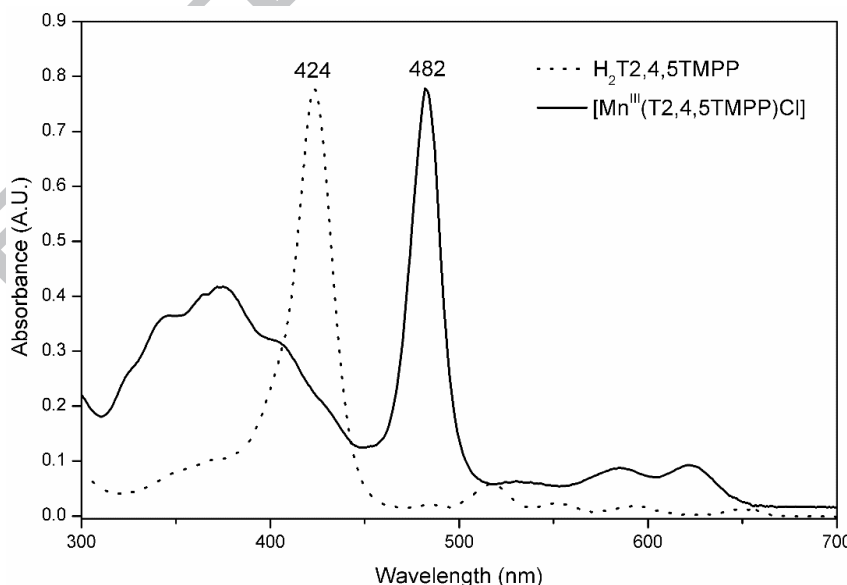
Figure 2. Absorption spectra in the UV-vis region of H$_2$T2,4,5TMPP (3.34×10^{-5} mol L^{-1}) and [Mn^{III}(T2,4,5TMPP)Cl] (9.08×10^{-6} mol L^{-1}) in CHCl$_3$.

The characterization of H$_2$T2,4,5TMPP by ^{1}H NMR spectroscopy was performed in CDCl$_3$ (Figure 3a). Two N-H pyrrole hydrogen (δ -2.60), eight hydrogen in the β-pyrrole positions (δ 8.81), four hydrogen in the ortho-aryl (δ 6.98) and meta-aryl (δ 7.57) positions were observed in the spectrum. In relation to the hydrogen of the three methoxy groups (-OCH$_3$), the spectrum indicated the

existence of three hydrogen atoms for each of the ortho (δ 4.20), meta (δ 3.91) and para (δ 3.52) positions of the aryl groups in the meso positions of the macrocycle (Figure 3b).

(a)

(b)
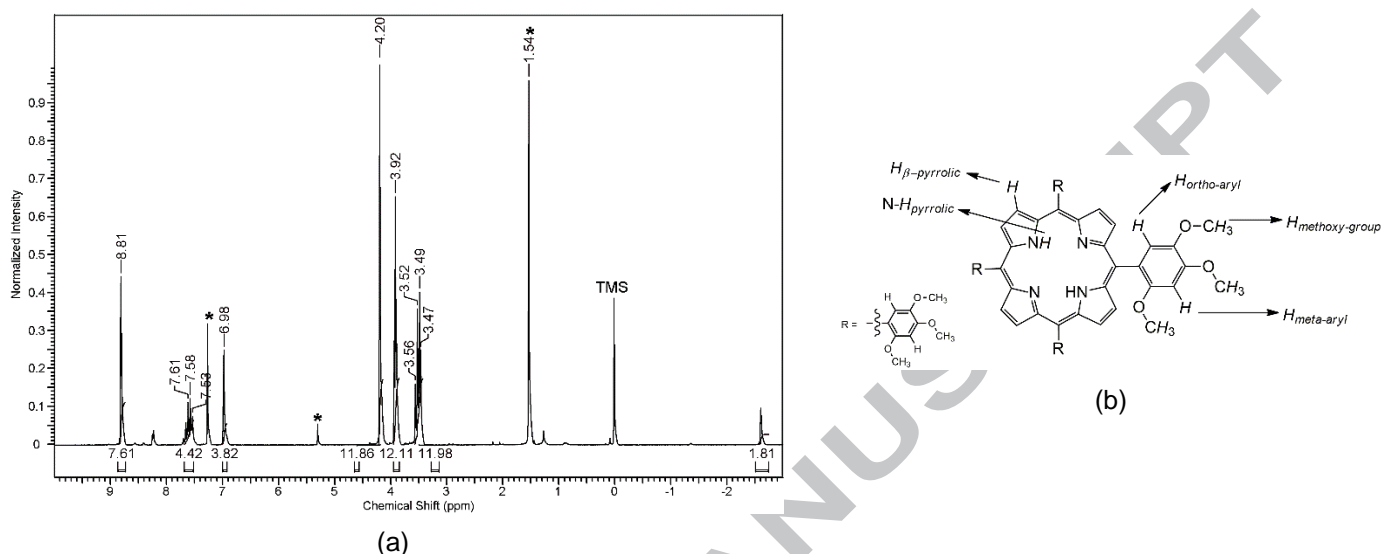
Figure 3. (a) ^{1}H NMR spectrum of $H_2T2,4,5TMPP$ in $CDCl_3$ (200 MHz, TMS) at 25 ^{o}C. δ -2.60 (s, 2H, N-H$_{pyrrolic}$), δ 3.52 (m, 12H, -OCH$_3$, *para*-), δ 3.91 (m, 12H, -OCH$_3$, *meta*-), δ 4.20 (s, 12H, -OCH$_3$, *ortho*-), δ 6.98 (m, 4H, 6H *ortho*-aryl), δ 7.57 (m, 4H, 5H *meta*-aryl), δ 8.81 (m, 8H β-pyrrolic); (b) Hydrogen atoms labeling in the structure of $H_2T2,4,5TMPP$.

$H_2T2,4,5TMPP$ and [Mn^{III}(T2,4,5TMPP)Cl] were also characterized by infrared spectroscopy (Figures S1-S4, Supplementary Material). By the results we confirmed the formation of the free base porphyrin $H_2T2,4,5TMPP$, evidenced by the bands referring to the groups (-OCH$_3$), C-O-C stretch, aromatic ether stretch, macrocycle deformation and N-H deformation (pyrrole) (Figure S2, Supplementary Material) [25]. Its metallation was confirmed by the absence of the deformation band (out of plane) of the N-H bond of the pyrrole groups, and a new band was observed referring to the deformation of the pyridinic Mn-N bond (Figure S4, Supplementary Material) [26].

The free base porphyrin $H_2T2,4,5TMPP$ and the new catalyst [Mn^{III}(T2,4,5TMPP)Cl] were characterized by mass spectrometry (Figures S5 and S6, Supplementary Material) with a signal centered at m/z 975.37 and 1027.29, respectively. These signals were associated with the species [$H_2T2,4,5TMPP + H$]$^+$ and [Mn^{III}(T2,4,5TMPP)]$^+$ with the loss of the chloride ion.

Cyclohexane oxidation

The cyclohexane oxidation using manganese porphyrins as catalysts has been studied for almost 40 years [9]. However, the vast majority of reports employs the use of chlorinated solvents (dichloromethane, for example) [10-14] and, to the best of our knowledge, none has described the use of green solvents. In this sense, we decided to evaluate the use of two green solvents in the cyclohexane oxidation reaction using [Mn^{III}(TPP)Cl] as a catalyst. The following observed results for

this catalyst stimulated the search for a more efficient catalyst, such as the new obtained catalyst [Mn^{III}(T2,4,5TMPP)Cl], as will be shown in this work.

Among the green solvent options, we have chosen ethyl acetate and dimethyl carbonate mainly because of the catalyst solubility. Moreover, ethyl acetate has shown itself to be a very useful green solvent. For example, at MADIX polymerization, Levere and co-workers observed that this solvent allowed the production of polymers with a high monomer conversion (near 100%) and high molecular weights [27]. Dimethyl carbonate is a biodegradable solvent that has demonstrated many efficient applications, for example, to synthesize unsymmetrical 2,6-diarylated aniline derivatives. The expected product was obtained in yields up to 91% [28]. In this way, these were the two green solvents selected for the present work. In order to verify the green solvent effect, we decided to study the standard oxygen donor iodosylbenzene (PhIO) and its precursor iodobenzene diacetate [PhI(OAc)$_2$].

In systems using PhIO as an oxidant (FIGURE 4a), both green solvents provided a slight increase in the selectivity for cyclohexanol and in the catalyst stability. However, the total yield for the products is practically unchanged. Our research group has shown that PhI(OAc)$_2$ can advantageously replace PhIO as an oxidant because it is commercially available, more stable, non-explosive and easily stored [14, 17, 22, 29-31]. In previous works, we demonstrated that the cyclohexane oxidation by [Mn^{III}(TPP)Cl] discretely increased the alcohol selectivity in the presence of PhI(OAc)$_2$ as an oxidant [56% with PhIO *versus* 65% with PhI(OAc)$_2$] [14]. Figure 4b shows that ethyl acetate increased the total product yield (25% and 54% with PhIO and PhI(OAc)$_2$, respectively) with little variation in selectivity. On the other hand, the catalyst stability was slightly lower in the PhI(OAc)$_2$ system. This behavior has already been observed in other systems in the literature [14, 29, 32], in which dichloromethane was employed as the solvent.
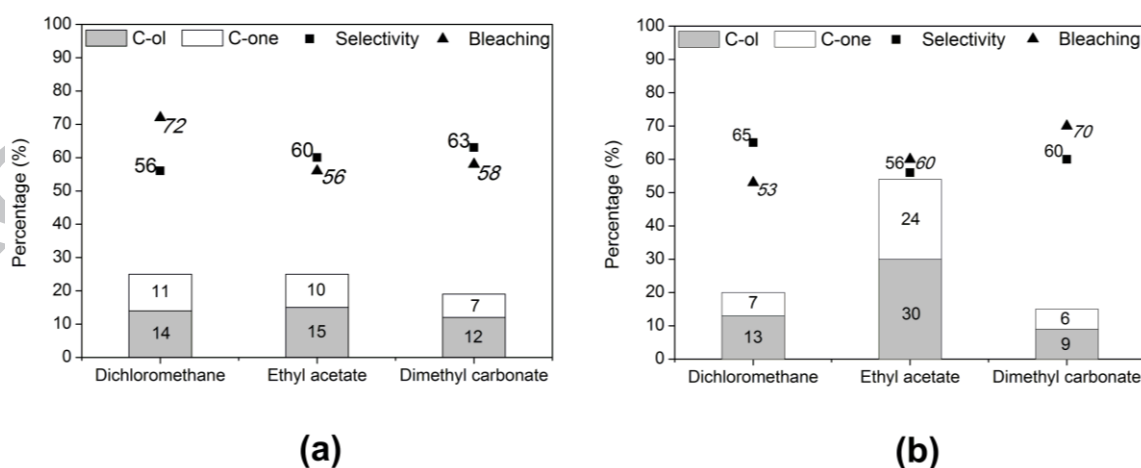
Figure 4. Cyclohexane oxidation reactions by (a) PhIO or (b) PhI(OAc)$_2$, in different solvents catalyzed by [Mn^{III}(TPP)Cl]. Reaction conditions: MnP/Oxidant/cyclohexane molar ratio = 1:10:4625, 25 $^{\circ}$C, magnetic stirring, 90 min. of reaction. Yields (%) based on the oxidant. C-ol: cyclohexanol and C-one: cyclohexanone. Selectivity for the alcohol was determined from the relation: Selectivity = 100 × [%C-ol/(%C-ol + %C-one)]. The degree of destruction of the catalyst was calculated based on the UV–Vis absorption spectra recorded at the end of the reaction.

Considering that ethyl acetate provided an increase in the total yield of the substrate oxidation system in the presence of iodobenzene diacetate (compared to dichloromethane), and that we have already shown the increase in total yield (with no changes of alcohol selectivity) in the presence of additives (imidazole and water) [14, 22, 29-31, 33, 34], we decided to verify the effect of these additives in the systems with the green solvents. It is important to emphasize that the amount of imidazole/water employed in this work was very small, showing that it is not necessary to use such a large excess of this additive as it has been observed in most studies [10, 33-35]. For example, in the work by Li and Xia, the molar ratio catalyst:imidazole was 1:50 [33], meanwhile in this work it is 1:1 (0.02% catalyst amount). Thus, we studied the effect of imidazole and water on cyclohexane oxidation by PhI(OAc)$_2$ catalyzed by [Mn^{III}(TPP)Cl] in ethyl acetate (Figure 5a). Figure 5a shows that the addition of water or imidazole reduces the total yield, but it slight increases of the selectivity and stability of the catalyst. This result was unexpected because, in most of the reports in the literature, imidazole and water provided systems which increased the total yield [14, 22, 29-31].
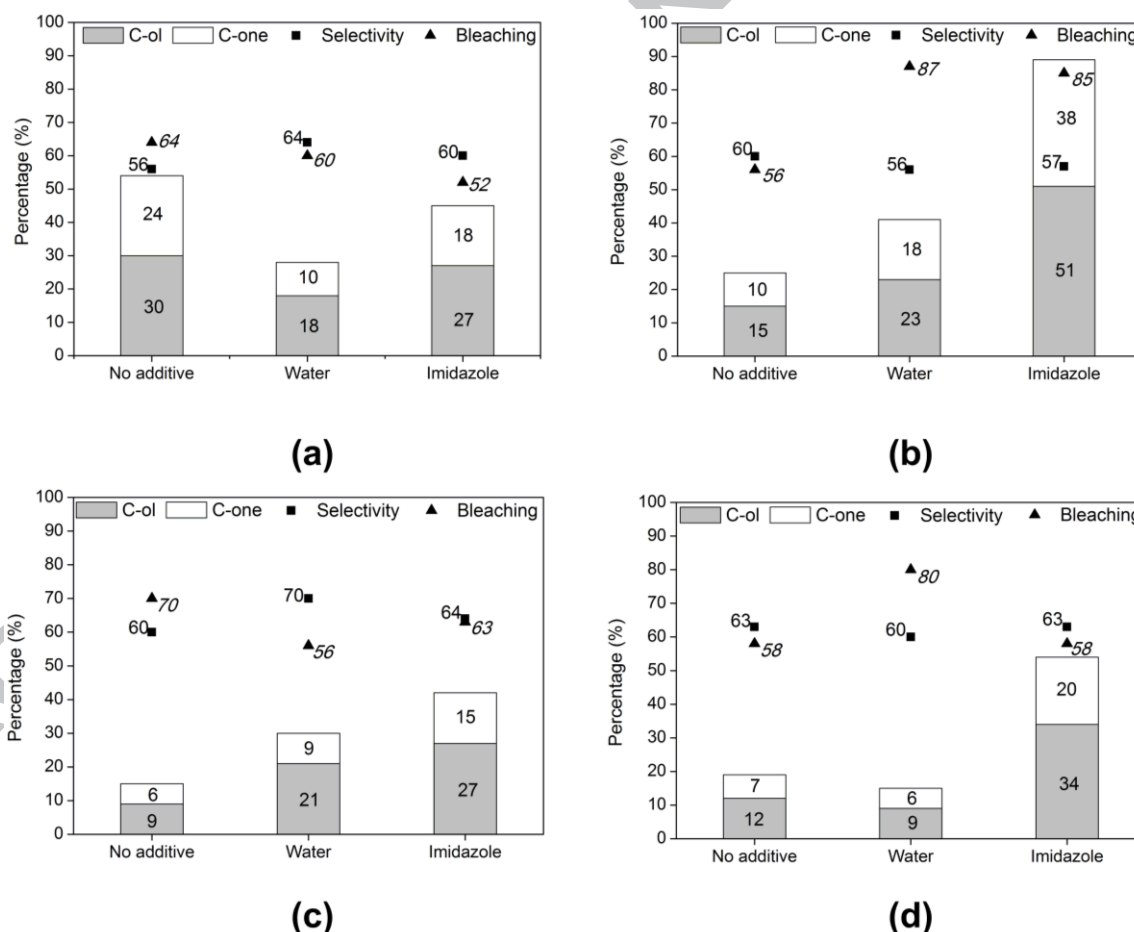
Figure 5. Cyclohexane oxidation reactions catalyzed by [Mn^{III}(TPP)Cl] in presence of additives (water or imidazole) with: (a) PhI(OAc)$_2$/ethyl acetate; (b) PhIO/ethyl acetate; (c) PhI(OAc)$_2$/dimethyl carbonate; (d) PhIO/dimethyl carbonate. Reaction conditions: MnP/Oxidant/cyclohexane molar ratio = 1:10:4625, 25 ^{o}C, magnetic stirring, 90 min. of reaction. Yields (%) based on the oxidant. C-ol: cyclohexanol and C-one: cyclohexanone. Selectivity for the alcohol was determined from the relation:

Selectivity = 100 × [%C-ol/(%C-ol + %C-one)]. The degree of destruction of the catalyst was calculated based on the UV–Vis absorption spectra recorded at the end of the reaction.

Facing these results, we decided to evaluate the way these same additives affected systems containing PhIO as an oxidant (in both green solvents) and the reaction performed with dimethyl carbonate/PhI(OAc)$_2$ (Figure 5b,c,d). For most of these systems, an increase in the total yield was observed with no changes of selectivity, highlighting the use of imidazole as additive ([Mn[III](TPP)Cl] + PhIO + ethyl acetate + imidazole, with 89% total yield). This result is associated with the destabilization of the high valence active species, caused by the presence of the axial ligand [36, 37].

Despite the higher total yields, the studied catalyst [Mn[III](TPP)Cl] was more degraded in the presence of additives (between 52 and 87% degradation) due to its structural and electronic characteristics. This catalyst belongs to the 1st generation MnP group, which are more easily degraded in the reaction medium due to the lack of substituents in the aryl group of the macrocycle at meso positions [38].

Thus, we decided to obtain a new catalyst that could present selectivity similar to the one observed in these systems {using [Mn[III](TPP)Cl]} with an increase of its stability in the catalytic systems. We have shown that cyclohexane oxidation by PhIO in dichloromethane and addition of imidazole have increased the total yield (with no changes of selectivity) when MnP containing two methoxy groups (positions 3 and 5 of the aryl group related to the porphyrin macrocycle) was compared to that containing only one group (position 4 of the aryl group related to the porphyrin macrocycle). Thus, we attempted to prepare a MnP containing three methoxy groups in order to further increase this total yield. In this sense, the [Mn[III](T2,4,5TMPP)Cl] complex, which contains three substituents in the aryl group at the meso positions of the macrocycle, was synthesized. This metalloporphyrin was inspired by these two previous works about manganese porphyrins with one or two methoxy substituents on the aryl group [30, 31]. Among the possible aldehydes precursors for the desired catalyst, the one with the methoxy groups at the 2, 4 and 5 positions of the phenyl ring was chosen because of its low commercial cost. This MnP was obtained relatively simply and with good yield (15.4%), using an adaptation of the method proposed by Gonsalves et al [20].
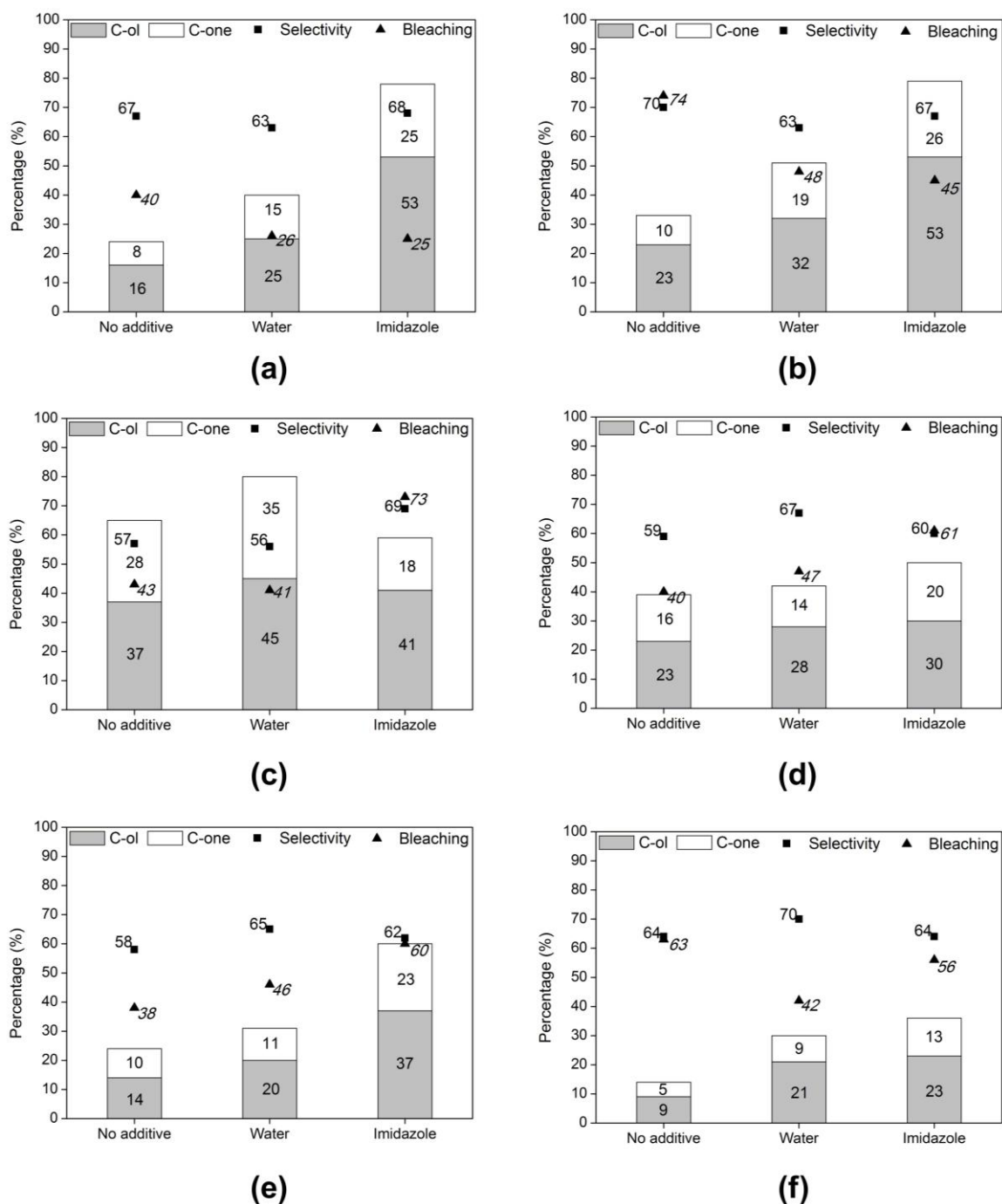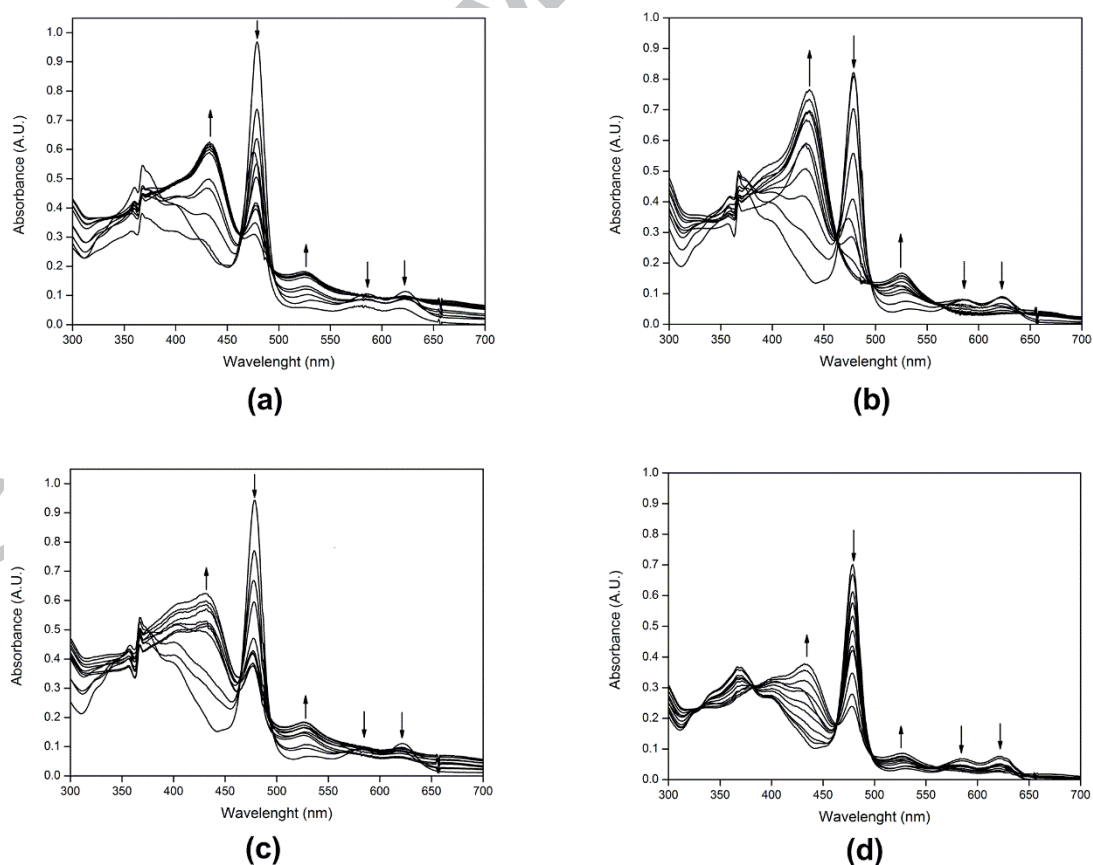
Figure 6. Cyclohexane oxidation reactions catalyzed by [Mn^{III}(T2,4,5TMPP)Cl] in presence of additives (water or imidazole) with: (a) PhIO/CH$_2$Cl$_2$; (b) PhI(OAc)$_2$/CH$_2$Cl$_2$; (c) PhIO/ethyl acetate; (d) PhI(OAc)$_2$/ethyl acetate; (e) PhIO/dimethyl carbonate; (f) PhI(OAc)$_2$/dimethyl carbonate. Reaction conditions: MnP/Oxidant/cyclohexane molar ratio = 1:10:4625, 25 °C, magnetic stirring, 90 min. of reaction. Yields (%) based on the oxidant. C-ol: cyclohexanol and C-one: cyclohexanone. Selectivity for the alcohol was determined from the relation: Selectivity = 100 × [%C-ol/(%C-ol + %C-one)]. The degree of destruction of the catalyst was calculated based on the UV–Vis absorption spectra recorded at the end of the reaction.

The experiments described in Figure 6 were performed using the new [Mn^{III}(T2,4,5TMPP)Cl] catalyst, reproducing those already demonstrated (Figures 4 and 5) for their first generation analog [Mn^{III}(TPP)Cl]. Comparing the systems with both catalysts, it was observed that the selectivity of the catalyst systems was similar (which was already expected) and the stability of the new catalyst was higher than the one observed for the first generation compound.

In general, the yields in the non-additive system in the presence of the green solvents for [Mn^{III}(T2,4,5TMPP)Cl] were higher when ethyl acetate was used. Probably, these differences are associated with the formation time of the active species in each system. A follow-up of the cyclohexane oxidation by UV-vis spectroscopy shows that, in dimethyl carbonate, this metalloporphyrin was not fully converted into the active species, maintaining a part in the form of Mn^{III}P (Figure 7), for both tested oxidants. On the other hand, in an analogous system involving the same catalyst, but in ethyl acetate, there is a complete conversion of the metalloporphyrin to the active species, with a very low amount of Mn^{III}P (Figure 7). The dipole moment values and dielectric constant for ethyl acetate are close to those for dichloromethane, which probably justifies the greater formation of the active species and higher yields for systems with ethyl acetate are higher than those observed in dimethyl carbonate.

Figure 7. Evolution of the UV-vis absorption spectrum of the cyclohexane oxidation catalyzed by [Mn^{III}(T2,4,5TMPP)Cl] in the green solvents: (a) PhIO/ethyl acetate; (b) PhI(OAc)$_2$/ethyl acetate; (c) PhIO/dimethyl carbonate; (d) PhI(OAc)$_2$/dimethyl carbonate.

The dichloromethane/PhIO/[Mn^{III}(T2,4,5TMPP)Cl] system yielded the products (16% alcohol and 24% total) to a similar extent to those when using the catalysts with only one methoxy ([Mn^{III}T4(-OMe)PPCl], 18% alcohol and 23% total) [31] or two methoxy groups ([Mn^{III}T3,5DMPP]Cl], 14% alcohol and 21% total) [30], while the dichloromethane/PhI(OAc)$_2$/[Mn^{III}(T2,4,5TMPP)Cl] system showed yields of the products (23% alcohol and 33% total) to a greater extent than those observed when using catalysts with only one methoxy {[Mn^{III}T4(-OMe)PPCl], 14% alcohol and 19% total} [31] or two methoxy groups {[Mn^{III}(T3,5DMPP)Cl], 14% alcohol and 19% total} [30]. These latter results confirm that the presence of three methoxy groups in the aryl group of the metalloporphyrin at meso positions afforded a more robust catalyst.

Once the metalloporphyrin [Mn^{III}(T2,4,5TMPP)Cl] was shown to be more stable in the reaction medium than the first-generation catalyst, we decided to evaluate the influence of temperature on product yields. When the reaction was carried out in ethyl acetate, using PhIO as oxidant, at 0 ^{o}C the total yield decreased to 21% and at 40 ^{o}C, this value increased to 84%; for both cases these results are following by an increase of the selectivity for alcohol and an decrease in the catalyst stability (Table S1, Supplementary Material). However, we believe that conducting the reaction at a higher temperature is not adequate, since we are seeking to develop efficient systems that meet the principles of green chemistry and under mild conditions.

We decided to evaluate how the change in catalyst concentration would affect the reaction yield in the system [Mn^{III}(T2,4,5TMPP)Cl]/PhIO/ethyl acetate (Results in Figure S7, Supplementary Material). It can be seen that the increase or decrease of the amount of catalyst in the medium do not cause an increase in yield for cyclohexanol or even in total yield (data not shown). For the case of the molar ratio 0.5:10 (catalyst:oxidant) there is a higher decrease in yields, probably because the number of effective collisions between reacting particles decreases. On the other hand, for the molar ratio 4:10, a higher catalyst destruction should occur. Thus, the 1:10 molar ratio proved to be the most adequate for the studied systems.

The systems using the new catalyst, in the presence of PhIO and additives, were more efficient than those already reported in the literature [30, 31]. In addition, an increase in the catalyst stability was observed, which probably explains the better catalytic efficiency of [Mn^{III}(T2,4,5TMPP)Cl] compared to analog systems. This same behavior was observed when PhI(OAc)$_2$ replaced PhIO. Thus, these results reinforce the possibility of using PhI(OAc)$_2$ instead of PhIO.

When we verified the performance of the second generation metalloporphyrin {[Mn^{III}(T2,4,5TMPP)Cl]} in the green solvents, in the presence or absence of the additive, the highest total yields (cyclohexanol + cyclohexanone) were obtained when using ethyl acetate, a similar trend observed for the first generation catalyst ([Mn^{III}(TPP)Cl]). We believe that these differences in yields in the two green solvents are directly associated with the formation of the active species (as observed in figure 7). For a better understanding of the process, in the different solvents studied, it is necessary to carry out theoretical studies to evaluate the influence in the formation/stabilization of the active species responsible for the oxidation of the substrate. To the best of our knowledge, these studies have not been developed in cyclohexane oxidation catalyzed by metalloporphyrins so far.

Considering only the selectivity for alcohol and the use of additives it was possible to observe the highest value of 70% was achieved for the systems with both catalysts in PhI(OAc)$_2$/water/dimethyl carbonate. A higher selectivity for alcohol (100%) has already been observed for second generation metalloporphyrins in acetonitrile (which is not a green solvent) [12] or in the absence of solvent [17].

In order to develop an even greener system and minimize waste generation, we tested the efficiency of the catalysts [Mn^{III}(TPP)Cl] and [Mn^{III}(T2,4,5TMPP)Cl] in the cyclohexane oxidation in the absence of solvent (Table 1). For these systems, imidazole was not evaluated as additive because it was insoluble in cyclohexane.

Table 1. Product yields obtained during the cyclohexane oxidation by PhIO or PhI(OAc)$_2$ in absence of solvents and under aerobic conditions, with and without water as an additive.

System	Yields (%)			Selectivity[c]	Catalyst
	C-ol[a]	C-one[a]	Total[b]	(%)	Bleaching[d] (%)
[Mn^{III}(TPP)Cl]/PhIO	15	4	19	79	72
[Mn^{III}(TPP)Cl]/PhIO/water	34	15	49	69	68
[Mn^{III}(T2,4,5TMPP)Cl]/PhIO	20	5	25	80	60
[Mn^{III}(T2,4,5TMPP)Cl]/PhIO/water	7	2	9	78	93
[Mn^{III}(TPP)Cl]/PhI(OAc)$_2$	5	3	8	63	50
[Mn^{III}(TPP)Cl]/PhI(OAc)$_2$/water	33	11	44	75	52
[Mn^{III}(T2,4,5TMPP)Cl]/PhI(OAc)$_2$	10	2	12	83	86
[Mn^{III}(T2,4,5TMPP)Cl]/PhI(OAc)$_2$/water	12	2	14	86	62

Reaction conditions: MnP/Oxidant/cyclohexane molar ratio = 1:10:13870, 25 ^{o}C, magnetic stirring, 90 min. of reaction. [a] Yields (%) based on the oxidant. C-ol: cyclohexanol and C-one: cyclohexanone. [b] Total yields = (%C-ol + %C-one). [c] Selectivity for the alcohol was determined from the relation: Selectivity = 100 × [%C-ol/(%C-ol + %C-one)]. [d] The degree of destruction of the catalyst was calculated based on the UV–Vis absorption spectra recorded at the end of the reaction.

Despite the lack of solvent (with or without additive), the systems showed an increase in the alcohol selectivity. The values were limited to 86% and the total yields were not higher than the ones in the presence of solvents. We believe that the differences observed for the second generation metalloporphyrin are due to the type of substituent in the aryl group of the meso positions of the macrocycle. In the work of Góes et al. [17], in which 100% alcohol selectivity was observed, the catalysts contained one or two nitro groups, which are electron withdrawing groups that promote destabilization of the Mn^{V}OP active species, favoring the exclusive formation of the alcohol. On the other hand, in the present work, the three substituents are an -OCH$_3$ type, which are donor groups of electronic density, justifying the lower alcohol selectivity [39, 40]. In addition, the catalyst [Mn^{III}(TPP)Cl], without any group that promotes this destabilization of the Mn^{V}OP active species, also did not present 100% selectivity for the oxidation of cyclohexane in the absence of solvents (greatest selectivity: 79%). Even in the presence of water [with PhIO or PhI(OAc)$_2$], the yields were still lower than those already observed for systems in the presence of the solvent.

Conclusions

Metalloporphyrin compounds have proved themselves to be of great interest for use as catalysts in the search for more efficient cyclohexane oxidation systems. Aiming to develop eco-friendly systems for this reaction, the known [Mn^{III}(TPP)Cl] and new [Mn^{III}(T2,4,5TMPP)Cl] catalysts were obtained and their activity was evaluated using green solvents (ethyl acetate and dimethyl carbonate) and solvent-free systems. In addition, the effect of additives (water and imidazole) was also studied.

Ethyl acetate was an appropriate solvent to replace the chlorinated solvents in the cyclohexane oxidation. In some systems, the addition of small amounts of additives (water or imidazole) improved the performance of the catalysts. It is important to emphasize that the amount of imidazole/water employed in this work was very small. Moreover, each metalloporphyrin must have its activity studied in each system of transformation of organic substrates, in order to determine which is the "ideal" system for its maximum performance.

We believe that these results may stimulate the development of new cyclohexane oxidation systems that employ other green solvents and/or environmentally friendly oxidants.

Acknowledgments

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An eco-friendly approach to the cyclohexane oxidation catalyzed by manganese porphyrins: green and solvent-free systems

Graphical Abstract Synopsis

Total yields (cyclohexanol + cyclohexanone) up to 90% were achieved in cyclohexane oxidation using ethyl acetate, which is an efficient green solvent to replace dichloromethane.