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Mild Peroxidative Oxidation of Cyclohexane Catalyzed by Mono-, Di-, Tri-, Tetra- and Polynuclear Copper Triethanolamine Complexes

Alexander M. Kirillov,[a] Maximilian N. Kopylovich,[a] Marina V. Kirillova,[a]
Evgeny Yu. Karabach,[a] Matti Haukka,[b] M. Fátima C. Guedes da Silva,[a,c]
Armando J. L. Pombeiro[a,]*

[a] Centro de Química Estrutural, Complexo I, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
Fax: (+351)-21-846-4455, e-mail: pombeiro@ist.utl.pt
[b] University of Joensuu, Department of Chemistry, P. O. Box 111, FIN-80101, Joensuu, Finland
[c] Universidade Lusófona de Humanidades e Tecnologias, Campo Grande 376, 1749-024 Lisbon, Portugal

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Abstract: The mono-, di-, tri-, tetra- and polynuclear copper(II) triethanolamine (H_3tea) complexes $[Cu(H_2tea)(N_3)]$ (**1**), $[Cu_2(H_2tea)_2(XC_6H_4COO)_2]\cdot 2\,H_2O$ (X = 4-H **2a**, 4-CH_3 **2b**, 3-Cl **2c**), $[Cu_3(H_2tea)_2(4\text{-}OC_6H_4COO)_2(H_2O)]\cdot 4H_2O$ (**3**), $[O\subset Cu_4(tea)_4(BOH)_4][BF_4]_2$ (**4**) and $[Cu_2(H_2tea)_2\{\mu\text{-}C_6H_4(COO)_2\text{-}1,4\}_n]\cdot 2n\,H_2O$ (**5**), respectively, are highly active and selective catalysts or catalyst precursors for the peroxidative oxidation of cyclohexane, in acetonitrile, to a cyclohexanol and cyclohexanone mixture, by aqueous hydrogen peroxide in acidic medium (liquid biphasic catalysis) at room temperature and atmospheric pressure. The effects on the catalytic activity of various factors, e.g., the relative amounts of cyclohexane, oxidant, catalyst, solvent and nitric acid, reaction time, catalyst recycling and impact of both carbon- and oxygen-centred radical traps (supporting mainly radical mechanisms) were investigated and allowed us to achieve yields and TONs up to *ca.* 39% and 380, respectively, corresponding to the most active copper systems so far reported for the oxidation of cyclohexane under mild conditions. The catalysts can be reused for recycling and, at least complex **4** maintains almost the same level of activity even after five reaction cycles. The preparation of the new complexes **1**, **2b** and **2c** by self-assembly at room temperature, and their full characterization by IR spectroscopy, FAB-MS$^+$, elemental and X-ray diffraction structural (for **1** and **2c**) analyses are also reported.

Keywords: biphasic catalysis; copper complexes; cyclohexane; N,O ligands; oxidation

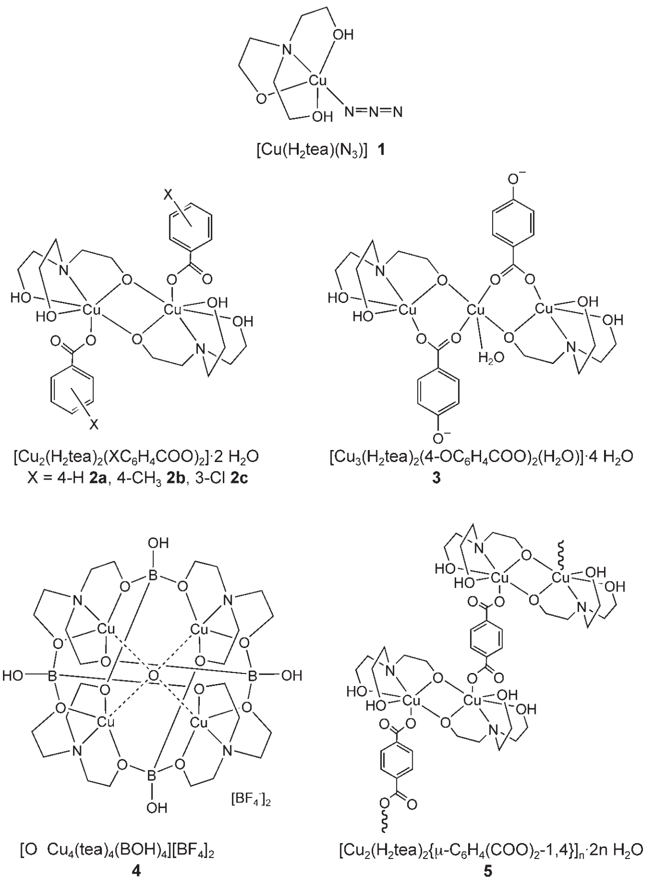
Introduction

Oxidation of cyclohexane is a rather important and much-studied process due to the large demand for its oxidized products, i.e., cyclohexanol and cyclohexanone which are commodity chemicals used as intermediates in the manufacture of adipic acid, nylon-6,6′, polyamide-6, urethane foams, acidulant in baking powder and lubricating additives.[1–5] Attempts[6–10] have been directed towards the development of more efficient processes than the current commercial ones [e.g., the Dupont process for cyclohexane oxidation appears to operate with only 4% conversion, 85% selectivity, at above 150 °C, using air at above 12 atm and Co(III) naphthenate as catalyst][6] by selective oxidation of cyclohexane under milder conditions using different oxidizing agents and catalytic systems comprising various transition metals. Among them, copper-containing catalysts are of a high potential interest,[11–14] since copper is a cheap and widespread metal in nature, the third most abundant essential trace metal in the human body, present in the active sites of many enzymes,[14–23] e.g., particulate methane monooxygenase (pMMO), an as yet incompletely characterized enzyme that is known to catalyze alkane hydroxylation and alkene epoxidation,[20–23] ceruloplasmin, haemocyanines, catechol oxidase, tyrosinase and blue oxidases.

The previously reported[24–34] examples of copper-catalyzed oxidation of cyclohexane under relatively mild conditions and using various oxidizing agents like H_2O_2, *t*-BuOOH, O_2, CH_3COOOH or their combinations, are based on different Cu(I and II) complexes with N,O imino ligands,[24] Cu-containing silicates[26] and zeolites[29], mono- and dinuclear Cu complexes with bis{2-

[*N,N*-bis(2-pyridylethyl)amino]-1,1-dimethylethyl} disulfide and related ligands,[28] a salen complex *N,N'*-(1,2-ethylene)-bis(salicylaldamine)-copper(II),[25] bis-(trimethylacetate)copper(II) and bis(ethylenediamine)-copper(II) nitrate,[30] Cu phthalocyanines and substituted (chloro- and nitro-) phthalocyanines encapsulated in zeolites X and Y,[31] Cu(II) complexes containing *N,N*-bis(2-pyridylmethyl)-β-alanineamide ligands,[32] copper(II) hydroxide[27] and various crown ether Cu-complexes,[33] Cu-Gif system,[34] etc. Nevertheless, most of these catalysts still provide very low yields (relative to cyclohexane)[26–29,32–34] and low selectivity,[26,30,31] require rather expensive[31,33] and environmentally unfriendly components,[34] are active only in the presence of various additives,[27,33,34] and/or involve complicated syntheses,[25,26,28,31–33] thus being inaccessible on a large scale.

Recently we have preliminary reported[35] a simple and convenient synthesis of several new multinuclear copper triethanolamine (H_3tea) complexes using cheap, commercially available and environmentally tolerable reagents and opened up their potential application as highly active and selective catalysts or catalyst precursors for the mild peroxidative oxidation of alkanes to the corresponding alcohols and ketones. Hence, the main purpose of this work is to provide a detailed investigation of cyclohexane oxidation catalyzed by known[35] and newly synthesized copper triethanolamine complexes of diverse nuclearity (Scheme 1), thus extending the catalytic activity studies to a variety of experimental conditions, e.g., the oxidant-to-catalyst and substrate-to-catalyst molar ratios, reaction time, amount of solvent, multiple recycling of catalyst and the influence of various types of radical traps, aiming at the optimization of this process and the identification of the general type of mechanism in the search for an efficient way for cyclohexane oxidation.



Scheme 1.

Results and Discussion

Synthesis and Spectroscopic Characterization of Complexes 1, 2b and 2c

Addition of sodium azide or aromatic carboxylates to the aqueous blue solution of $Cu(NO_3)_2$, H_3tea and NaOH provides the formation, by self-assembly at room temperature, of mono- and dinuclear Cu complexes. Hence, by adding sodium azide, *p*-toluic acid or 3-chlorobenzoic acid one obtains **1**, **2b** or **2c** (Scheme 1), respectively, isolated as crystalline solids in good yields (79–86%), and characterized by IR and FAB$^+$-mass spectroscopy, elemental analysis and X-ray crystallography (for **1** and **2c**).

The IR-spectrum of **1** shows a set of vibrations due to the H_2tea ligand, e.g., ν(OH) bands at 3480 and 3308 cm^{-1}, and ν(CH) bands at 2985, 2909 and 2859 cm^{-1}. Two high intensity bands associated with ν_{as} and ν_s vibrations of azide ligand are also observed at 2048 and 1384 cm^{-1}, respectively. For complexes **2b** and **2c**, the vibrations related to the H_2tea ligands show common features and contain broad bands in the 3500–3100 cm^{-1} range assigned to the stretching vibrations of OH groups and H_2O molecules, and strong or medium intensity ν(CH) bands in the 3000–2850 cm^{-1} range. Several high intensity bands associated with ν_{as} and ν_s vibrations of carboxylate groups were observed in the spectra of complexes **2b** and **2c** in the 1600–1530 and 1420–1370 cm^{-1} ranges, respectively.

The molecular ions were clearly observed with the expected isotopic patterns in the FAB$^+$-MS of **2b** and **2c**. Other typical peaks correspond to the stepwise fragmentations by loss of tea, carboxylates, and Cu(tea) fragments or to dissociation of dimeric structures to give monomeric fragments, e.g., $[Cu(H_2tea)(C_6H_4ClCOO)]^+$ in **2c**. Elemental analyses are also consistent with the proposed formulations which are authenticated by single crystal X-ray diffraction studies (for **1** and **2c**), as indicated below.

X-Ray Crystal Structures of Complexes 1 and 2c

In complex **1** (Figure 1), triethanolamine is deprotonated at one oxygen atom (O3) and binds the pentacoordinated metal *via* the amino-*N* and three oxygen atoms which occupy the axial positions of a trigonal-bipyramidal coordination mode. The geometry is completed by an azide ligand *trans* to the amino nitrogen N1, the N1–Cu–N2 angle of 177.57(5)° being essentially linear. The mononuclear units are held together by O–H···O intermolecular hydrogen bonds forming a polynuclear network (Figure 2) with the shortest Cu–Cu separation of 4.435(2) Å, which is in the range of 4–5 Å found for the trinuclear clusters of some multicopper oxidases.[23]

The Cu–O1 and Cu–O2 lengths of *ca.* 2.07–2.13 Å are unexceptional for protonated oxygen atoms bonded to a copper centre,[36,37] and are slightly longer than Cu–O3 [2.0289(11) Å] with the deprotonated oxygen atom. The binding of the H_2tea ligand involves the chelate rings Cu–N1–C1–C2–O1, Cu–N1–C3–C4–O2 and Cu–N1–C5–C6–O3 with bite N1–Cu–O angles of 81.67(4), 84.60(4) and 85.87(5)°, respectively. The Cu–N1 bond length, 2.0186(12) Å, is slightly longer than the Cu–N2 [1.9550(13) Å], though shorter than the Cu–O bonds. The azide ligand is linear with the N2–N3–N4 angle of 176.62(15)°, the N2–N3 and N3–N4 bond lengths of 1.2059(19) and 1.1525(19) Å being within the normal values reported for such bonds.[38] It coordinates the metal with a Cu–N2–N3 angle of 118.45(10)°. For **1** most of the bond distances are similar to those of related triethanolaminate complexes of copper such as [Cu(H_2tea)Cl],[36] [Cu(H_2tea)NCS],[36] [$Cu_2(H_2tea)_2$(4,4′-bipy)]$(ClO_4)_2$[37] and [Cu(H_2tea)-(CF_3C*O*CHC*O*CF_3)][39].

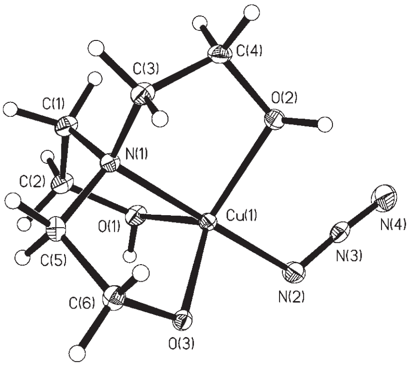


Figure 1. An ORTEP-3 representation of **1**. Selected bond lengths (Å) and bond angles (°): C(1)–N(1) 1.4882(18), C(2)–O(1) 1.4443(18), C(3)–N(1) 1.4903(18), C(4)–O(2) 1.4402(17), C(5)–N(1) 1.4852(19), C(6)–O(3) 1.4342(17), N(1)–Cu(1) 2.0186(12), N(2)–N(3) 1.2059(19), N(2)–Cu(1) 1.9550(13), N(3)–N(4) 1.1525(19), O(1)–Cu(1) 2.1343(11), O(1)–H(1) 0.9026(10), O(2)–Cu(1) 2.0655(10), O(2)–H(2) 0.9529(10), O(3)–Cu(1) 2.0289(11); N(3)–N(2)–Cu(1) 118.45(10), N(4)–N(3)–N(2) 176.62(15), N(2)–Cu(1)–N(1) 177.57(5), N(2)–Cu(1)–O(3) 96.09(5), N(1)–Cu(1)–O(3) 85.87(5), N(2)–Cu(1)–O(2) 95.57(5), N(1)–Cu(1)–O(2) 84.60(4), O(3)–Cu(1)–O(2) 121.31(4), N(2)–Cu(1)–O(1) 96.17(5), N(1)–Cu(1)–O(1) 81.67(4), O(3)–Cu(1)–O(1) 114.92(4), O(2)–Cu(1)–O(1) 120.60(4).

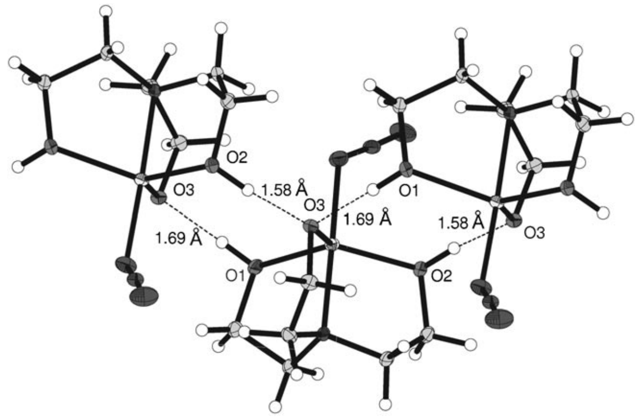


Figure 2. Fragment of the crystal packing of complex **1** illustrating the intermolecular hydrogen bonding pattern.

The molecular structure of **2c** consists of centrosymmetric binuclear fragments $[Cu_2(H_2tea)_2]^{2+}$ stabilized by two monodentate 3-chlorobenzoate ligands (Figure 3), which are further involved in an intermolecular hydrogen bonding network with non-coordinated water molecules, thus forming parallel chains in neighbouring layers (Figure 4). Each Cu ion in the molecule has a distorted tetragonal bipyramidal geometry, and each H_2tea acts as a tetradentate ligand with one bridging alkoxo group. The binding of the H_2tea ligands involves the five-membered chelate rings Cu1–N1–C1–C2–O1, Cu–N1–C3–C4–O2 and Cu–N1–C5–C6–O3A with bite N1–Cu–O angles of 78.73(6), 76.62(6) and 82.88(6)°, respectively. The Cu–O3A bond length of 1.9420(14) Å does not differ from the standard values for μ-O–Cu bonds and agrees with the lengths (*ca.* 1.91–1.95 Å) found in related compounds,[35,40,41] whereas the Cu–O1 and Cu–O2 distances [2.5640(18) and 2.4445(18) Å, respectively] are remarkably longer than the normal Cu–$O_{\text{amino alcohol}}$ bond distances. Nevertheless, they lie in the 2.43–2.56 Å range reported for **2a**, **5**[35] and other triethanolaminate complexes.[41,42] The Cu1–O3–Cu1A–O3A bridging mode is planar. The μ-O3 atoms of the triethanolamine ligands generate a centrosymmetric Cu_2O_2 core with an inversion centre disposed between the two copper atoms. The Cu–Cu separation of 2.9222(5) and most of other bonding parameters agree with those found in related dinuclear complexes.[35,40,41]

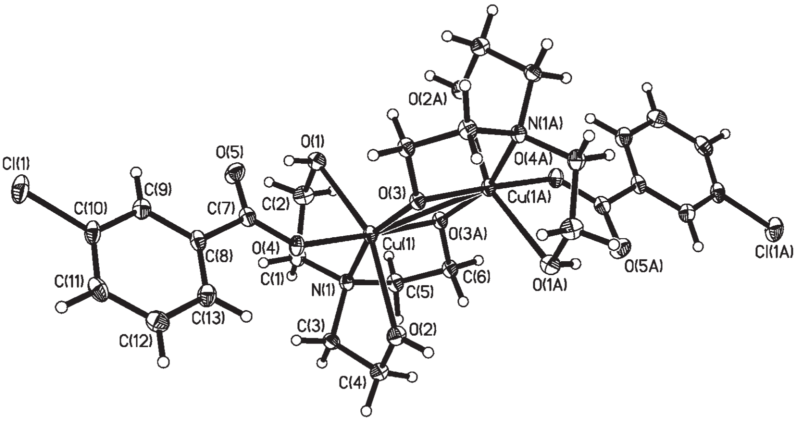


Figure 3. An ORTEP-3 representation of **2c**. Selected bond lengths (Å) and bond angles (°): C(1)–N(1) 1.485(3), C(2)–O(1) 1.426(3), C(3)–N(1) 1.493(3), C(4)–O(2) 1.426(3), C(5)–N(1) 1.499(3), C(6)–O(3A) 1.422(2), C(7)–O(5) 1.250(3), C(7)–O(4) 1.265(3), N(1)–Cu(1) 2.0431(18), O(1)–H(1) 0.8911(12), O(2)–H(2) 0.8856(17), O(1)–Cu(1) 2.5640(18), O(2)–Cu(1) 2.4445(18), O(3A)–Cu(1) 1.9420(14), O(4)–Cu(1) 1.9672(14), O(99)–H(99A) 0.8601; C(1)–N(1)–Cu(1) 109.92(13), C(3)–N(1)–Cu(1) 108.79(13), C(5)–N(1)–Cu(1) 107.22(12), C(6A)–O(3)–Cu(1) 128.81(12), Cu(1)–O(3)–Cu(1A) 97.12(6), C(7)–O(4)–Cu(1) 133.28(14), O(3)–Cu(1)–O(3A) 82.88(6), O(3)–Cu(1)–O(4) 95.42(6), O(3A)–Cu(1)–O(4) 177.40(6), O(1)–Cu(1)–N(1) 78.73(6), O(2)–Cu(1)–N(1) 76.62(6), O(3)–Cu(1)–N(1) 161.61(6), O(3A)–Cu(1)–N(1) 84.95(6), O(4)–Cu(1)–N(1) 97.17(6), O(3)–Cu(1)–Cu(1A) 41.62(4), O(3A)–Cu(1)–Cu(1A) 41.26(4), O(4)–Cu(1)–Cu(1A) 137.01(5), N(1)–Cu(1)–Cu(1A) 124.87(5).

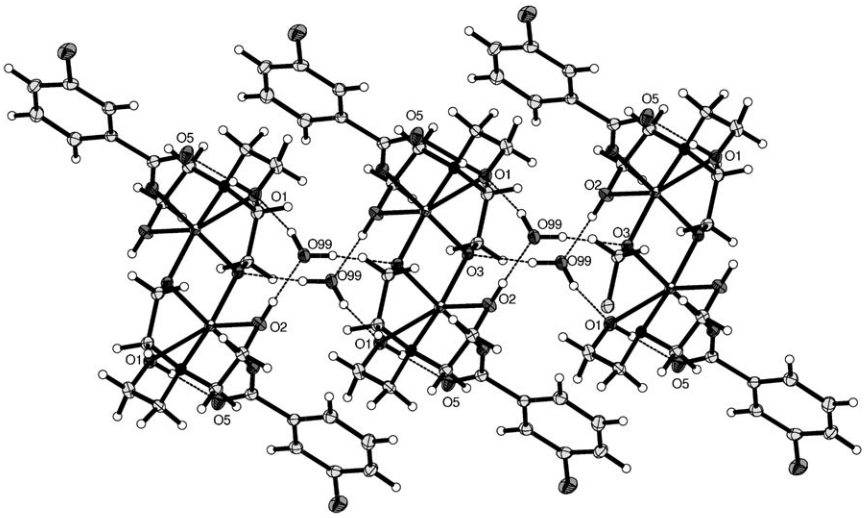
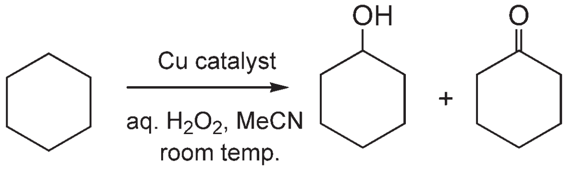


Figure 4. Fragment of the crystal packing of complex **2c**·2 H_2O illustrating the intermolecular hydrogen bonding pattern.

Catalytic Activity of Copper Triethanolamine Complexes towards Peroxidative Oxidation of Cyclohexane

All the copper complexes **1**–**5** (Scheme 1) act as catalysts or catalyst precursors for the oxidation of cyclohexane, in acetonitrile, to a cyclohexanol and cyclohexanone mixture, by aqueous hydrogen peroxide in acidic medium (liquid biphasic catalysis) at room temperature (Scheme 2). The influence of various factors like the relative amounts of HNO_3, H_2O_2, catalyst and solvent, reaction time, catalyst recycling and impact of radical traps on the activity of catalysts were investigated in a systematic way, the results being shown in Tables 1–6 and discussed below.



Scheme 2.

Effect of the Amount of Nitric Acid

It is known[5,6,8] that the peroxidative oxidation of cyclohexane catalyzed by some derivatives of Mn, Cr, Pd, Pt, Hg, etc. proceeds more efficiently in acidic medium. We have also found that the addition of nitric acid to the reaction mixtures strongly enhances the activity towards alkane hydroxylation of various catalysts like iron-chromium hydroxides and hydroxo complexes,[43] vanadium[44, 45] and copper[35] complexes with N,O ligands.

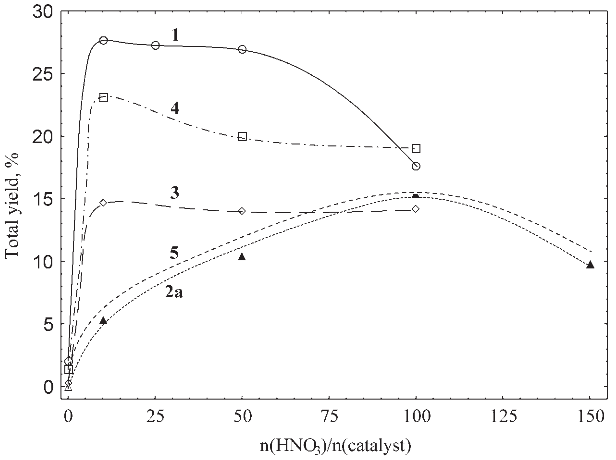


Figure 5. Effect of the nitric acid-to-catalyst molar ratio on the total yield of products in the cyclohexane oxidation catalyzed by complexes **1**, **2a**, **3**, **4** and **5**. Reaction conditions are those of Table 1.

In the current study, the cyclohexane oxidation in the presence of the copper catalysts **1**–**5** practically does not proceed unless nitric acid is added (Table 1, Figure 5). Thus, in the absence of acid a lack of activity (complexes **2a** and **5**) or a very weak activity of 0.3–2.0% (complexes **1**, **3**, **4**) was detected (Table 1, entries 1, 6, 11, 15, 19). The addition of ten equivalents of HNO_3 relative to catalyst leads to a dramatic increase of activity, e.g., for catalyst **1** the total yield increases from 2.0 to 27.7% on changing the acid-to-catalyst molar ratio from 0 to 10 (Figure 5, curve 1). The total yield of cyclohexanol and cyclohexanone remains practically constant in the 10–50 range of n(HNO_3)/n(catalyst), whereas further enhancement of such a ratio up to 100 provides a decrease of the yield to *ca.* 10% (Table 1, entries 4, 5). A related effect of nitric acid on the catalytic activity is displayed by complexes **3** and **4** which exhibit the highest yields at n(HNO_3)/n(catalyst) = 10 (Figure 5, curves 3, 4). Complexes **2a** and **5** require a higher amount of acid to display a maximum activity, *ca.* 15% yield at the acid-to-catalyst molar ratio of 100 (Table 1,

Table 1. Peroxidative oxidation of cyclohexane catalyzed by complexes **1**–**5**. Effect of the nitric acid-to-catalyst molar ratio.

Entry	Catalyst[a]	n(HNO_3)/n(catalyst)	Yield[b] of products [%]			Molar ratio $C_6H_{10}O/C_6H_{11}OH$
			Cyclohexanol	Cyclohexanone	Total[c]	
1	**1**	0	0.6	1.4	2.0	2.3
2	**1**	10	16.0	11.7	27.7	0.7
3	**1**	25	11.3	16.0	27.3	1.4
4	**1**	50	12.1	14.9	27.0	1.2
5	**1**	100	7.5	10.1	17.6	1.3
6	**2a**	0	0.0	0.0	0.0	–
7	**2a**	10	2.5	2.8	5.3	1.1
8	**2a**	50	4.8	5.6	10.4	1.2
9	**2a**	100	6.0	9.4	15.4	1.6
10	**2a**	150	5.8	4.0	9.8	0.7
11	**3**	0	0.0	0.3	0.3	–
12	**3**	10	7.9	6.8	14.7	0.9
13	**3**	50	8.3	5.8	14.1	0.7
14	**3**	100	8.6	5.6	14.2	0.7
15	**4**	0	0.4	1.0	1.4	2.5
16	**4**	10	14.2	8.9	23.1	0.6
17	**4**	50	10.7	9.4	20.1	0.9
18	**4**	100	10.0	9.1	19.1	0.9
19	**5**	0	0.0	0.0	0.0	–
20	**5**	10	3.5	3.0	6.5	0.9
21	**5**	50	5.5	5.8	11.3	1.1
22	**5**	100	7.0	8.6	15.6	1.2
23	**5**	150	5.7	5.2	10.9	0.9

[a] *Reaction conditions:* catalyst (25 μmol), H_2O_2 (10.00 mmol), C_6H_{12} (0.63 mmol), MeCN (3 mL), 6 h reaction time.
[b] Moles of product/100 moles of cyclohexane.
[c] Cyclohexanol + cyclohexanone.

Figure 5). Thus, the catalysts that are pentacoordinate and comprise evident labile sites like Cu–N_3, Cu–H_2O and Cu-μ_4-O (complexes **1**, **3**, **4**, respectively) exhibit the highest activity at a relatively low amount of acid, whereas the other complexes, **2** and **5**, that are hexacoordinate require a higher amount of acid conceivably to promote unsaturation at the metal upon ligand protonation. Although the cyclohexanone-to-cyclohexanol molar ratio for complexes **1** and **4** is maximal at higher amounts of nitric acid (Table 1, entries 2–4, 16–18), such an excess of acid should be avoided due to the tendency for lowering the overall reaction selectivity towards the formation of cyclohexanol and cyclohexanone, i.e., the formation of side products can then be favoured. Based on these data, a controlled amount of acid was used in further experiments, i.e., $n(HNO_3)/n(\text{catalyst}) = 10$ (for **1**, **3**, **4**) or 100 (for **2** and **5**).

Hence, the need of acid for the peroxidative oxidation of cyclohexane is evident and presumably can be associated with (i) its involvement in proton transfer steps, activation of catalyst by unsaturation of the metal centres upon ligand protonation and acceleration of the oxidation reaction,[5,6,8,9,35] (ii) the enhancement of oxidative properties of the metal complexes,[5,46] (iii) the hampering of decomposition of hydrogen peroxide to water and oxygen,[6,47] and enhancement of the formation of peroxo complexes,[5,48] and (iv) the increase of selectivity towards the formation of cyclohexanone (a main raw material for production of polyamide-*6*) by dehydrogenation of cyclohexanol, which can efficiently be catalyzed by strong mineral acids and some heterogeneous copper catalysts.[6]

Effect of the Oxidant-to-Catalyst Molar Ratio

The amount of hydrogen peroxide has a significant effect and the overall yields of cyclohexanol and cyclohexanone are enhanced in all catalytic systems upon increasing the peroxide-to-catalyst molar ratio up to 200 (Table 2, Figure 6). The highest activity with total yields of 30.6 and 27.2% is displayed by complexes **3** and **4**, respectively (Table 2, entries 19, 23), followed by other complexes which exhibit 12.2–17.5% yields for the above molar ratio of 200. Further enhancement of $n(H_2O_2)/n(\text{catalyst})$ up to 400 leads to the increase of activity of complexes **1**, **2** and **5** up to 27.7, 17.0 (for **2b**) and 15.6%, respectively (Figure 6, Table 2), while a yield drop of *ca.* 15 and 5% was detected when using catalysts **3** and **4** (Figure 6, curves 3, 4). Such a decrease of activity can probably be associated to the decreased concentration of acetonitrile which, as shown below, has also a relevant effect.

All the complexes **2a**, **2b**, **2c** and **5** exhibit similar activities under the reaction conditions used (Table 2), which are significantly lower than those of complexes **1**, **3** and **4**. The higher activity of the latter complexes can possibly be accounted for by their lower coordination number (they are pentacoordinate, whereas the others are hexacoordinate) (Scheme 1), and the presence of a labile ligand (H_2O, N_3).[35] Moreover, a very high *selectivity* towards the formation of cyclohexanol and cyclohexanone is exhibited by systems comprising complexes **3** and **4** since no traces of any by-products were detected by GC or GC-MS analyses of the final reaction mixtures. In contrast, a simple copper salt like $Cu(NO_3)_2$ under the same reaction conditions exhibits a much lower activity, i.e., total yield of 3.2 and 5.4% at the peroxide-to-catalyst molar ratio of 200 and 400, respectively (Table 2, entries 29, 30). Therefore, the relevance of polydentate N,O triethanolaminate ligands is evident and probably associated to their involvement (upon decoordination of an N or O atom) in proton-transfer steps, e.g., among H_2O_2, oxo and/or peroxo ligands, as suggested[8,44,49,50] for some vanadium catalysts that can even require particular N,O additives[8,50] as cocatalysts. Some copper-containing systems which are active only in the presence of additives like pyridine and acetaldehyde were also reported.[27,33,34]

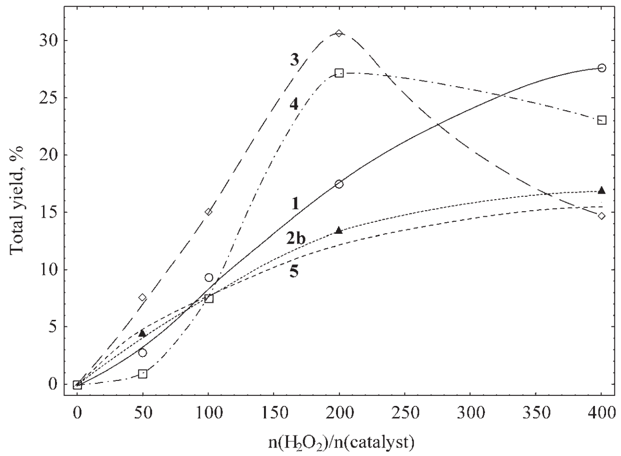


Figure 6. Effect of the oxidant-to-catalyst molar ratio on the total yield of products in the cyclohexane oxidation catalyzed by complexes **1**, **2b**, **3**, **4** and **5**. Reaction conditions are those of Table 2.

Effects of the Cyclohexane-to-Catalyst Molar Ratio and the Reaction Time

The oxidation of cyclohexane proceeds even if a very small relative amount of metal complex catalyst is used leading to rather high turnover numbers (TONs) (Table 3). They gradually increase on changing the cyclohexane-to-catalyst molar ratio from 800 to 6400 (Figure 7, Table 3, first four entries for each catalyst), and values of 111 and 121 are reached within 6 h reaction time for the most active catalysts **3** and **4**, respectively (Figure 7, curves 3, 4). Other catalysts exhibit lower activity under these reaction conditions with maximal TONs of *ca.* 48–87 (Figure 7).

The activity of all catalytic systems is also dependent on the reaction time. TONs tend to increase on the extension of reaction time from 6 to 72 h (Figure 8, Table 3, last three entries for each catalyst), e.g., from 87 to 359, respectively, for catalyst **2b**. At 24 h reaction time a TON of 285 was displayed by complex **3**, while at 72 h a TON of 378 was observed for complex **5** with tendency for even further increases with time (Figure 8, curves 3, 5). The highest TON values found for all studied catalytic systems are within the range of *ca.* 215–380 (Table 3). In contrast, copper nitrate under similar reaction conditions shows a much lower TON of 45, which is *ca.* 5- and 8.5-times lower than the least and the highest TON values (Table 3, entries 6, 42), respectively, exhibited by the copper complexes.

Effect of the Amount of Solvent

Acetonitrile was used as a solvent for the liquid biphasic oxidation of cyclohexane due to (i) the solubilization of the alkane and products in this solvent, (ii) the high stability towards oxidation under the reaction conditions applied (in contrast with other solvents, e.g., methanol, ethanol or acetone), (iii) the similarity of its boiling point with that of cyclohexane what allows an easy recirculation of the cyclohexane and solvent mixture, (iv) its coordination ability and also in view of the best results previously obtained in this solvent.[2,6,43]

The amount of acetonitrile in the reaction mixture has a significant effect on the yields of products (Table 4, Figure 9). At a low content of this solvent, only negligible yields of products are detected (Table 4, entries 1, 5). The increase of its amount leads to a marked growth of activity (Figure 9) which reaches the maximum yield values of 37.2 and 38.5% for complexes **3** and **4**, respec-

Table 2. Peroxidative oxidation of cyclohexane catalyzed by complexes **1**–**5**. Effect of the oxidant-to-catalyst molar ratio.

Entry	Catalyst[a]	$n(H_2O_2)/n(\text{catalyst})$	Yield[b] of products [%]			Molar ratio $C_6H_{10}O/C_6H_{11}OH$
			Cyclohexanol	Cyclohexanone	Total[c]	
1	**1**	50	1.1	1.7	2.8	1.6
2	**1**	100	4.4	4.9	9.3	1.1
3	**1**	200	8.2	9.3	17.5	1.1
4	**1**	400	16.0	11.7	27.7	0.7
5	**2a**	50	1.9	2.5	4.4	1.3
6	**2a**	100	3.8	4.1	7.9	1.1
7	**2a**	200	5.0	7.2	12.2	1.4
8	**2a**	400	6.0	9.4	15.4	1.6
9	**2b**	50	2.5	2.0	4.5	0.8
10	**2b**	100	4.4	3.1	7.5	0.7
11	**2b**	200	7.5	6.0	13.5	0.8
12	**2b**	400	9.4	7.6	17.0	0.8
13	**2c**	50	3.5	2.8	6.3	0.8
14	**2c**	100	3.9	3.7	7.6	0.9
15	**2c**	200	7.0	6.8	13.8	1.0
16	**2c**	400	6.8	7.8	14.6	1.1
17	**3**	50	4.8	2.8	7.6	0.6
18	**3**	100	9.6	5.4	15.0	0.6
19	**3**	200	20.0	10.6	30.6	0.5
20	**3**	400	7.9	6.8	14.7	0.8
21	**4**	50	0.0	0.9	0.9	–
22	**4**	100	3.5	4.0	7.5	1.2
23	**4**	200	15.4	11.8	27.2	0.8
24	**4**	400	14.2	8.9	23.1	0.6
25	**5**	50	2.6	2.4	5.0	0.9
26	**5**	100	4.1	3.5	7.6	0.9
27	**5**	200	6.5	5.8	12.3	0.9
28	**5**	400	7.0	8.6	15.6	1.2
29[d]	$Cu(NO_3)_2$	200	1.1	2.1	3.2	1.5
30[d]	$Cu(NO_3)_2$	400	1.6	3.8	5.4	2.4

[a] *Reaction conditions:* catalyst (25 μmol), H_2O_2 (1.25–10.00 mmol), C_6H_{12} (0.63 mmol), MeCN (3 mL), 6 h reaction time.
[b] Moles of product/100 moles of cyclohexane.
[c] Cyclohexanol + cyclohexanone.
[d] For comparative purposes.

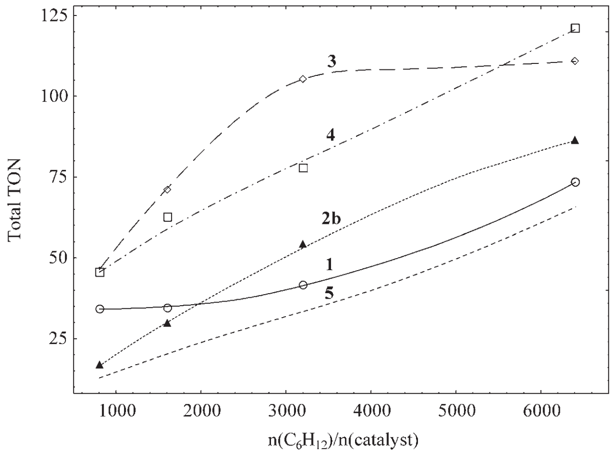


Figure 7. Effect of the cyclohexane-to-catalyst molar ratio on the total turnover number of catalyst in the cyclohexane oxidation catalyzed by complexes **1**, **2b**, **3**, **4** and **5** (6 h reaction time). For other reaction conditions, see Table 3.

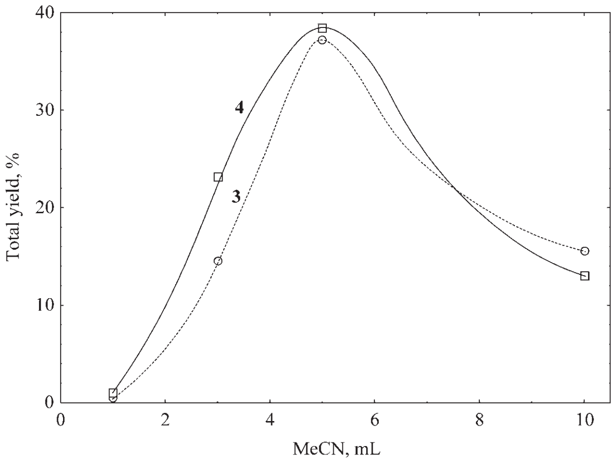


Figure 9. Effect of the amount of solvent on the total yield of products in the cyclohexane oxidation catalyzed by complexes **3** and **4**. Reaction conditions are those of Table 4.

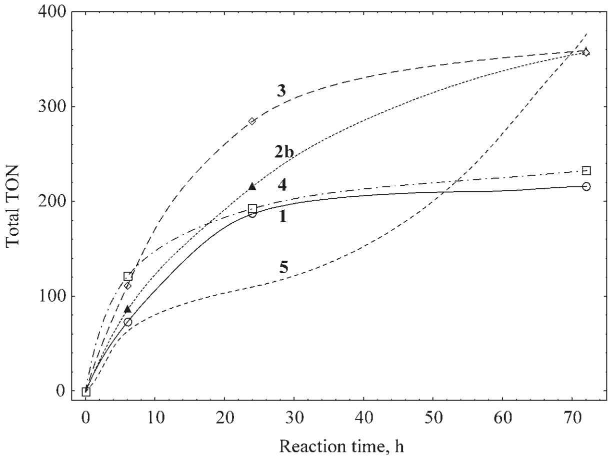


Figure 8. Effect of the reaction time on the total turnover number of catalyst in the cyclohexane oxidation catalyzed by complexes **1**, **2b**, **3**, **4** and **5**. Reaction conditions are those of Table 3.

tively, at 5 mL of acetonitrile. Further enhancement of the content of acetonitrile in the reaction mixture up to 10 mL leads to a significant yield drop, which conceivably can be associated with the concomitant reduction of the concentration of the oxidant.

Catalyst Recycling

Recycling reagents is a common practice in industrial oxidation of cyclohexane. Such a type of methodology has been tested for complex **4** (Table 5) due to its higher activity and stability as accounted for by its isolation, after the reaction, in a pure crystalline form. On completion of each stage, the products were analyzed as usual and the catalyst was recovered by full evaporation of the reaction mixture under vacuum. The subsequent cycles were initiated upon addition of new standard portions of all other reagents. For comparative purposes, the reactions were run in duplicate, in the presence and in the absence of nitric acid.

The first cycle was performed with acid as required for the initial activation of the catalyst and affords cyclohexanol and cyclohexanone with an overall yield of 34.2% under the reaction conditions used (Table 5, entry 1, Figure 10). Repeating the experiment without and with added nitric acid gives only very slightly decreased yields of 33.4 and 32.9%, respectively (Table 5, entries 2, 3). A similar behaviour of catalyst **4** is observed for further reaction cycles, i.e., only a slight yield drop of 2.1 and 5.2% is detected after the fifth reaction stage

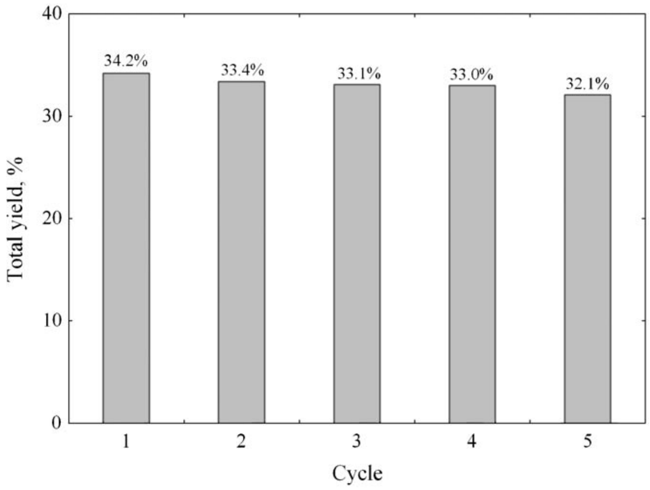


Figure 10. Effect of the catalyst recycling on the peroxidative oxidation of cyclohexane catalyzed by complex **4**. Reaction conditions are those of Table 5.

Table 3. Peroxidative oxidation of cyclohexane catalyzed by complexes **1**–**5**. Effects of the cyclohexane-to-catalyst molar ratio and the reaction time on the turnover number (TON).

Entry	Catalyst[a]	n(C_6H_{12})/(catalyst)	Reaction time [h]	TON[b]			Molar ratio $C_6H_{10}O/C_6H_{11}OH$
				Cyclohexanol	Cyclohexanone	Total[c]	
1	**1**	800	6	15	20	35	1.4
2	**1**	1600	6	14	21	35	1.6
3	**1**	3200	6	16	26	42	1.6
4	**1**	6400	6	29	45	74	1.6
5	**1**	6400	24	72	116	188	1.6
6	**1**	6400	72	90	127	217	1.4
7	**2a**	800	6	6	6	12	1.0
8	**2a**	1600	6	10	10	20	1.0
9	**2a**	3200	6	13	17	30	1.2
10	**2a**	6400	6	39	25	64	0.7
11	**2a**	6400	24	109	86	195	0.8
12	**2a**	6400	72	163	196	359	1.2
13	**2b**	800	6	10	7	17	0.8
14	**2b**	1600	6	18	12	30	0.7
15	**2b**	3200	6	30	25	55	0.9
16	**2b**	6400	6	47	39	86	0.8
17	**2b**	6400	24	124	92	216	0.7
18	**2b**	6400	72	157	202	359	1.3
19	**2c**	800	6	7	6	13	1.0
20	**2c**	1600	6	11	12	23	1.2
21	**2c**	3200	6	14	16	30	1.1
22	**2c**	6400	6	24	24	48	1.0
23	**2c**	6400	24	101	82	183	0.8
24	**2c**	6400	72	144	170	314	1.2
25	**3**	800	6	21	25	46	1.2
26	**3**	1600	6	28	43	71	1.6
27	**3**	3200	6	39	66	105	1.7
28	**3**	6400	6	41	70	111	1.7
29	**3**	6400	24	112	173	285	1.5
30	**3**	6400	72	182	175	357	1.0
31	**4**	800	6	23	23	46	1.0
32	**4**	1600	6	24	39	63	1.7
33	**4**	3200	6	30	48	78	1.6
34	**4**	6400	6	48	73	121	1.5
35	**4**	6400	24	70	123	193	1.7
36	**4**	6400	72	86	147	233	1.7
37	**5**	800	6	7	6	13	0.8
38	**5**	1600	6	11	10	21	1.0
39	**5**	3200	6	17	17	34	1.1
40	**5**	6400	6	33	33	66	1.0
41	**5**	6400	24	61	50	111	0.8
42	**5**	6400	72	166	212	378	1.3
43	$Cu(NO_3)_2$	6400	72	16	29	45	0.5

[a] *Reaction conditions:* catalyst (1.56–12.50 μmol), H_2O_2 (10.00 mmol), C_6H_{12} (10.00 mmol), MeCN (3 mL).

[b] Moles of product/mol of catalyst.

[c] Cyclohexanol + cyclohexanone.

for the experiments performed, respectively, in the absence or in the presence of nitric acid (Table 5, Figure 10). The better results obtained without added acid are in agreement with the detected small loss of activity of catalyst **4** (Table 1, entries 16–18) upon increasing the relative amount of acid in the reaction mixture. A slight activity decrease can also be explained by the corresponding lowering of catalyst concentration in the reaction mixture as a result of the losses of the samples taken for the GC tests. Thus, the performed experiments open up the possibility of recycling catalyst **4** which maintains almost the original level of activity after several reaction cycles providing *ca.* 32–34% of cyclohexane conversion after each stage, with a rather high selec-

Table 4. Effect of the amount of solvent on the peroxidative oxidation of cyclohexane catalyzed by complexes **3** and **4**.

Entry	Catalyst[a]	MeCN [mL]	Yield[b] of products [%]			Molar ratio $C_6H_{10}O/C_6H_{11}OH$
			Cyclohexanol	Cyclohexanone	Total[c]	
1	**3**	1	0.1	0.4	0.5	4.0
2	**3**	3	7.9	6.8	14.7	0.9
3	**3**	5	22.9	14.3	37.2	0.6
4	**3**	10	7.0	8.6	15.6	1.2
5	**4**	1	0.3	0.7	1.0	2.3
6	**4**	3	14.2	8.9	23.1	0.6
7	**4**	5	24.3	14.2	38.5	0.6
8	**4**	10	5.7	7.3	13.0	1.3

[a] *Reaction conditions:* catalyst (25 μmol), H_2O_2 (10.00 mmol; 1.02 mL of 30% aqueous H_2O_2), C_6H_{12} (0.63 mmol), 6 h reaction time.

[b] Moles of product/100 moles of cyclohexane.

[c] Cyclohexanol + cyclohexanone.

Table 5. Effect of the catalyst recycling on the peroxidative oxidation of cyclohexane catalyzed by complex **4**.[a]

Entry	Cycle	$n(HNO_3)/n(catalyst)$	Yield[b] of products [%]		
			Cyclohexanol	Cyclohexanone	Total[c]
1	1st	10	24.1	10.1	34.2
2	2nd	–	22.1	11.3	33.4
3	2nd	10	22.2	10.7	32.9
4	3rd	–	22.3	10.8	33.1
5	3rd	10	20.8	9.3	30.1
6	4th	–	20.0	13.0	33.0
7	4th	10	17.8	11.4	29.2
8	5th	–	20.9	11.2	32.1
9	5th	10	18.1	10.9	29.0

[a] *Reaction conditions:* catalyst (25 μmol), H_2O_2 (6.30 mmol), C_6H_{12} (0.63 mmol), MeCN (3 mL), 6 h reaction time. The catalyst was recovered after each reaction cycle by full evaporation of the reaction mixture under vacuum, followed by the addition of new standard portions of all reagents to run a subsequent batch.

[b] Moles of product/100 moles of cyclohexane.

[c] Cyclohexanol + cyclohexanone.

tivity (possibly close to 100%) to cyclohexanol and cyclohexanone (Figure 10).

Effect of Radical Traps

In order to determinate the type of mechanism of the peroxidative oxidation of cyclohexane, several reactions were performed in the presence of various radical trapping agents. The obtained results for reactions catalyzed by complex **3** are given in Table 6, and the other copper complexes exhibit similar behaviour upon addition of radical traps. The cyclohexane oxidation appears to proceed mainly *via* radical mechanisms involving both carbon-centred radicals (upon homolysis of an alkane C–H bond) and oxygen-centred radicals on account of the pronounced decrease of the catalytic activity when the experiments are performed in the presence of either a carbon radical trap[51] like $CBrCl_3$ or TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl), or an oxygen radical trap[51] such as Ph_2NH. The addition of $CBrCl_3$ in a stoichiometric amount relative to cyclohexane or hydrogen peroxide leads to 88 and 98% suppression of the product formation, respectively (entries 2, 3). TEMPO leads to 60% suppression when used in a stoichiometric amount in relation to cyclohexane (entry 4). Ph_2NH has also a high effect, i.e., 71 and 89% of activity suppression is detected for the equimolar amount or an excess relative to cyclohexane, correspondingly (entries 5, 6). BHT (2,6-di-*tert*-butyl-4-methylphenol) has a lower inhibition effect, commonly below 50% (entries 7–9), whereas quinone almost completely suppresses the formation of cyclohexanol and cyclohexanone when used in a stoichiometric amount relative to H_2O_2 (entry 11).

However, competitive non-radical pathways[35] cannot be ruled out. They can involve electrophilic attack of an oxidized metal-peroxo, metal-superoxo or metal-oxo centre to a C–H bond of cyclohexane with hetero-

Table 6. Effect of radical traps on the peroxidative oxidation of cyclohexane catalyzed by complex **3**.

Entry	Radical trap	n(rad. trap)/ n(C_6H_{12})[a]	n(rad. trap)/ n(H_2O_2)	Yield[b] of products [%]			Yield drop owing to rad. trap[d] [%]
				Cyclohexanol	Cyclohexanone	Total[c]	
1	–	–	–	20.0	10.6	30.6	0
2	$CBrCl_3$	1:1	1:8	2.6	1.1	3.7	88
3	$CBrCl_3$	8:1	1:1	0.3	0.3	0.6	98
4	TEMPO	1:1	1:8	3.7	8.5	12.2	60
5	Ph_2NH	1:1	1:8	5.6	3.3	8.9	71
6	Ph_2NH	8:1	1:1	2.4	1.0	3.4	89
7	BHT	0.5:1	1:16	14.4	9.5	23.9	22
8	BHT	1:1	1:8	12.0	6.8	18.8	38
9	BHT	8:1	1:1	9.7	6.6	16.3	47
10	Quinone	1:1	1:8	3.3	2.7	6.0	80
11	Quinone	8:1	1:1	0.2	0.5	0.7	98

[a] R*eaction conditions:* complex **3** (25 μmol), H_2O_2 (5.00 mmol), C_6H_{12} (0.63 mmol), MeCN (3 mL), 6 h reaction time.
[b] Moles of product/100 moles of cyclohexane.
[c] Cyclohexanol + cyclohexanone.
[d] (1 – total yield with radical trap/total yield without radical trap) × 100.

lytic cleavage of this bond to form an organocopper intermediate as proposed for other metals.[2,52,53] Alternatively, a concerted mechanism *via* a direct insertion of an activated electrophilic oxygen atom, e.g., a bridging oxygen, into an alkane C–H bond, or through a pairwise process with C–H addition to two oxygen atoms, as suggested[21] for the biological alkane hydroxylation by pMMO, can, in principle, also be involved.

Comparison of Activities of Various Copper Catalysts towards Mild Oxidation of Cyclohexane

The known examples of mild copper-catalyzed oxidation of cyclohexane to the alcohol and ketone are summarized in Table 7 and Figure 11. For comparative purposes, unified yield values were recalculated (whenever required) relative to cyclohexane as moles of products/100 moles of cyclohexane, and the best quoted yields and selectivities were considered, when available. The highest reported activity, 18%, for a Cu complex different from those of this study is displayed by [Cu(salen)] at 80 °C and using hydrogen peroxide as oxidant,[25] followed by $[Cu(MeCN)_4][BF_4]$ which provides 12% yield at 60 °C when using *tert*-butyl hydroperoxide or peroxyacetic acid as oxidant.[24] Identical levels of activity, 11.9 and 11.0%, are shown by $[CuCl_{16}Pc]$ and $[Cu(tma)_2]$ catalysts,[31,30] although with a limited selectivity of 64–82 and 91%, respectively, due to the formation of various side products[31] like valeraldehyde, succinic and glutaric acids, in significant yield, or of cyclohexene[30] which is further oxidized under the reaction conditions applied (e.g., refluxing with *t*-BuOOH) to cyclohexen-3-one and cyclohexen-3-ol. Oxidation of cyclohexane with hydrogen peroxide catalyzed by copper(II) complexes containing *N,N*-bis(2-pyridylmethyl)-β-alanineamide ligands providing a maximum yield of 7.2% was studied.[32] Other reported catalysts (Figure 11, Table 7)[26–29,33,34] exhibit overall maximum yields of cyclohexanol and cyclohexanone in the range of 2.0–4.9%, which are even lower that that (5.4%) found for copper nitrate. Thus, most of the previously reported copper-containing catalytic systems display a considerably low activity and selectivity, require expensive components, inaccessible on a large scale, and therefore likely will not become industrially viable.

Our systems with copper triethanolaminate catalysts, to the best of our knowledge, are the most active ones so far reported for copper-catalyzed cyclohexane oxidation under mild conditions.

Conclusion

We have synthesized, by easily accessible self-assembled routes, a number of copper(II) complexes with a variable nuclearity, presenting the polydentate triethanolaminate ligand in the $\{Cu_n(H_2tea)_m\}$ (n = 1, m = 1; n = 2, m = 2; n = 3, m = 2) or $\{Cu_4(tea)_4\}$ core, and found that they act as remarkably active and selective catalysts or catalyst precursors for the liquid biphasic peroxidative oxidation, under mild conditions, of cyclohexane to cyclohexanol and cyclohexanone.

The effects of various parameters have been investigated and allowed us to achieve, in a single batch, yields and TONs of *ca.* 39% and 380, respectively, corresponding, as far as we are aware, to the most active copper systems so far reported for that alkane oxidation reaction. The catalysts can be reused for recycling and, at least for the tetranuclear one, its activity remains almost unchanged even after five cycles.

Table 7. Comparison of activities of copper catalysts towards mild oxidation of cyclohexane into the cyclohexanol and cyclohexanone mixture.

Entry	Catalyst[a]	Oxidant	Temp. [°C]	Time [h]	Selectivity [%][b]	Max. total yield [%][c]	Ref.
1	$[Cu(MeCN)_4][BF_4]$	t-BuOOH or CH_3COOOH	60	5	–[d]	12.0	[24]
2	$[Cu_2(Py_2SSPy_2)](ClO_4)_2$[e]	H_2O_2 or t-BuOOH	25	0.5	–	3.7	[28]
3	[Cu(salen)][f]	H_2O_2	80	5	–	18.0	[25]
4	$[Cu(tma)_2]$[g]	t-BuOOH	70	24	91	11.0	[30]
5	$[CuCl_{16}Pc]$[h]	O_2/t-BuOOH	70	8	64–82	11.9	[31]
6	[Cu(bdpg)Cl]Cl[i]	H_2O_2	r.t.	2	–	7.2	[32]
7	$[(CuCl_2)_4(18\text{-crown-}6)_2(H_2O)_2]$[j]	O_2	70	24	96	4.4	[33]
8	$Cu(OH)_2$[j]	O_2	20	24	96	4.3	[27]
9	$Cu\text{-}SiO_2$	t-BuOOH	75	24	84	4.4	[26]
10	$Cu(NC_3)Si\text{-}MCM\text{-}41$	H_2O_2	100	12	–	4.9	[29]
11	Cu-Gif system[k]	H_2O_2 or O_2	r.t.	6	–	2.0	[34]
12	$Cu(NO_3)_2$	H_2O_2	r.t.	6	90	5.4	this work
13	Complex **4**	H_2O_2	r.t.	6	100	38.5	this work

[a] The most active copper catalyst from each reference is considered.
[b] Towards formation of cyclohexanol and cyclohexanone.
[c] Moles of products (cyclohexanol + cyclohexanone)/100 moles of cyclohexane.
[d] Here and there selectivity data are not available.
[e] Py_2SSPy_2 = bis{2-[*N,N*-bis(2-pyridylethyl)amino]-1,1-dimethylethyl} disulfide.
[f] *N,N′*-(1,2-ethylene)-bis(salicylaldamine)-copper(II).
[g] tma = trimethyl acetate.
[h] Pc = phthalocyanines, used also as encapsulated in zeolites X and Y.
[i] bdpg = *N,N*-bis(2-pyridylmethyl)-β-alanineamide.
[j] Active only in the presence of acetaldehyde additive.
[k] Cu-Gif = Cu-powder/pyridine/acetic acid.

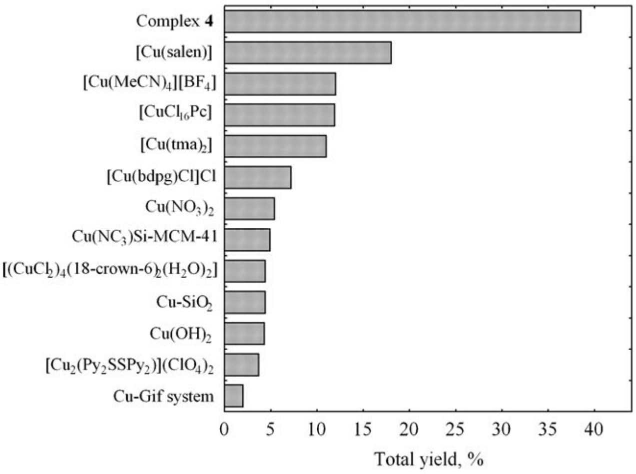


Figure 11. Comparison of activities of copper catalysts towards mild oxidation of cyclohexane into the cyclohexanol and cyclohexanone mixture. For details see Table 7.

Other advantages of our systems, over most of the other reported copper catalysts, include their easy and cheap synthesis and/or the use of easily available and environmentally tolerable starting materials.

The most active catalysts for the optimized conditions (Figures 6, 7) are the pentacoordinate tri- and tetranuclear ones, **3** and **4**, suggesting the preferable involvement of unsaturated dicopper(II) centres in the catalytic reaction. In this respect, it is noteworthy to mention that the crystal structure of pMMO (from the methanotroph *Methylococcus capsulatus*) has just been established[23] and shows that the enzyme is a trimer, each subunit containing one dinuclear copper centre (with two Cu ions in close proximity) and one mononuclear copper site, apart from a third metal centre with zinc that can come from the buffer used to crystallize the protein. The attractive possibility of the dicopper centre to behave as the active site of this enzyme for the hydroxylation of alkanes has also been considered,[21–23] albeit not yet confirmed.

Supporting testimony for a main radical mechanism of the cyclohexane oxidation by our copper catalysts, involving both C-centred and O-centred radicals has been provided by experiments with radical traps. Cyclohexyl hydroperoxide is a plausible product of the peroxidative oxidation of cyclohexane (formed, e.g., from reaction of this alkane with a hydroxyl radical generated from the reaction of H_2O_2 with a metal centre), and it can decompose to the final cyclohexanol and cyclohexanone species.[8,50] The amount of that peroxide can be estimated from the variations in the alcohol and ketone yields, determined by GC analyses, upon addition to the final reaction solution of PPh_3 or $Na_2S_2O_3$, according to a method reported by Shul’pin et al.[8,47] However, in our case, no significant effect (yields remain identical within the standard deviations) was detected by addition of any of those reagents what suggests that, under the experimental conditions used, the decomposition of cyclohexyl hydroperoxide, if formed, to the corresponding alcohol and ketone can be promoted by our copper catalysts. Such a type of decomposition reaction has been reported to be catalyzed by some copper[54,55] and other transition metal (V, Cr, Mo, Mn, Fe, Co, etc.)[56–58] compounds. Attempts to isolate and fully characterize active intermediates have so far been unsuccessful, but will be pursued.

Experimental Section

General Materials and Procedures

$Cu(NO_3)_2 \cdot 2.5\,H_2O$ (Fluka), triethanolamine (H_3tea) (Fluka), sodium hydroxide (Fluka), nitric acid (Fluka), sodium azide (Merck), benzoic acid (Merck), *p*-toluic acid (Aldrich), 3-chlorobenzoic acid (Fluka), *p*-hydroxybenzoic acid (Aldrich), terephthalic acid (Fluka), sodium tetrafluoroborate (Aldrich), cyclohexane (Aldrich), acetonitrile (Lab-Scan), hydrogen peroxide (30% in H_2O) (Fluka), diethyl ether (Lab-Scan), cycloheptanone (Aldrich), cyclohexanol (Aldrich), cyclohexanone (Aldrich), 2,6-di-*tert*-butyl-4-methylphenol (BHT) (Aldrich), 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) (Aldrich), diphenylamine (Fluka), bromotrichloromethane (Fluka) and quinone (Fluka) were obtained from commercial sources and used as received. Complexes **2a**, **3**, **4** and 5 were prepared according to the procedures described earlier.[35]

C, H and N elemental analyses were carried out by the Microanalytical Service of the Instituto Superior Técnico. Melting points were determined on a Köfler table. Positive-ion FAB mass spectra were obtained on a Trio 2000 instrument by bombarding 3-nitrobenzyl alcohol (NBA) matrices of the samples with 8 keV (*ca.* 1.18×10^{15} J) Xe atoms. Mass calibration for data system acquisition was achieved using CsI. Infrared spectra (4000–400 cm^{-1}) were recorded on a Jasco FT/IR-430 instrument in KBr pellets.

Synthesis and Characterization of New Copper Complexes

Synthesis of 1: To an aqueous solution (10 mL) of $Cu(NO_3)_2 \cdot 2.5\,H_2O$ (232 mg, 1 mmol) in HNO_3 (1 mmol) (the acid was added to avoid a spontaneous hydrolysis of the metal salt) were added dropwise triethanolamine (0.13 mL, 1 mmol) and an aqueous solution (6 mL) of NaOH (120 mg, 3 mmol) with continuous stirring at room temperature. To the resulting deep-blue purple solution an excess of sodium azide (130 mg, 2 mmol) was added. The system was stirred overnight and then left to concentrate in a beaker at ambient temperature. Green X-ray quality crystals of **1** were formed in a few days, then collected and dried in air; yield: 80% (based on copper nitrate). Complex **1** is slightly soluble in H_2O, MeOH, EtOH, MeCN and DMSO; anal. calcd. for $C_6H_{14}CuN_4O_3$ (MW 253.7): C 28.40, H 5.56, N 22.08; found: C 28.41, H 5.82, N 21.72; FTIR (selected bands, cm^{-1}): 3480 m br and 3308 m $\nu(OH)$, 2985 w $\nu_{as}(CH)$, 2909 m and 2859 m $\nu_s(CH)$, 2048 s $\nu_{as}(N_3)$, 1384 s $\nu_s(N_3)$.

Synthesis of 2b·2 H₂O: To an aqueous solution (10 mL) of $Cu(NO_3)_2 \cdot 2.5\,H_2O$ (232 mg, 1 mmol) in HNO_3 (1 mmol) was added dropwise triethanolamine (0.13 mL, 1 mmol) and then an aqueous solution (3 mL) of NaOH (120 mg, 3 mmol) with continuous stirring at room temperature. *p*-Toluic acid (136 mg, 1 mmol) was dissolved in an aqueous solution (1 mL) of NaOH (40 mg, 1 mmol) and added to the resulting deep blue solution. The reaction mixture was stirred overnight, filtered off in case a slight amount of precipitate formed, and then left to evaporate in a beaker at ambient temperature. Blue crystals of **2b** were formed in a few days, then collected and dried in air; yield: 86% (based on copper nitrate). Product **2b** is soluble in H_2O (slightly), MeOH, EtOH, Me_2CO, MeCN, CH_2Cl_2 and THF; mp 160 °C (dec.), 110–125 °C (dehydration); anal. calcd. for $C_{28}H_{46}Cu_2N_2O_{12}$ (MW 729.8): C 46.08, H 6.35, N 3.84; found: C 46.07, H 6.33, N 3.85; FAB$^+$-MS: $m/z = 692$ $[M - 2\,H_2O + 2H]^+$, 546 $[M - 2\,H_2O - \{tea\}]^+$, 423 $[Cu_2\{H_2tea\}_2 + H]^+$, 275 $[Cu_2\{H_2tea\} + H]^+$, 211 $[Cu\{H_2tea\}]^+$; FTIR (selected bands, cm^{-1}): 3434 s br and 3202 s br $\nu(OH) + \nu(H_2O)$, 2976 s and 2948 m $\nu_{as}(CH)$, 2904 s and 2871 s $\nu_s(CH)$, 1590 s and 1546 s $\nu_{as}(COO)$, 1404 s $\nu_s(COO)$, 1092 s $\nu(C{-}O)$.

Synthesis of 2c·2 H₂O: Complex **2c** was obtained as light-blue X-ray quality crystals by the same procedure as for **2b** except that benzoic acid was replaced by 3-chlorobenzoic acid (157 mg, 1 mmol); yield: 79% (based on copper nitrate). Product **2c** is soluble in H_2O (slightly), MeOH, EtOH, Me_2CO, MeCN, CH_2Cl_2 and THF; mp 154 °C; anal. calcd. for $C_{26}H_{40}Cl_2Cu_2N_2O_{12}$ (MW 770.6): C 40.52, H 5.23, N 3.64; found: C 40.14, H 5.24, N 3.62; FAB$^+$-MS: $m/z = 739$ $[M - 2\,H_2O + 5H]^+$, 443 $[M - 2\,H_2O - 2\,(C_6H_4ClCOO) - H]^+$, 421 $[Cu_2\{H_2tea\}_2 - H]^+$, 369 $[Cu\{H_2tea\}(C_6H_4ClCOO) + 3H\ ]^+$, 274 $[Cu_2\{H_2tea\}]^+$, 212 $[Cu\{H_2tea\} + H]^+$; FTIR (selected bands, cm^{-1}): 3420 s br and 3173 s br $\nu(OH) + \nu(H_2O)$, 2976 s ν_{as}(CH), 2912 s and 2873 s $\nu_s(CH)$, 1588 s and 1550 s $\nu_{as}(COO)$, 1385 s $\nu_s(COO)$, 1092 s $\nu(C{-}O)$.

X-Ray Crystal Structure Determinations

X-ray data were collected on a Nonius-Kappa CCD diffractometer using Mo-Kα radiation ($\lambda = 0.71073$ Å) and the Collect[59] data collection program. The Denzo-Scalepack[60] or EvalCCD[61] program packages were used for cell refinements and data reduction. The structures were solved by direct methods using the SHELXL-97 program.[62] An empirical absorption correction based on equivalent reflections was applied.[63,64] Structures were refined with the SHELXL-97 program[62] and the WinGX graphical user interface.[65] H_2O and OH hydrogens were located from the difference Fourier map but were not refined. Other hydrogens were placed in idealized positions and constrained to ride on their parent atom. The crystal data and structure refinement details are summarized in Table 8. The molecular structures of complexes **1** and **2c** including selected bond lengths and angles as well as hydrogen bonding networks are shown in Figures 1–4.

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-271523 (**1**) and CCDC-271524 (**2c**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK

Table 8. Crystal data and structure refinement details for compounds **1** and **2c**·2 H_2O.

	1	**2c**·2 H_2O
Empirical formula	$C_6H_{14}CuN_4O_3$	$C_{26}H_{40}Cl_2Cu_2N_2O_{12}$
Formula weight	253.75	770.58
Crystal dimensions (mm^3)	0.56 × 0.33 × 0.30	0.33 × 0.11 × 0.06
Temp (K)	120(2)	100(2)
Wavelength (Å)	0.71073	0.71073
Crystal system, Space group	Monoclinic, $P2_1/n$	Triclinic, $P\bar{1}$
Colour	Green	Light blue
Unit cell dimensions (Å; deg.)	$a = 8.5995(2)$, $b = 7.94300(10)$, $c = 14.4653(7)$ $\alpha = 90$, $\beta = 107.090(2)$, $\gamma = 90$	$a = 7.4754(2)$, $b = 8.0440(3)$, $c = 14.4204(6)$ $\alpha = 97.420(2)$, $\beta = 97.481(2)$, $\gamma = 112.014(2)$
Volume ($Å^3$)	944.44(5)	781.99(5)
Z, calcd density (Mg/m^3)	4, 1.785	1, 1.636
Abs coeff (mm^{-1})	2.301	1.595
F(000)	524	398
Max/min transmission factors	0.28815/0.23546	0.28352/0.22765
θ range for data collection (deg.)	3.57–27.48	3.00–27.45
No. of collected reflns	8646	12027
No. of unique reflns	1999 [R(int) = 0.0190]	3529 [R(int) = 0.0373]
No. of data/restraints/parameters	1999/0/127	3529/0/199
Goodness-of-fit on F^2	1.061	1.044
Final R1,[a] wR2[b] indices [$I > 2\sigma(I)$]	0.0211, 0.0545	0.0313, 0.0709
R1, wR2 indices (all data)	0.0220, 0.0550	0.0429, 0.0757
Largest diff. peak and hole ($eÅ^{-3}$)	0.354, −0.390	0.730, −0.623

[a] $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$.
[b] $wR2 = [\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]]^{1/2}$.

[Fax: int. code + 44(1223)336–033; E-mail: deposit@ccdc.cam.ac.uk].

Catalytic Activity Studies

The reaction mixtures were prepared as follows: to 1.56–25.00 μmol of metal complex catalyst (used either as a solid or as a 0.02 M MeCN solution) contained in the reaction flask were added 1.00–10.00 mL MeCN, 1.25–10.00 mmol H_2O_2 (30% in H_2O), HNO_3 (acid-to-catalyst molar ratio = 10:1 for **1**, **3** and **4**; or 100:**1** for **2** and **5**), and 0.63–10.00 mmol C_6H_{12}, in this order. The reaction mixture was stirred for 6–72 h at room temperature and normal pressure, then 90 μL of cycloheptanone (as internal standard) and 10.00 mL diethyl ether (to extract the substrate and the products from the reaction mixture) were added. The obtained mixture was stirred during 10 min and then a sample was taken from the organic phase and analyzed by GC using a FISONS Instruments GC 8000 series gas chromatograph with a DB WAX fused silica capillary column (P/N 123–7032) and the JASCO-BORWIN v.1.50 software, or by GS-MS using a Trio 2000 Fisons spectrometer with a coupled Carlo Erba (Auto/HRGC/MS) gas chromatograph. The GC-MS analysis of the aqueous phase showed the presence of only traces (less than 0.05%) of oxidation products.

Blank experiments were performed with different amounts of H_2O_2 and other reagents, and confirmed that no product of cyclohexane oxidation was obtained unless the metal catalyst was used.

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