

New Multicopper(II) Cores for Mild Oxidative Functionalization of Alkanes

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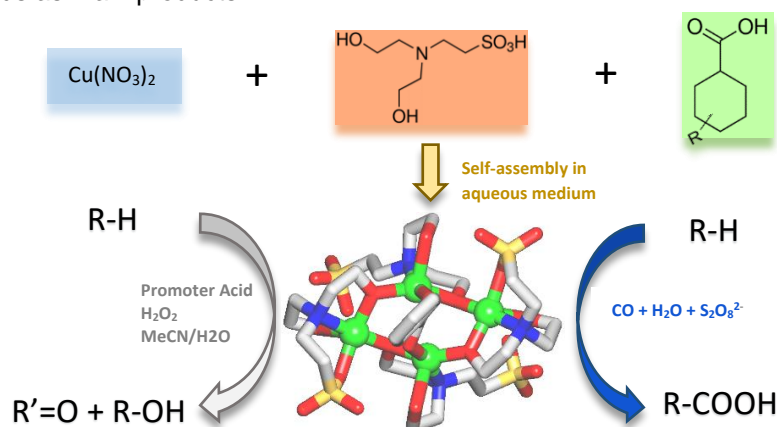
Abstract

The development of new, highly efficient and selective catalysts for the oxidative functionalization of alkanes under mild conditions to produce industrially valuable and desirable oxidation products represents a challenge to modern chemistry. In this sense, the objectives of the present work have been the synthesis and characterization of new multicopper(II) catalysts, evaluation of their catalytic activity in model reactions of oxidation and hydrocarboxylation of different alkanes and investigation of the mechanistic features.

Eight new copper(II) coordination compounds have been synthesized from the aminoalcohol-sulfonic acid [N,N-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid, H₃bes] as a main chelating ligand, and several carboxylic acids as auxiliary ligands, namely benzoic acid (Hba), 4-hydroxybenzoic acid (Hfba), 4-methoxybenzoic acid (Hfmba), 3-hydroxybenzoic acid (Hthba), 4-nitrobenzoic acid (Hfcba) and homophthalic acid (H₂hfa).

The obtained compounds have been formulated as follows: [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-ba)]·2H₂O (1), [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-fhba)]·2H₂O (2), [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-fmba)]·2H₂O (3), [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-thba)]·2H₂O (4), [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-fnba)]·2H₂O (5) and [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-fcba)]·4H₂O (6) (discrete complexes) as well [Cu(μ-OH)(μ-fcba)]_n (7) and [Cu(μ₄-hfa)(H₂O)]_n (8) (1D coordination polymers). All the compounds synthesized have been characterized by the techniques of infrared spectroscopy (IR), mass spectrometry (ESI-MS), single-crystal X-ray diffraction and elemental analysis.

The synthesized compounds have been tested as catalysts in the mild oxidation of different alkanes (C₅-C₈ cycloalkanes and propane), leading to the formation of the respective alcohols and ketones as main products. The studied effects include the type and amount of promoter and substrate, amount of catalyst, oxidant and water, and the analysis of selectivity parameters and mechanism. The catalytic study has also included the application of the obtained Cu(II) compounds in the hydrocarboxylation reactions of C₅-C₈ cyclic alkanes and propane by carbon monoxide, water and potassium peroxodisulfate oxidant, resulting in the formation of carboxylic acids as main products.



Keywords: Alkanes, coordination complexes, coordination polymers, copper, crystal structure, catalysis, oxidation, hydrocarboxylation.

Introduction

The development of new selective and highly efficient catalysts for the mild oxidative functionalization of alkanes constitutes a subject of high relevance in areas such as homogeneous catalysis, coordination and organic chemistry.^[1-7,15-17]

In particular, Cu-containing complexes represent an interesting class of compounds capable of functionalizing C–H bonds in rather inert substrates such as alkanes. In fact, various copper enzymes are known to act as efficient biocatalysts for the oxidative functionalization of various substrates including alkanes.^[9-19]

Hence, the main objectives of the present work were: (1) synthesis and characterization of new multicopper(II) coordination compounds using H₃bes as a primary N,O ligand source; (2) catalytic application of the obtained compounds in the mild oxidation and hydrocarboxylation of alkanes.

Thus, herein we report the self-assembly synthesis, characterization, crystal structures and catalytic application of a new series of multicopper(II) compounds **1-8**, derived from an aminoalcohol building block (N,N-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid, H₃bes, fig. 1).

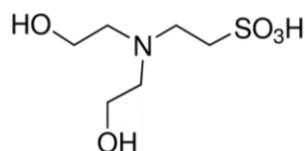


Figure 1. Structural formula of aminoalcohol-sulfonic acid block, H₃bes.

The synthesis of copper(II) coordination compounds was performed by the self-assembly method, by combining in aqueous solution and at room temperature a metal source with an aminoalcohol (main chelating ligand), a carboxylic acid (auxiliary ligand source), and a pH regulator (base). The carboxylic acids applied as supporting ligands are shown in figure 2.

Discrete compounds **1-6** have the general formula of: [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-carboxylate)].

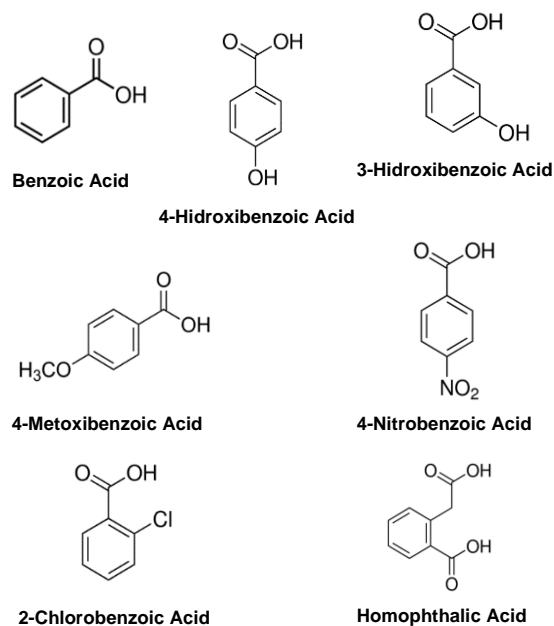


Figure 2. Structural formulae of carboxylic acids used as auxiliary ligands.

The obtained complexes act as efficient catalysts for: (1) the oxidation of different C₅-C₈ cycloalkanes and propane by hydrogen peroxide to give a mixture of alcohols and ketones, and (2) the hydrocarboxylation of C₅-C₈ cycloalkanes by carbon monoxide, water and peroxodisulfate oxidant to give the corresponding cycloalkanecarboxylic acids.

The effects of various reaction parameters were studied in detail and are reported below.

Experimental section

Materials and methods. All reagents were obtained from commercial suppliers and used without further purification. Synthetic work was performed in air and at room temperature (~25°C). Infrared spectra (4000–400 cm⁻¹) were recorded on a JASCO FT/IR-4100 Type A instrument using KBr pellets. Mass spectra (ESI-MS) were recorded on LCQ Fleet apparatus equipped with an electrospray (ESI) ion source. Elemental analyses were carried out on a Perkin Elmer PE 2400 Series II analyzer using diluted aqueous solutions of Cu compounds. The crystal structure data of **1-8** were collected using a Bruker AXS-KAPPA APEX II diffractometer with graphite-monochromated radiation (Mo K α , λ =0.17073 Å).

General synthetic procedure for 1-8

To an aqueous 0,1 M solution of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (1 mmol, 10 mL), was added N,N-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid (H_3bes , 213 mg, 1 mmol), with a continuous stirring at room temperature. Then, 1 mmol of carboxylic acid (Hba –122 mg for **1**, Hthba – 138 mg for **2**, Hfhba – 138 mg for **3**, Hfmba – 152 mg for **4**, Hfnba – 167 mg for **5**, Hfcba – 157 mg for **6** and **7** e H_2hfa – 180 mg for **8**) was dissolved in NH_4OH (up to 1,87 mL, 25% m/m, 4-12 mmol) and added to the reaction mixture. The resulting solution was continuously stirred for ~25 minutes and then filtered off. The filtrate was left to evaporate in a beaker at r.t. Green (**1**, **2**, **3**, **4**, **5**, and **6**), and blue (**7** and **8**) crystals were formed in 1-2 weeks, then collected and dried in air to furnish the compounds **1-8**. Crystals were characterized using IR, DRX, EA and ESI-MS techniques.

1 – $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-ba})] \cdot 2\text{H}_2\text{O}$

IR (KBr, cm^{-1}): 3568 (m br) $\nu(\text{OH}/\text{H}_2\text{O})$, 2872 (w) $\nu(\text{CH})$, 1598 (s) $\delta(\text{OH}/\text{H}_2\text{O})$, 1546 (vs) $\nu_{\text{as}}(\text{COO})$, 1401 (s) $\nu_{\text{s}}(\text{COO})$, 1241 (s) $\nu(\text{C-C})$, 1151 (vs) $\nu(\text{C-N})$, 1025 (vs) $\nu(\text{C-S})$. Anal. Calcd for **1**+ H_2O : ($\text{Cu}_4\text{C}_{31}\text{H}_{63}\text{N}_4\text{O}_{24}\text{S}_4$) (MM=1257) C, 29,18%; H, 5,10%; N, 4,39%; S, 10,04%. Found: C, 28,99%; H, 5,13%; N, 5,52%; S, 9,73%. ESI-MS(\pm)(H_2O), selected fragments: MS(+), m/z: 1099 (20%) $[\{\text{Cu}_4(\mu\text{-Hbes})_4\} + \text{H}]^+$, 1038 (60%) $[\{\text{Cu}_3(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})_2\} + \text{H}]^+$, 977 (42%) $[\{\text{Cu}_2(\mu\text{-H}_2\text{bes})_4\} + \text{H}]^+$, 825 (20%) $[\{\text{Cu}_3(\mu\text{-Hbes})_3\} + \text{H}]^+$. MS(-), m/z: 760 (5%) $[\{\text{Cu}_2(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})\}]^-$, 699 (8%) $[\{\text{Cu}(\mu\text{-H}_2\text{bes})_3\}]^-$, 547 (5%) $[\{\text{Cu}_2(\mu\text{-Hbes})(\mu\text{-bes})\}]^-$

2 – $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-fhba})] \cdot 2\text{H}_2\text{O}$

IR (KBr, cm^{-1}): 3541 (m br) $\nu(\text{OH}/\text{H}_2\text{O})$, 2880 (w) $\nu(\text{CH})$, 1609 (s) $\delta(\text{OH}/\text{H}_2\text{O})$, 1540 (s) $\nu_{\text{as}}(\text{COO})$, 1398 (vs) $\nu_{\text{s}}(\text{COO})$, 1242 (vs) $\nu(\text{C-C})$, 1150 (vs) $\nu(\text{C-N})$, 1024 (vs) $\nu(\text{C-S})$. Anal. Calcd for **2**- H_2O : ($\text{Cu}_4\text{C}_{31}\text{H}_{63}\text{N}_4\text{O}_{25}\text{S}_4$) (MM=1273) C, 29,64%; H, 4,86%; N, 4,46%. Found: C, 30,91%; H, 4,85%; N, 4,62%. ESI-MS(\pm)(H_2O), selected fragments: MS(+), m/z: 1376 (5%) $[\{\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})\}\{\mu\text{-Hfhba}\}_2 + \text{H}]^+$, 1099 (16%) $[\{\text{Cu}_4(\mu\text{-Hbes})_4\} + \text{H}]^+$, 1038 (58%) $[\{\text{Cu}_3(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})_2\} + \text{H}]^+$, 977 (50%) $[\{\text{Cu}_3(\mu\text{-Hbes})_3\} + \text{H}]^+$.

$[\{\text{Cu}_2(\mu\text{-H}_2\text{bes})_4\} + \text{H}]^+$. MS(-), m/z: 760 (5%) $[\{\text{Cu}_2(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})\}]^-$, 699 (8%) $[\{\text{Cu}(\mu\text{-H}_2\text{bes})_3\}]^-$.

3 – $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-fmba})] \cdot 2\text{H}_2\text{O}$

IR (KBr, cm^{-1}): 3560 (m br) $\nu(\text{OH}/\text{H}_2\text{O})$, 2923 (w) $\nu(\text{CH})$, 1605 (m) $\delta(\text{OH}/\text{H}_2\text{O})$, 1537 (m) $\nu_{\text{as}}(\text{COO})$, 1400 (s) $\nu_{\text{s}}(\text{COO})$, 1242 (m) $\nu(\text{C-C})$, 1151 (s) $\nu(\text{C-N})$, 1024 (vs) $\nu(\text{C-S})$. Anal. Calcd for **3**+ H_2O : ($\text{Cu}_4\text{C}_{32}\text{H}_{65}\text{N}_4\text{O}_{25}\text{S}_4$) (MM=1287) C, 29,43%; H, 5,13%; N, 4,29%; S, 9,81%. Found: C, 28,49%; H, 5,03%; N, 5,69%; S, 9,81%. ESI-MS(\pm)(H_2O), selected fragments: MS(+), m/z: 1099 (18%) $[\{\text{Cu}_4(\mu\text{-Hbes})_4\} + \text{H}]^+$, 1038 (55%) $[\{\text{Cu}_3(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})_2\} + \text{H}]^+$, 977 (44%) $[\{\text{Cu}_2(\mu\text{-H}_2\text{bes})_4\} + \text{H}]^+$, 825 (18%) $[\{\text{Cu}_3(\mu\text{-Hbes})_3\} + \text{H}]^+$.

4 – $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-thba})] \cdot 2\text{H}_2\text{O}$

IR (KBr, cm^{-1}): 3568 (m br) $\nu(\text{OH}/\text{H}_2\text{O})$, 2870 (w) $\nu(\text{CH})$, 1600 (s) $\delta(\text{OH}/\text{H}_2\text{O})$, 1546 (s) $\nu_{\text{as}}(\text{COO})$, 1401 (s) $\nu_{\text{s}}(\text{COO})$, 1240 (m) $\nu(\text{C-C})$, 1151 (vs) $\nu(\text{C-N})$, 1025 (vs) $\nu(\text{C-S})$. Anal. Calcd for **4**+ H_2O : ($\text{Cu}_4\text{C}_{31}\text{H}_{63}\text{N}_4\text{O}_{25}\text{S}_4$) (MM=1273) C, 28,81%; H, 5,03%; N, 4,34%; S, 9,91%. Found: C, 28,86%; H, 5,09%; N, 5,23%; S, 9,70%. ESI-MS(\pm)(H_2O), selected fragments: MS(+), m/z: 1376 (5%) $[\{\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})\}\{\mu\text{-Hthba}\}_2 + \text{H}]^+$, 1237 (1%) $[\{\text{Cu}_4(\mu\text{-Hbes})_4\}\{\mu\text{-Hthba}\} + \text{H}]^+$, 1099 (20%) $[\{\text{Cu}_4(\mu\text{-Hbes})_4\} + \text{H}]^+$, 1038 (60%) $[\{\text{Cu}_3(\mu\text{-Hbes})_2(\mu\text{-H}_2\text{bes})_2\} + \text{H}]^+$. MS(-), m/z: 823 (5%) $[\{\text{Cu}_3(\mu\text{-H}_2\text{bes})_2(\mu\text{-Hbes})\}]^-$, 760 (5%) $[\{\text{Cu}_2(\mu\text{-H}_2\text{bes})_2(\mu\text{-Hbes})\}]^-$.

5 – $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-fnba})] \cdot 2\text{H}_2\text{O}$

IR (KBr, cm^{-1}): 3542 (m br) $\nu(\text{OH}/\text{H}_2\text{O})$, 2921 (m) $\nu(\text{CH})$, 1605 (s) $\delta(\text{OH}/\text{H}_2\text{O})$, 1470 (vs) $\nu_{\text{as}}(\text{COO})$, 1384 (s) $\nu_{\text{s}}(\text{COO})$, 1234 (s) $\nu(\text{C-C})$, 1154 (m) $\nu(\text{C-N})$, 1024 (vs) $\nu(\text{C-S})$. Anal. Calcd for **5**+ H_2O : ($\text{Cu}_4\text{C}_{31}\text{H}_{62}\text{N}_5\text{O}_{26}\text{S}_4$) (MM=1302) C, 28,18%; H, 4,85%; N, 5,30%; S, 9,70%. Found: C, 27,71%; H, 4,85%; N, 6,10%; S, 9,88%. ESI-MS(\pm)(H_2O), selected fragments: MS(+), m/z: 1372 (5%) $[\{\text{Cu}_3(\mu\text{-H bes})_3(\mu\text{-H}_3 \text{ bes})\}\{\mu\text{-Hfnba}\}_2 + \text{H}]^+$, 1099 (20%) $[\{\text{Cu}_4(\mu\text{-H bes})_4\} + \text{H}]^+$, 1038 (60%) $[\{\text{Cu}_3(\mu\text{-H bes})_2(\mu\text{-H}_2 \text{ bes})_2\} + \text{H}]^+$.

6 – [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-fcba)]·4H₂O.

IR (KBr, cm⁻¹): 3521 (m br) ν(OH/H₂O), 1650 (w), 1600 (w) δ(OH/H₂O), 1556 (s) ν_{as}(COO), 1388 (s) ν_s(COO), 1151 (s) ν(C-N), 1069 (s) ν(C-S). Anal. Calcd for 6+2H₂O: (Cu₄C₃₁H₆₂N₅O₂₆S₄) (MM=1302) C, 28,18%; H, 4,85%; N, 5,30%; S, 9,70%. Found: C, 27,71%; H, 4,85%; N, 6,10%; S, 9,88%.

Catalytic studies. The catalytic reactions of alkane oxidation were typically carried out in thermostated glass reactors equipped with a condenser under continuous stirring at 50 °C and using MeCN as solvent (up to 2,5 mL of total volume).

In a typical experiment, catalysts 1-8 (2,5 μmol) were introduced into MeCN solution, followed by the addition of acid promotor (50 μmol) and gas chromatography (GC) internal standard (MeNO₂, 250 μL). Then, the alkane substrate (1 mmol) and hydrogen peroxide (50% in H₂O) were introduced. The oxidation reactions were monitored by removing small aliquots after different periods of time, which were treated with PPh₃ for the reduction of remaining H₂O₂ and alkyl hydroperoxides that are typically formed as primary products in cycloalkane oxidations. The samples were analyzed by GC using nitromethane as an internal standard. Attribution of peaks was made by comparison with chromatograms of authentic samples.

Gas chromatography (GC) analyses were run on an Agilent Technologies 7820A series gas chromatograph (He as carrier gas) equipped with the FID detector and BP20/SGE (30 m × 0.22 mm × 0.25 μm) capillary column and using Jasco-Borwin v.1.50 software. The effects of various reaction parameters were investigated.

Results and Discussion

IR characterization. The IR spectra of 1-6 feature common aspects due to the presence of similar type of Cu(II) cores [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-carboxylate)] and water molecules. Characteristic vibrations include the ν(H₂O)/ν(OH) bands with maxima in the 3629–3324 cm⁻¹ range due to H₂O molecules and OH groups of aminoalcohol ligands. Broad bands in 1-4 indicate more intense H bonds. Bands observed in the 1500-1700 cm⁻¹ range for

compounds 6 and 8, correspond to δ(OH/H₂O) vibrations.

In the 3000-2300 cm⁻¹ range, the weak ν_{as} e ν_s (CH) bands are observed due to antisymmetric and symmetric CH vibrations. The spectra of 1-8 also reveal two groups of intense ν_{as} (COO) and ν_s (COO) vibrations in the range of 1600-1500 cm⁻¹ e 1400-1300 cm⁻¹, respectively; these correspond to the carboxylate linkers. Besides, there are strong bands in the 1300-1000 cm⁻¹ range, associated to the Hbes/H₂bes vibrations ν(C-X) (X = C, N, S).

ESI-MS studies. In aqueous medium the ESI-MS(+) plot of 4 presents the [(Cu₄(μ-Hbes)₄{μ-C₆H₄COOH(3-OH)} + 2H₂O + H]⁺ (m/z = 1273), fragment related to unity cell. Other related adducts can also be identified: [(Cu₄(μ-Hbes)₄{μ-Hthba} + H]⁺ (m/z = 1237), [(Cu₄(μ-Hbes)₃(μ-H₂bes){μ-Hthba}₂ + H]⁺ (m/z = 1376). In a positive mode, the most intense signals are due adducts without 3-hydroxybenzoic acid moiety: [(Cu(μ-H₂bes)₂(μ-H₃bes) + H]⁺ (m/z = 701, 100%), [(Cu₂(μ-Hbes)(μ-H₂bes)₂ + H]⁺ (m/z = 764, 90%), [(Cu(μ-H₂bes)₂ + H]⁺ (m/z = 488, 86%), [(Cu₃(μ-Hbes)₂(μ-H₂bes)₂ + H]⁺ (m/z = 1038, 60%), [(Cu₂(μ-H₂bes)₄ + H]⁺ (m/z = 977, 55%). The MSⁿ fragmentation of [(Cu₄(μ-Hbes)₄{μ-Hthba} + 2H₂O + H]⁺ (m/z = 1273) leads to the adduct: [(Cu₃(μ-Hbes)₄{μ-C₆H₄(3-OH)}]⁺ (m/z=1126) due to the loss of Cu and COOH. Further fragmentation leads to the adducts: [(Cu(μ-H₂bes)₂(μ-H₃bes) + H]⁺ (m/z=701) and [(Cu₄(μ-bes)₃) + Na]⁺ (m/z=913).

The ESI-MS (+) plots of 1-5 present similar spectra. The only difference concerns the benzoic acid used. Since the more intense signals are due adducts with Hbes/H₂bes, the observed spectra are very similar.

In the MS(-) mode, the fragmentation is poor and less informative for all samples (1-5). Nevertheless, major differences are due the presence of different substituted benzoate ligands.

The obtained data suggest that upon dissolution and in the course of catalytic reactions the compounds 1-5 may partially disaggregate to generate a series of different multi-copper blocks bearing Hbes/H₂bes ligands.

Description of crystals structures. All compounds 1–6 feature a similar type of crystal structure that is composed of the neutral discrete tetracopper(II) molecular units with a general formula $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-carboxylate})]$.

Hence, the structure of **1** bears a discrete $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-ba})]$ molecular unit and two water molecules of crystallization (fig.3). The tetracopper(II) unit is composed of two symmetry non-equivalent “central” Cu_1 and “side” Cu_2 atoms, four bridging aminoalcoholate ligands (three $\mu\text{-Hbes}^{2-}$ and one $\mu\text{-H}_2\text{bes}^-$), and one μ -benzoate linker (fig. 3).

Within the $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-ba})]$ molecular unit, all the Cu centers act as square pyramids that are fused via common vertices into a cyclic $[\text{Cu}_4(\mu\text{-O}_{\text{bes}})_4(\mu\text{-COO})]$ cluster core. The Cu_4 unit is further stabilized by the intramolecular O–H...O hydrogen bonds between the $-\text{SO}_3\text{H}$ or $-\text{OH}$ groups of $\mu\text{-Hbes}^{2-}/\mu\text{-H}_2\text{bes}^-$ and the O atoms of adjacent aminoalcoholate moieties.

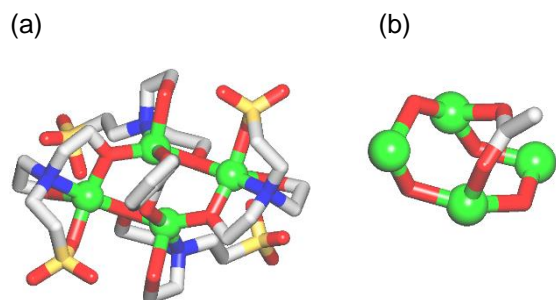


Figure 3 - Crystal structure (a) and tetracopper(II) core (b) of compound **1**.

Furthermore, the intermolecular H-bonds between the $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-ba})]$ units and water molecules of crystallization give rise to an extension of the structure (0D→3D) with the formation of a 3D H-bonded net.

Similarly to **1**, the structures of **2-6** also reveal a discrete 0D structure composed of $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-carboxylate})]$ molecular unit and two water molecules of crystallization. However, in the tetracopper(II) unit the μ -carboxylate linker is different for each compound. The structures of **2** and **6** are represented in figure **4 a** and **4b**, respectively. Compound **7** was obtained as a second product in the course of the synthesis of tetracopper(II)

complex $[\text{Cu}_4(\mu\text{-Hbes})_3(\mu\text{-H}_2\text{bes})(\mu\text{-fcba})]\cdot 4\text{H}_2\text{O}$ (**6**).

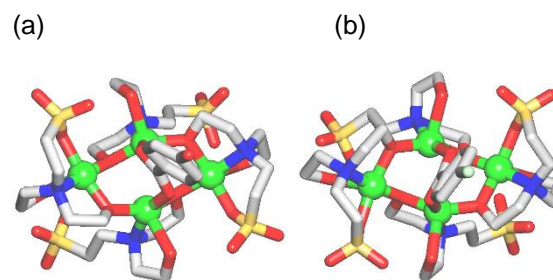


Figure 4 - Crystal structures of **2** (a) and **6** (b).

The crystal structure of $[\text{Cu}(\mu\text{-OH})(\mu\text{-fcba})]_n$ (**7**) is composed of a Cu_1 center, one $\mu\text{-fcba}^-$ (μ_4 -chlorobenzoate⁻) and one $\mu\text{-OH}^-$ linker. These building blocks are infinitely repeated, leading to a generation of the 1D coordination polymer with the tubular chain structure (fig. 5).

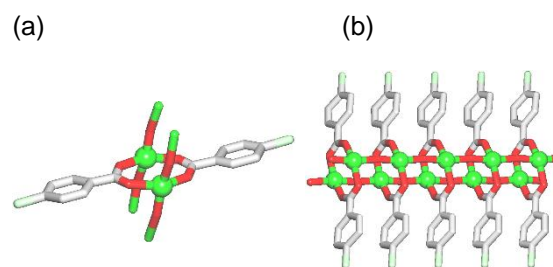


Figure 5 - Crystal structure of **7** showing connectivity of Cu(II) centers (a) and 1D tubular chain (b).

The crystal structure of $[\text{Cu}(\mu_4\text{-hfa})(\text{H}_2\text{O})]_n$ (**8**) also reveals a 1D metal-organic network which is, however, different from that of **7**. A formula unit of **8** is composed of the Cu_1 center, $\mu_4\text{-hfa}^{2-}$ spacer and a terminal H_2O ligand (fig. 6).

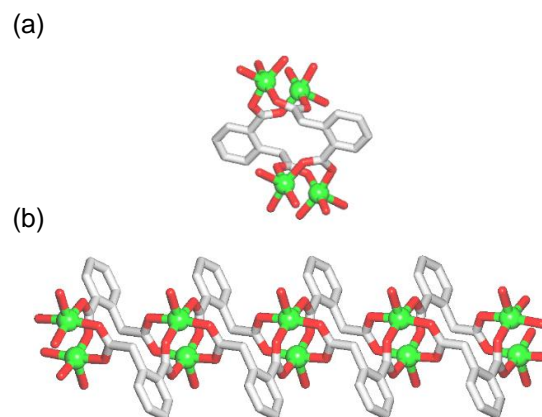


Figure 6- Crystal structure of **8** showing a connectivity of Cu(II) centers (a) and 1D coordination polymer chain (b).

Mild catalytic oxidation of alkanes. The compounds **1–7** were applied as catalysts in the mild oxidation of C₅–C₈ cycloalkanes, by aqueous H₂O₂ in acetonitrile solution and in the presence of an acid promoter (co-catalyst), to a mixture of the corresponding alcohols and ketones (fig. 7).^[8,14-19]

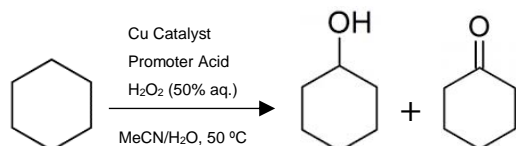


Figure 7 - Cycloalkane oxidation to cyclohexanol and cyclohexanone.

The effects of various reaction parameters were studied, namely the type of acid promoter acid, TFA (trifluoroacetic acid) amount, type of substrate, amount of water and amount of oxidant (H₂O₂). The obtained data are summarized in figures **7-10**.

For all the catalytic systems, cyclohexane was used as model substrate in typical reaction conditions. The maximum product yields are summarized in table **1**.

It was observed that the C₆H₁₂ oxidations catalyzed by the **5**/TFA system leads to 18,3% of the maximum total product yield, based on substrate, which represents the highest catalytic activity, followed by complexes **6** (16,3%), **1** (15,7%), **3** (14,7%), and **2** (13,4%). It was also investigated the influence of the type of acid on the efficiency of catalytic system, namely TFA, HCl, H₂SO₄ and HNO₃ in the oxidation of C₆H₁₂ with the catalyst **2** (fig. **8**).

Table 1- Cyclohexane oxidation catalyzed by **1-6**.^a

Catalyst	η products (%)		
	Cyclohexanol	Cyclohexanone	Total
1	10,4	5,9	15,7
2	8,8	4,6	13,4
3	8,1	7,4	14,7
4	7,8	4,3	12,1
5	14,6	4,2	18,3
6	11,5	4,8	16,3

^aReaction conditions: catalysts **1-6** (2,5 μmol), C₆H₁₂ (1 mmol), TFA (50 μmol), H₂O₂ (5 mmol), CH₃CN (up to 2,5 mL of total volume), T (50 °C).

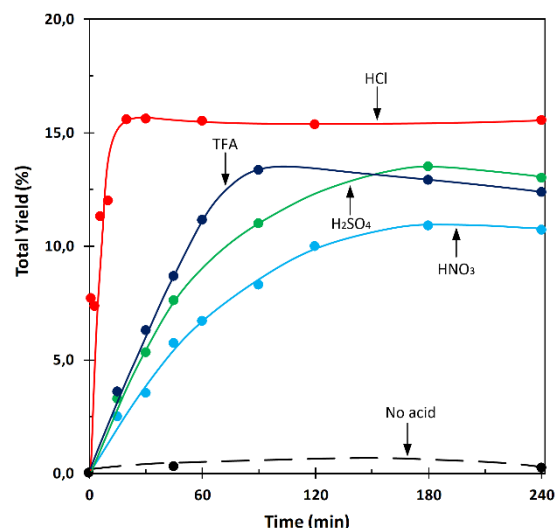


Figure 8 - Effect of promoter acid on the total yield of products in the oxidation of C₆H₁₂ catalyzed by **2**.

The oxidation is exceptionally quick in the presence of HCl leading to a total product yield of 16% at 20 minutes of reaction. TFA, HNO₃ and H₂SO₄ have a weaker promoting behaviour with total product yields of 13,4%, 10,9% e 13,5%, respectively. Those maximum yields are achieved at more prolonged reaction times relatively to a system operating with HCl. The highest maximum value of TOF when using HCl was obtained for compound **5** (584 h⁻¹). Comparing these three types of acid, HNO₃ is the least active acid and TFA the most active one.

We also studied the promoting effects of acids for catalysts **1, 3, 4, 5**, and **6**, revealing similar behaviors. Concerning the TFA amount (fig. **9**), catalytic system **2**/TFA presents low catalytic activity in the absence of any acid promoter. Globally, it was verified that the total product yield grows up with an enhancement of the TFA amount.

However, the system with the highest TFA amount (30 eq.) doesn't follow this trend. We can verify a significant yield drop, with a maximum yield value of 10% at 240 minutes of reaction. For the catalytic system with 20 equiv. of TFA relatively to catalyst, the maximum total product yield is higher than of other tested TFA amounts. In this case, the maximum total yield is 13,4% at 90 minutes. Total yield tends to stabilize at ~13%.

The catalytic study continued with the investigation of the effect of the catalyst amount (fig. **10**).

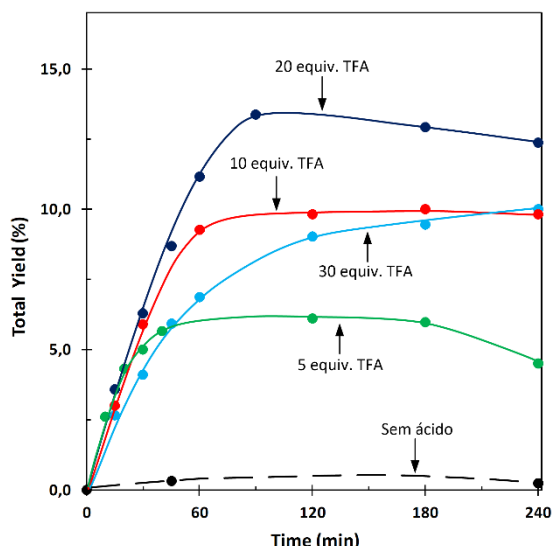


Figure 9 - Effect of acid amount on the total yield of products in the oxidation of C_6H_{12} catalyzed by **2**.

Increase of the catalyst amount (1,25 μmol to 5 μmol) results in a gradual growth of the reaction rate and the total product yield. The highest yield (17,2%) was obtained for 5 μmol of catalyst at 180 minutes.

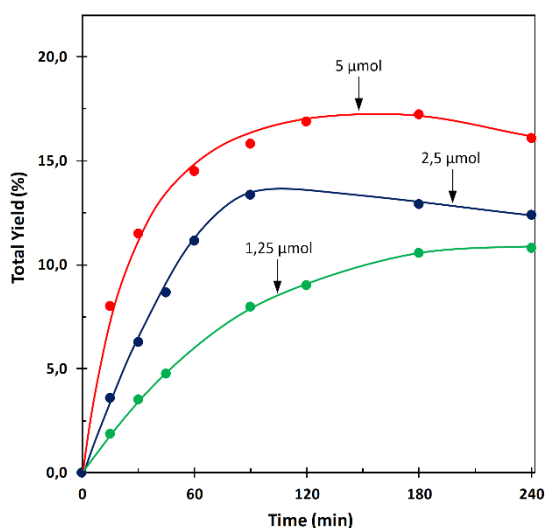


Figure 10 - Effect of the catalyst amount on the total yield of products in the oxidation of C_6H_{12} catalyzed by **2**.

Catalytic system **2**/TFA was also tested in the mild oxidation of different cyclic alkane substrates, C_5 - C_8 (table **2**). Cycloheptane and cyclooctane are the substrates with higher reactivity. The maximum total yield is achieved for cycloheptane (27% at 180 minutes), followed by cyclooctane (24%) and cyclohexane (13,4%).

Cyclopentane represents the least efficient substrate. This behavior is similar for the other tested catalytic systems (**1**, **3**, **4** and **5**).

Table 2 - Cycloalkane oxidation catalyzed by **2**.^a

Catalyst 2	η products (%)			
	Substrate	Alcohol	Ketone	Total
	Ciclopentane	4,0	5,0	9,0
	Ciclohexane	8,8	4,6	13,4
	Cicloheptane	14,5	12,6	27,0
	Ciclooctane	9,3	19,8	24,0

^aReaction conditions: catalyst **2** (2,5 μmol), C_5 - C_8 substrates (1 mmol), TFA (50 μmol), H_2O_2 (5 mmol), CH_3CN (up to 2,5 mL of total volume), T (50 $^\circ\text{C}$).

Aiming at verifying the influence of the amount of water on the efficiency of the catalytic system (fig.11), we studied this parameter by adding more water into the system, 200 μL (4,1 M) and 400 μL (12,9 M).

Increase of the H_2O concentration (up to 12,9 M) leads to a lower maximum yield. For prolonged reaction times, it was observed a significant yield drop. This situation is more evident for the highest concentration of H_2O (12,9 M) in the reaction mixture, suggesting that the additional amount of water in the system can promote overoxidation reactions.

Relatively to a gaseous alkane (propane), acetone and isopropanol are the products with higher yields, due to the oxidation of the secondary carbon atom (total yields of 10-11% were achieved).

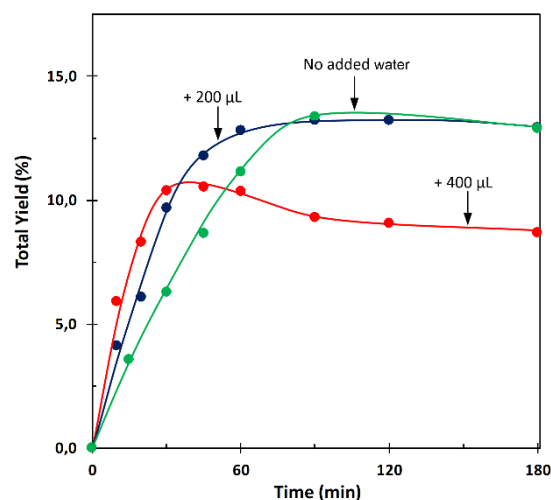


Figure 11 - Effect of the water amount on the total yield of products in the oxidation of C_6H_{12} catalyzed by **2**.

The studied catalytic systems, **1-7/TFA**, represent a good catalytic activity under mild conditions, especially if considering the inertness of the substrate (propane).

We also tested the oxidation of linear and branched alkanes in the presence of catalysts **1-5**, to obtain additional information about the nature of the reactive oxidizing species. The observed bond-, regio- and stereoselectivity parameters (relatively low values) are indicative of the involvement of hydroxyl radicals as active oxidizing species.^[10-15]

Catalytic hydrocarboxylation of alkanes. In addition to the oxidation reactions, the catalytic activity of compounds **1-7** in the mild hydrocarboxylation of cycloalkanes was also investigated. The reaction of a C_n alkane with CO (carbonyl source), H_2O (hydroxyl source) in the presence of potassium peroxodisulfate (oxidant), forms a C_{n+1} carboxylic acid, as a main product (fig.12).^[8,14-19]

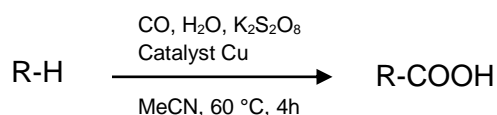


Figure 12- Hydrocarboxylation of C_n alkanes to give C_{n+1} carboxylic acids.

Table 3 - Cyclohexane hydrocarboxylation catalyzed by **1-7**.

Catalyst	η products (%)			
	Acid	Ketone	Alcohol	Total
1	41,4	1,5	0,3	43,2
2	42,9	2,6	0,6	46,1
3	25,0	1,7	0,4	27,2
4	40,0	2,4	0,5	42,8
5	25,0	1,7	0,4	27,2
6	30,0	1,4	0,5	31,9
7	45,0	1,4	0,5	46,6

^aReaction conditions: catalysts **1-7** (2,5 μmol), cyclohexane (1 mmol), H_2O (2 mL)/MeCN (4 mL), $p(\text{CO})=20$ atm, $K_2S_2O_8$ (1,5 mmol), reaction time (4 h), T (60 $^\circ\text{C}$).

Using cyclohexane as a substrate (table **3**), higher total yields were obtained relatively to

other substrates (27-47%) and the main product formed is cyclohexanecarboxylic acid.

In this case, catalyst **7** presents the higher activity, with a total yield of acid up to 45%.

All catalysts reveal higher activity for the conversion of cycloheptane and cyclooctane if compared to cyclopentane. The highest yields are observed for compound **4** with the yields of 27% and 14% for $C_7H_{13}COOH$ e $C_8H_{15}COOH$, respectively. Minor products (alcohols and ketones) are formed due to a partial oxidation of cycloalkanes. The obtained yields when using cycloheptane as substrate are represented in table **4**.

Table 3 - Cyclohexane hydrocarboxylation catalyzed by **1-5**.

Catalyst	η products (%)			
	Acid	Ketone	Alcohol	Total
1	22,5	10,9	3,6	37,1
2	22,4	9,1	3,5	35,1
3	21,1	9,3	2,5	32,8
4	27,3	10,4	3,1	40,9
5	15,1	10,0	2,0	28,0

^aReaction conditions: catalysts **1-5** (2,5 μmol), cyclohexane (1 mmol), H_2O (2 mL)/MeCN (4 mL), $p(\text{CO})=20$ atm, $K_2S_2O_8$ (1,5 mmol), reaction time (4 h), T (60 $^\circ\text{C}$).

Compounds **1-4** also catalyze the hydrocarboxylation of propane to give 2-methylpropanoic and butanoic acid (table **5**).

Table 5 - Propane hydrocarboxylation catalyzed by **1-4**.^a

Catalyst	η products (%)		
	2-Metilpropanoic acid	Butanoic acid	Total (%)
1	28,2	5,7	33,9
2	23,1	4,8	27,9
3	28,2	5,7	33,9
4	33,3	6,7	40,1

^aReaction conditions: catalysts **1-4** (2,5 μmol), propane (3 atm), H_2O (2 mL)/MeCN (4 mL), $p(\text{CO})=20$ atm, $K_2S_2O_8$ (1,5 mmol), reaction time (4 h), T (60 $^\circ\text{C}$).

All catalysts show a good catalytic activity level. 2-Metilpropanoic acid is formed preferentially to n-butanoic, since the secondary carbon atom of

propane is more reactive relatively to both primary carbon atoms. The highest yields are obtained for 2-methylpropanoic acid (4,8-6,7%). For butanoic acid, product yields vary between 4,8% and 6,7%. The highest yield is achieved for catalyst **4** with a value of 40,1%, representing the best catalyst.

Conclusions

In the present work, we applied H₃bes as a N,O-building block for the generation of eight new copper(II) coordination compounds, **1-8**. Crystal structures of **1-6** feature neutral discrete tetracopper(II) molecular units with a general formula of [Cu₄(μ-Hbes)₃(μ-H₂bes)(μ-carboxylate)]. In the course of the synthesis of tetracopper(II) complex **6**, we also obtained compound **7** as a second product. Its infinitely repeated building blocks lead to a generation of 1D coordination polymer. Compound **8** reveals a 1D metal-organic network composed of dicopper(II) paddle-wheel tetrahomophthalate motifs.

We also showed that the compounds **1-7** act as efficient catalysts for the mild oxidation of cycloalkanes to give the corresponding alcohols and ketones. Using typical reaction conditions and cyclohexane as a substrate, catalytic system **5**/TFA represents higher activity (18,3% of total yield). Cycloheptane and cyclooctane correspond to more reactive substrates. The maximum total yield is achieved for cycloheptane (27%).

We have also found that the compounds **1-5** act as efficient catalysts for the mild hydrocarboxylation of propane and C₅-C₈ cycloalkanes into the corresponding carboxylic acids (up to 47% of total yield). The obtained yields are high considering the inertness of alkane substrates and mild reaction conditions. Using cyclohexane as substrate, catalyst **7** exhibits a superior activity with a maximum product yield of cyclohexanecarboxylic acid of 45%.

The mild oxidative functionalization of alkanes using new catalysts bearing copper and other transition metals and versatile N-O-building blocks represents an interesting research direction consideration for future studies. This research direction could possibly focus on the design of new structurally related metal-organic networks for application as heterogeneous

catalysts in C-H functionalization of alkanes under mild conditions.

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