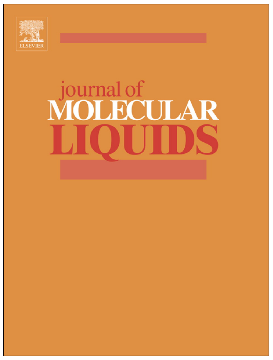

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New benzothiazole based copper(II) hydrazone Schiff base complexes for selective and environmentally friendly oxidation of benzylic alcohols: the importance of the bimetallic species tuned by the choice of the counterion

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Abstract

Green and sustainable chemistry approaches necessitate an ongoing investigation towards new, environmentally benign and selective catalysts. We have thus prepared a new benzothiazole-scaffolded hydrazone Schiff base ligand **L** and coordinated it with copper(II) ions leading to five different complexes, the form of which in the solid state is counterion-dependent. Nitrate, chloride and triflate anions lead to monometallic species, whereas utilization of sulfates and tetrafluoroborates is responsible for the formation of bimetallic assemblies. The catalytic efficiency of synthesized compounds was shown in Cu-TEMPO (2,2,6,6-tetramethyl-l-piperidinoxyl) aerobic oxidation of activated alcohols resulting in good to excellent conversions and 100% selectivity to form the corresponding aldehydes. Considering the experimental results and Density Functional Theory calculations we propose two most plausible reaction mechanisms that further corroborate the enhanced activity of bimetallic species. It appears that the tridentate character of the ligand sacrifices some of the overall catalytic efficiency for the selectivity of the process. Aqueous reaction medium, low catalyst loading, air as oxidant and exclusive oxidative selectivity render these Cu^{II} complexes promising candidates for further improvement.

Keywords: Copper; Coordination compounds; Complexes; Schiff base; Hydrazone; Alcohol oxidation; Density Functional Theory (DFT); Green Chemistry; Environmental chemistry

1. Introduction

Selective transformation of alcohols into their carbonyl derivatives without their over-oxidation is a challenging task that remains of significant importance due to the widespread application of those products in many industrial processes. [1-3] Though there exists a variety of oxidation methods [4-6] bearing in mind the necessity to implement sustainable, green chemistry approaches [7], most of the currently applied oxidants fail to meet those standards. Utilization of stoichiometric amounts followed by formation of hazardous and toxic byproducts rendered environmentally benign species such as H_2O_2 and O_2 a viable alternatives. [8] One of the intensively studied protocol for such a process involves a copper(I/II)-TEMPO (2,2,6,6-tetramethyl-l-piperidinoxyl) system[9,10], which allows one to use catalytic amounts of substrates. [11-13] Since the first processes reported by Semmelhack in 1983 and 1984, [14]'[15] the latter of which used CuCl/TEMPO system in DMF, lots of improvements were made [16-22], which clearly showed that $Cu^{I/II}$ oxidation state, solvent as well as basic additives could significantly affect the catalytic process. [23] One of the most efficient and promising up-to-date systems include $[Cu(MeCN)_4]OTf$ as the source of the metallic centre, bpy (2,2'-bipyridine) ligand and NMI (*N*-methylimidazole) in acetonitrile as the reaction medium. It must be noted however that those Cu^I species are known to be of limited stability, oligopyridine N-heterocycles are rather expensive and H_2O inhibits reactivity in that system. Moreover, studies of new Cu-TEMPO catalytic systems are necessary to shed light on mechanistic aspects of these processes [23-28], serendipitous discoveries still having place. [22, 29, 30] This still motivates the scientists to look for new catalytic systems and the inspiration could also come from the nature itself. [31-33] Copper biochemistry was given significant attention due to important role it plays in active sites of metalloenzymes, allowing among others for oxygen activation and reduction processes. [34, 35] One may distinguish two general classes of enzymes, where the copper active sites are either co-operating (e.g. catechol oxidase or tyrozinase) or the single metallic centre performs selective biological transformations (*e.g.* amine oxidase or galactose oxidaze), with imidazole moieties (mostly) playing the part of the N-heterocyclic scaffold. [36] Furthermore, the aspect of cooperativity (or its lack) in the copper-mediated catalytic transformations was emphasized. [27]

In view of the above aspects, we surmised that by applying the tridentate N-heterocyclic Schiff base scaffold and using stable Cu^{II} ion as the metallic centre, we would be able to provide selective catalytic systems for the TEMPO-mediated oxidation reactions. Up to our knowledge, benzothiazole-based copper(II) systems were not yet evaluated for such processes. At the same time, different choice of the counterions allowed us to tune the activity of synthesized species, herein showing the enhanced activity of the bimetallic assemblies in comparison to the monometallic ones. Our aim of environmental reaction conditions - water as the reaction medium and air as oxidant - followed by tridentate character of the synthesized ligand all resulted in slightly sacrificed activity of catalytic species. On the other hand, thanks to this reactivity-limitation, we were able to show that the benzothiazole-decorated hydrazone Schiff base ligand is potent scaffold for generation of selective Cu^{II} catalysts that follow the green chemistry notions.

2. Experimental section

2.1. Materials and methods

2-Chlorobenzothiazole, methylhydrazine, 2-benzoylpyridine and metal salts were used as supplied Aldrich without any further purification. Intermediate product **A** was synthesized as reported by us previously.[37] ESI mass spectra for acetonitrile solutions ~10 $^{-4}$ M were measured using a Waters Micromass ZQ spectrometer. All NMR Spectra were recorded on Bruker Fourier 300 MHz spectrometer. NMR solvents were purchased from Aldrich, and used as received. Spectra were referenced at solvent residual peaks (^{1}H: $(CD_3)_2CO$: 2.05 ppm, ^{13}C: 29.84 ppm, 196.8). IR spectra were obtained with a Perkin–Elmer 580 spectrophotometer and peak positions are reported in cm^{-1}. Chromatographic measurements were carried out on a Brucer Scion 436-GC series gas chromatograph (helium as carrier gas) with a 30 m Varian DB-5 0.25 mm capillary column and a Scion SQ-MS mass spectrometry detector, whereas the analyses of the chromatographic peaks were done by the corresponding Brucer MS Workstation 8 software. The temperature program was as follows: 60°C (3 min), 10°C/min, 250°C (15 min). Quantum mechanical calculations for systems in the possible reaction pathways were performed with Gaussian 09 [38] software package at the DFT(B3PW91)/6-31G* level. [39-44] The molecular geometries were fully optimized at 298 K *in vacuo* and with the PCM-model to account for the effect of solvent. The details are in the SI.

2.2. Catalytic activity studies

Oxidation reactions of alcohols under atmospheric pressure of air were carried out in 10 mL round-bottom flask equipped with a condenser. The reaction mixtures were prepared as follows: 0.01 mmol (1 mol% based on substrate) of the Cu catalyst, 0.05 mmol (5 mol%) of TEMPO, 1 mmol of substrate and 3.33 mL of 1M K_2CO_3 aqueous solution. The reaction solutions were stirred for 24 h at 40 °C. After the oxidations 1 M HCl for neutralization and 5 mL of diethyl ether for the extraction were added. The organic phase was analyzed by GCMS chromatography. The quantitative analysis was carried out using GCMS chromatography.

2.3. Synthesis of 2-(1-methyl-2-(phenyl(pyridin-2-yl)methylene)hydrazinyl)benzothiazole (L)

2-Benzoylpyridine (1.04 g, 5.67 mmol) was added to a solution of 2-(1-methylhydrazinyl)benzothiazole (1.02 g, 5.67 mmol) in ethanol. The mixture was stirred and heated at 60^{o}C for 48 hours. The product was isolated by evaporation of the solvent and recrystallization of the residue from a minimum volume of CH_3CN by the gradual addition of diethyl ether/hexane mixture, filtration and vacuum drying. Yield: 79 % (1.54 g). ESI-MS: m/z (%) = 345 [L+H]$^+$ (100).

^{1}H NMR (300 MHz, Acetone-d6) δ 8.04 (ddd, J = 4.8, 1.8, 1.0 Hz, 1H), 7.70 (dt, J = 8.1, 1.1 Hz, 1H), 7.50 (ddd, J = 8.1, 7.5, 1.8 Hz, 1H), 7.42 (ddd, J = 7.9, 1.3, 0.6 Hz, 1H), 7.15 (ddd, J = 8.1, 1.2, 0.6 Hz, 1H), 7.05 – 6.85 (m, 7H), 6.73 (ddd, J = 7.9, 7.3, 1.2 Hz, 1H), 2.67 (s, 3H).

^{13}C NMR (75 MHz, $(CD_3)_2CO$): δ ppm 161.3, 146.3. 142.1, 141.3, 139.0, 127.1, 125.4, 122.5, 120.0, 119.3, 118.3, 116.2, 114.2, 112.7, 111.9, 111.7, 110.3, 21.0. IR (KBr): $\nu(C\text{-}H)_{ar}$ 3049; $\nu_{as}(CH_3)$ 2942; $\nu_s(CH_3)$ 2863; $\nu(C{=}N)_{imin}$ 1523; $\nu(C{=}C)_{ar}$ 1594, 1578, 1561, ν(C-N) 1465, 1444; $\nu(C{=}N)_{ar}$ 1298, 1281, 1217; $\rho(C\text{-}H)_{ar}$ 1165, 1156, 1142, 1127; $\gamma(C\text{-}H)_{ar}$ 861, 796, 754, 729, 697, 656, 583 cm^{-1}. Anal calc. For $C_{20}H_{16}N_4S$ (344.43): C, 69.74; H, 4.68; N, 16.27; Found: C, 69.85; H, 4.78; N, 16.14 %

2.4. Synthesis of complexes

2.4.1. Synthesis of $2[CuL(NO_3)_2]\cdot1.25MeCN$ (1)

A mixture of $Cu(NO_3)_2\cdot3H_2O$ (200 mg, 0.83 mmol) and ligand **L** (285 mg, 0.83 mmol) in a mixture of $MeOH:CH_2Cl_2$ in 1:1 volume ratio (30 mL) was stirred at room temperature for 24 h. The product was isolated by evaporation of solvents and recrystallization of the residue from a minimum volume of MeOH by the gradual addition of diethyl ether to obtain complex **1** as a green solid. Crystal appropriate for X-ray diffraction was obtained by vial to vial diffusion of Et_2O to MeCN/MeOH solution of complex at 4°C. Yield: 77.1 % (357 mg, 0.64 mmol)

ESI-MS: m/z (%) = 345 $[H+L]^+$ (100), 367 $[Na+L]^+$ (35); 407 $[Cu(L\text{-}H)]^+$ (90); 469 $(CuL(NO_3))^+$ (85). IR (KBr): $\nu(C\text{-}H)_{ar}$ 3045; $\nu_{as}(CH_3)$ 2946; $\nu_s(CH_3)$ 2864; $\nu(C{=}N)_{imin}$ 1522; $\nu(C{=}C)_{ar}$ 1592, 1573, 1565, ν(C-N) 1461, 1442; $\nu(C{=}N)_{ar}$ 1293, 1283, $\rho(C\text{-}H)_{ar}$ 1161, 1144, 1129; $\gamma(C\text{-}H)_{ar}$ 865, 792, 752, 584 cm^{-1}. Anal calc. for $[Cu(C_{20}H_{16}N_4S)(NO_3)_2(MeCN)_{0.625}]$ (557.65): C. 45.77; H. 3.23; N, 16.64; Found: C. 45.59; H. 3.30; N, 16.72 %.

2.4.2. Synthesis of $[CuL(\mu\text{-}SO_4)_2CuL]\cdot2MeOH$ (2)

A mixture of $CuSO_4\cdot5H_2O$ (300 mg, 1.20 mmol) and ligand **L** (414 mg, 1.20 mmol) in a mixture of $MeOH:CH_2Cl_2$ in 1:1 volume ratio (35 mL) was stirred at room temperature for 24 h. The product was isolated by evaporation of solvent and recrystallization of the residue from a minimum volume of MeOH by the gradual addition of diethyl ether to obtain complex **2** as a green solid. Crystal appropriate for X-ray diffraction was obtained by vial to vial diffusion of Et_2O to MeOH solution of complex at 4°C. Yield: 72.1 % (928 mg, 0.87 mmol).

ESI-MS: m/z (%) = 345 $[H+L]^+$ (70), 407 $[Cu(L\text{-}H)]^+$ (10), 442 $[CuLCl]^+$ (100).; IR (KBr): $\nu(C\text{-}H)_{ar}$ 3027; $\nu_{as}(CH_3)$ 2952; $\nu_s(CH_3)$ 2872; $\nu(C{=}N)_{imin}$ 1532; $\nu(C{=}C)_{ar}$ 1572, 1552, 1549, ν(C-N) 1473, 1438; $\nu(C{=}N)_{ar}$ 1283, 1253, $\rho(C\text{-}H)_{ar}$ 1184, 1164, 1121; $\gamma(C\text{-}H)_{ar}$ 885, 799, 749, 572 cm^{-1}. Anal. calc. for $[Cu_2(C_{20}H_{16}N_4S)_2(SO_4)_2]\cdot2CH_3OH$ (1072.17): C, 47.05; H, 3.75; N, 10.45; Found: C, 47.11; H. 3.87; N, 10.40 %.

2.4.3. Synthesis of $[(CuL(\mu\text{-}F)_2CuL)(BF_4)_2]\cdot2MeOH$ (3)

A mixture of $Cu(BF_4)_2$ (300 mg, 1.26 mmol) and ligand **L** (436 mg, 1.26 mmol) in a mixture of $MeOH:CH_2Cl_2$ 1:1 volume ratio (30 mL) was stirred at room temperature for 24 h. The product was isolated by evaporation of solvents and recrystallization of the residue from a minimum volume of MeOH by the gradual addition of diethyl ether to obtain complex **3** as a green solid. Crystal appropriate for X-ray diffraction was obtained by vial to vial diffusion of Et_2O to MeOH solution of complex at 4^{o}C. Yield: 76.3 % (988 mg, 0.97 mmol).

ESI-MS: m/z (%) = 345 $[H+L]^+$ (30), 442 $[CuLCl]^+$ (90). IR (KBr): $\nu(C\text{-}H)_{ar}$, 3041; $\nu(CH_3)$ 2959; $\nu(CH_3)$ 2877; $\nu(C{=}N)_{imin}$ 1537; $\nu(C{=}C)_{ar}$ 1565, 1545, 1529, $\nu(C\text{-}N)$ 1479, 1431; $\nu(C{=}N)_{ar}$ 1281, 1259, $\rho(C\text{-}H)_{ar}$ 1188, 1173, 1137; $\gamma(C\text{-}H)_{ar}$ 865, 783, 738, 563 cm^{-1}. Anal. calc. for $[Cu_2(C_{20}H_{16}N_4S)_2F_2(BF_4)_2(MeOH)_2]$ (1092.13): C, 46.21; H, 3.69; N, 10.26; Found: C, 46.79; H, 3.24; N, 10.34 %.

2.4.4. Synthesis of $[CuLCl_2]$ (4)

A mixture of $CuCl_2{\cdot}2H_2O$ (200 mg, 1.17 mmol) and ligand **L** (404 mg, 1.17 mmol) in a mixture of $MeOH{:}CH_2Cl_2$ in 1:1 volume ratio (30 mL) was stirred at room temperature for 24 h. The product was isolated by evaporation of solvents and recrystallization of the residue from a minimum volume of MeOH by the gradual addition of diisopropyl ether to obtain complex **4** as a green solid. Crystal appropriate for X-ray diffraction was obtained by vial to vial diffusion of iPr_2O to MeOH solution of complex at 4^{o}C. Yield: 85.2 % (477 mg, 1.00 mmol).

ESI-MS: m/z (%) = 407 $[Cu(L\text{-}H)]^+$ (10), 442 $[CuLCl]^+$ (90). IR (KBr): $\nu(C\text{-}H)_{ar}$ 3041; $\nu_{as}(CH_3)$ 2959; $\nu_s(CH_3)$ 2877; $\nu(C{=}N)_{imin}$ 1537; $\nu(C{=}C)_{ar}$ 1579, 1537, 1518, $\nu(C\text{-}N)$ 1488, 1422; $\nu(C{=}N)_{ar}$ 1261, 1245, $\rho(C\text{-}H)_{ar}$ 1196, 1184, 1149; $\gamma(C\text{-}H)_{ar}$ 873, 795, 748, 571 cm^{-1}. Anal. calc. for $[Cu(C_{20}H_{16}N_4S)Cl_2]$ (478.88): C, 50.16; H, 3.37; N, 11.70; Found: C, 50.08; H, 3.50; N, 11.62 %

2.4.5. Synthesis of $[CuL(MeOH)(CF_3SO_3)(H_2O)](CF_3SO_3)$ (5)

A mixture of $Cu(CF_3SO_3)_2$ (200 mg, 0.55 mmol) and ligand **L** (190 mg, 0.55 mmol) in a mixture of $MeOH{:}CH_2Cl_2$ in 1:1 volume ratio (30 mL) was stirred at room temperature for 24 h. The product was isolated by evaporation of solvents and recrystallization of the residue from a minimum volume of MeOH by the gradual addition of diethyl ether to obtain complex **5** as a green solid. Crystal appropriate for X-ray diffraction was obtained by vial to vial diffusion at 4^{o}C. Yield: 80.3 % (335 mg, 0.44 mmol).

ESI-MS: m/z (%) = 345 $[H+L]^+$ (100), 407 $[Cu(L\text{-}H)]^+$ (90). IR (KBr): $\nu(C\text{-}H)_{ar}$ 3053; $\nu_{as}(CH_3)$ 2972; $\nu_s(CH_3)$ 2877; $\nu(C{=}N)_{imin}$ 1553; $\nu(C{=}C)_{ar}$ 1581, 1547, 1525, $\nu(C\text{-}N)$ 1488, 1422; $\nu(C{=}N)_{ar}$ 1279, 1235, $\rho(C\text{-}H)_{ar}$ 1187, 1172, 1137; $\gamma(C\text{-}H)_{ar}$ 891, 782, 723, 551 cm^{-1}. Anal. calc. for $[Cu(C_{20}H_{16}N_4S)(CF_3SO_3)(MeOH)(H_2O)](CF_3SO_3)]$ (756.17): C, 36.53; H, 2.93; N, 7.41; Found: C, 36.40; H, 2.99; N, 7.35 %.

3. Results and discussion

3.1. Synthesis of ligand L and complexes 1-5

The ligand **L** was synthesized in two-step reaction as shown in **Fig. 1**.

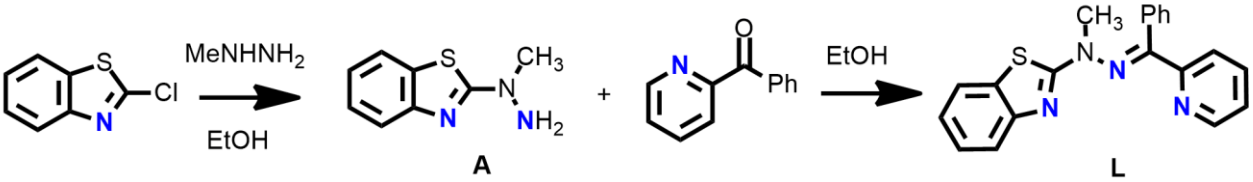


Fig. 1. Two-step synthesis of benzothiazole ligand **L** obtained in the study.

2-(1-Methylhydrazinyl)benzothiazole (**A**) was obtained from 2-chlorobenzothiazole in nucleophilic substitution reaction with methylhydrazine in anhydrous ethanol. Further condensation reaction of synthesized intermediate with benzoylpyridine gave ligand **L** in 79 % overall yield. The new coordinating agent was characterized by spectroscopic and analytical methods, which confirm the purity of the sample (**Figs**. **S1** and **S2**). It was designed so as to ensure one, tridentate binding pocket (with SNN or NNN coordination motif) that should coordinate *d* block metal ions and thus form stable, open-species complexes of potential utility in catalysis.

Upon complexation with Cu^{II} cation, 5 different coordination compounds **1-5** (**Fig. 2**) were obtained that differ in the counterion chosen during the synthesis: nitrate (**1**), sulfate (**2**), tetrafluoroborate (**3**), chloride (**4**) and trifluoromethanesulfonate (**5**). Our motivation was to determine the effect of the anion coordination strength as well as its charge on the formation of (potentially) catalytically active species in the reaction of alcohol oxidation.

All of the reactions of **L** with copper(II) salts were carried out in 1:1 ratio of ligand:metal ion in the mixture of methanol and dichloromethane (1:1 volume ratio) at room temperature for 24h. The complexes were isolated with good to very good yields (60–80%) by precipitation from their methanolic solutions using diethyl ether. In all cases, formation of complexes in their original oxidation state was efficient and the products were readily isolated as stable, green solids. Single crystals of complexes **1** – **5** suitable for X-ray structure determination were obtained by slow diffusion of diethyl ether into their methanolic or acetonitrile solutions. This allowed for unambiguous determination of the ligands binding mode as well as architecture (mono- vs bimetallic) of obtained species, resulting in the following complexes: 2[Cu**L**$(NO_3)_2$]·1.25MeCN (**1**), [Cu**L**$(\mu\text{-}SO_4)_2$Cu**L**]·2MeOH (**2**), [Cu**L**$(\mu\text{-}F)_2$Cu**L**]$(BF_4)_2$·2MeOH (**3**), [Cu**L**Cl_2] (**4**), [Cu**L**(MeOH)$(CF_3SO_3)(H_2O)$](CF_3SO_3) (**5**). Of particular notice was the observation that free fluoride anion was generated from tetrafluoroborate moiety and coordinates to two cationic centres in the bridging fashion in **3**. An examples of such fluoride abstraction from tetrafluoroborate anions were observed in the literature and could be ascribed to stronger Lewis acid character of certain transition metal ions than the BF_3 itself, also facilitated by steric effects of the organic ligand.[45-48]ESI-MS studies indicate formation of copper(II) species, with only monometallic structures observed under ionisation conditions, nonetheless this behaviour is amenable to cone voltage and is known to occur. UV-Vis studies show that the form of the complexes in solution is dependent on the solvent chosen and their spectral profile is time-dependent. (**Figs. S3-S5**) The solvent mixture that was used during the synthesis (CH_2Cl_2/MeOH) follows what was established in the solid state - two sets of spectra are observed, which are similar for monometallic (**1**,**4**,**5**) and bimetallic (**2**,**3**) systems within each group. Studied copper(II) complexes are also stable in water as a catalytic medium for further organic transformation and in the presence of K_2CO_3, though a time-dependent hipsochromism of bands is observed. With base in the system it is even more profound, nonetheless please notice that this goes in line the results obtained from catalytic studies. Since the optimum concentration of active species was 1 mol% for monometallic and 0.5 mol% for bimetallic species, lower activity of the latter one can be related to the gradual decomplexation of copper(II) species.

3.2. Crystal structures and geometrical analyses of copper(II) complexes

The type of coordination compound (mono- vs bimetallic) formed and the mode of ligands binding were unambiguously established by single crystal X-ray diffraction for all 5 compounds and are shown in **Fig. 2**.

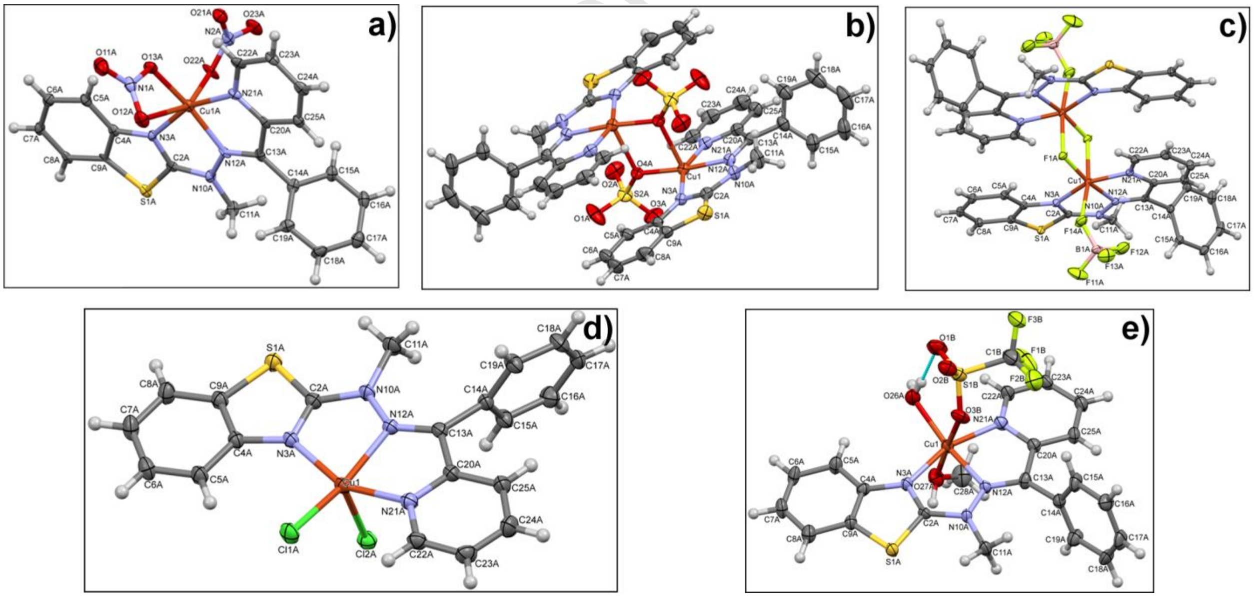


Fig. 2. Thermal-ellipsoid representations of copper(II) complexes **1**-**5** (a-e) synthesized in the present study. Details of specific contacts and symmetry elements are provided in the supplementary information (**Figs. S6-S10**).

Schiff base ligand **L** acts as tridentate one and coordinates Cu^{II} ions by three nitrogen atoms (N3, N12 and N21). Interestingly, in all cases aromatic parts of the ligand molecule (condensed ring system, linker and pyridine ring) are almost planar, the dihedral angles between the terminal ring planes are between 1.9° and 11.4°. One could envisage that the methyl and pyridine moieties should interact and thus result in deformations of the above-noted dihedral angle, nonetheless it is not the case herein. Such conformation allows all three coordination centers to be in the similar distance from the central ion. The spread of the Cu-N distances is very narrow: 1.956Å – 2.032Å.

There are examples of mono- (**1**, **4**, **5**) and bimetallic (**2**, **3**) complexes. The latter ones are C_i-symmetrical; the copper ions are bridged by oxygen atoms from sulphate ions (**2**) or by fluorine ions (**3**). The Cu^{II} ions are in most of the cases 5-coordinated, and the coordination geometry is close to tetragonal pyramid. The *tau* parameters are close to ideal value of 0 (0.03° – 0.27°) and are listed in **Table S2**, together with SHAPE [49] analysis.

True octahedral coordination is found only in **3**, there are also doubtful cases of **1** and **5**, when the sixth contact is significantly longer than the others (longer than 2.5 Å), and therefore the very existence of such interaction is far from obvious. The latter has been also supported by SHAPE analysis, which was conducted for the sake of symmetry comparisons as well as to gain deeper knowledge about structure/properties relations with regard to the alcohol oxidation. **Tables S2** and **S3** gather calculations from the point of view of continuous shape measurements (SChM) for CN = 5 (**1**, **2**, **4**, **5**) and CN = 6. (**1**, **3**, **5**).

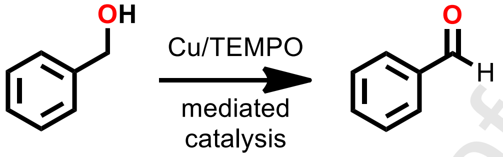
Compound **1** was subjected to calculations that include cases of both with and without consideration of the O_2NO-Cu^{II} distances that are above 2.6Å and they clearly show that Cu^{II} coordination spheres therein are more appropriately described as 5-coordinated spheres of C_{4v} symmetry instead of the octahedral ones. It is of note that the lowest values in **Table S3** correspond to O_h symmetry (**1**- Cu1A: 5.840, **1**- Cu1B: 6.495 and **5** – Cu1: 6.945) nonetheless it has been established that CShM values that are above 3 indicate important distortions[49], what is in line with above considerations. In case of complex **5** that exhibits OTf-Cu^{II} bonding, omission of the longest anion-Cu^{II} contact was also calculated, albeit obtained CShM values are acceptable for both coordination numbers. From the CN = 5 series, all but one complex (**2**) are better described as classical (Berry) square pyramid, whereas the sulphate dimer is more similar in nature to octahedron yet with one vacant vertex (Johnson square pyramid, J1).[50] Interestingly, similar CShM values for Cu1A in **1** (1.276; 1.340) led us to question whether or not it belongs to the interconversion path between Berry and Johnsons square pyramids, yet calculated deviation threshold (73.2 %) is too large for Cu1A to belong therein. From the CN = 6 series, octahedral geometry is the only reference shape that gives reasonable CShM values for compounds **3** and **5** although certain deviations from perfect symmetry are observed, accounted to the Jahn-Teller effect observed for Cu^{II} species.

In the crystal structures the solvent molecules can be often found to fill the voids between the complex molecules; an example of such crystal packing (**1**) is shown in **Fig. S11**. In the complex **5**, in which there are classical hydrogen bond donors, these interaction play also an important role in the determination of its crystal architecture.

3.3. Catalytic activity of copper(II) complexes

Recent studies on similar systems showed that bimetallic individuals might be responsible for more efficient catalysis with regard to $Cu^{I/II}$ mediated oxidation reactions[51],[52] therefore compound **3** from **1-5** was chosen as the starting point for evaluation of their catalytic activity. Initial screening tests showed that TEMPO/air/**3** system leads to 27% conversion of benzylic alcohol to benzaldehyde after 5h under ambient conditions (**Table 1** – entry 1).

Table 1 Optimization of the reaction conditions for aerobic oxidation of benzyl alcohol to the corresponding aldehydes



Entry	Catalyst	Conversion [%][b]	Variations[a]	Selectivity[c]
1	**3**	27	5h, RT	100
2	**3**	64	RT	100
3	**3**	100	-	100
4	**3**	78	2,5 mol% TEMPO	83.3
5	**3**	79	0,5 M K_2CO_3	84.8
6	**3**	1	no TEMPO	-
7	**2**	77	-	100
8	**2**	90	50°C	100
9	**2**	89	Catalyst formed in situ from **L** and $CuSO_4$, 50°C	100
10	**3**	100	1.25 mol% of **3**	100
11	**3**	56	0.5 mol% of **3**	100
12	**3**	42	0.25 mol% of **3**	100
13	**2**	90	1.25 mol% of **2**, 50°C	100
14	**2**	70	0.5 mol% of **2**, 50°C	100
15	**2**	35	0.25 mol% of **2**, 50°C	100
16	**$CuSO_4$**	50	-	100
17	**$Cu(BF_4)_2$**	33	-	100

[a] Standard conditions (unless noted otherwise in the table) 0.01 mmol (1 mol% based on substrate) of the Cu catalyst, 0.05 mmol (5 mol%) of TEMPO, 1 mmol of substrate and K_2CO_3 aqueous solution (3.33 ml, 1 M), 1 atm, air, 24h, 40°C; [b] measured by GC-MS, overall yield of carbonyl products i.e. moles of products (aromatic aldehyde and acid)/100 moles of alcohol; [c] molar amount of benzaldehyde/total amount of products x 100

Prolonging the reaction time leads to improvement of conversion (64 % - entry 2), whereas quantitative (100% - entry 3) and selective (overoxidation to benzoic acid was not observed) oxidation was found upon 24 h of stirring under 40°C. It must be noted that lowering the amount of TEMPO (from 5 mol% to 2.5 mol% - entry 4) or K_2CO_3 (from 1 M to 0.5 M – entry 5) leads to losses in conversion and selectivity, whereas the former one is indispensable for the oxidation to occur (no TEMPO - entry 6). Such observations also confirm the role of TEMPO as an effective radical trap. [5] In addition, initial screening was also performed on compound **2** (bimetallic sulphate analogue – entries 7-9, 13-15), nonetheless even at higher temperature (50°C – entry 8) maximum of 90% conversion was achieved, which is still lower than for **3**, though higher than for monometallic (**1**, **5**) species (**Table 2**, entries 2 and 5). It was shown by Ahmad et al. that copper catalyzed oxidations in the presence of sulfates usually necessitate high temperatures. [53]

Identical reaction performed in the presence of **2** formed *in situ* from $CuSO_4$ and ligand **L** lead to similar activity (entry 9).

Optimal Cu catalyst concentration was found to be 1 mol% based on the substrate, since lowering of concentration led to the reduced conversion of alcohol (entries 11, 12 – compound **3**; 14, 15 – compound **2**; **Fig. S12**). Importantly, selectivity in such systems was still preserved, which is important in case that gradual deactivation of the active species was to occur.

Please note that actual concentration of copper catalyst would be 0.5 mol% if calculated per one metallic center. Interestingly, the highest conversion of alcohol with **2** as catalyst was observed when the temperature was 50°C (entries 13 and 14), what could indicate that redox changes associated with reaction mechanism are hindered when dianionic counterion is used. Control experiments also showed that $CuSO_4$ and $Cu(BF_4)_2$ alone (copper salts used for syntheses of **2** and **3**) lead to the significant loss in activity (entries 16 and 17) which proves that new Schiff base ligand scaffold favors the observed high catalytic activity.

Therefore, with optimal conditions to perform selective oxidation of benzyl alcohol in hand, the effect of varying the counterion on the effectiveness of the process was studied (**Table 2**).

Table 2 Aerobic oxidation of selected benzylic alcohols to the corresponding aldehydes[a]

Entry	Catalyst	Substrate	Product	Conversion [%][b]	Selectivity[c]
1	**3**	benzyl alcohol	benzaldehyde	100	100
2	**1**	benzyl alcohol	benzaldehyde	63	100
3	**2**	benzyl alcohol	benzaldehyde	90[d]	100
4	**4**	benzyl alcohol	benzaldehyde	92	100
5	**5**	benzyl alcohol	benzaldehyde	75	100
7	**1**	4-Me-benzyl alcohol	4-Me-benzaldehyde	64	100
8	**1**	4-Br-benzyl alcohol	4-Br-benzaldehyde	60	100
9	**2**	4-Me-benzyl alcohol	4-Me-benzaldehyde	90[d]	100
10	**2**	4-Br-benzyl alcohol	4-Br-benzaldehyde	83[d]	100
11	**2**	4-OMe-benzyl alcohol	4-OMe-benzaldehyde	98[d]	100
12	**2**	4-F-benzyl alcohol	4-F- benzaldehyde	80[d]	100
13	**3**	4-Me-benzyl alcohol	4-Me-benzaldehyde	80	100
14	**3**	4-Br-benzyl alcohol	4-Br-benzaldehyde	87	100
15	**3**	4-OMe-benzyl alcohol	4-OMe- benzaldehyde	98	100
16	**3**	4-F-benzyl alcohol	4-F- benzaldehyde	99	85.9
17	**3**	exo-norborneol	bicyclo[2.2.1]heptan-2-one	0	-
18	**3**	1-cyclopropylethanol	1-cyclopropylethanone	0	-
19	**3**	cis-2-methylcyclohexanol	(S)-2-methylcyclohexanone	0	-
20	**3**	3-buten-2-ol	but-3-en-2-one	0	-

[a] Optimized conditions: 0.01 mmol (1 mol% based on substrate) of the Cu catalyst, 0.05 mmol (5 mol%) of TEMPO, 1 mmol of substrate and K_2CO_3 aqueous solution (3.33 ml, 1 M), 40°C, 1 atm, air; 24h [b] measured by GC-MS, overall yield of carbonyl products i.e. moles of products (aromatic aldehyde and acid)/100 moles of alcohol; [c] molar amount of benzaldehyde/total amount of products x 100; [d] reaction performed at 50°C

Copper(II) compounds with benzothiazole scaffolded ligand **L** (**1**-**5**) displayed fair to excellent conversions (entries 1-5; 63-100%), with monometallic chloride **4** and bimetallic sulphate **2** as well as mixed fluoride/tetrafluoroborate **3** being the most efficient. This would fall in line with results obtained by Zhang et al. [51] for similar N_3 complexes of 2,2':6',2''- terpyridine (tpy) ligands, since such N_3-meridional framework followed by bridging species would facilitate formation of active mixed valence Cu^ICu^{II} assemblies. Despite that **4** is monometallic in the solid state, chloride architectures of this kind are known to form μ-chlorido species with TEMPO [54], thus excellent yields are observed for this compound as well.

Investigated protocol was expanded to other alcohols so as to gain insight into the scope and limitations as far as applicability of the studied copper(II) complexes is concerned. Results of catalytic studies obtained for monometallic **1** (entries 7, 8) showed that *p*-substituted benzyl alcohols were also oxidized, albeit with fair yields, possibly due to strong coordinating character of the nitrate anions. Higher conversion is achieved when bridged dinuclear compounds **2** and **3** are used (entries 9-16), which is applicable for both electron withdrawing (F, Br) and electron donating groups (Me, OMe), with the latter ones being activating moieties, thus facilitating conversion. Interestingly, when fluorine was present as the moiety both in benzylic alcohol and as the bridging entity between Cu^{II} centers, overoxidation to acid was observed (*ca*. 6:1 of aldehyde:acid). Despite slight loss of selectivity therein, it is important aspect that is planned on to pursue further, *i.e.* that mimicking the target substrate with the structure of the catalyst may synergically lead to higher catalytic activity than when treated individually. Such behavior is yet unprecedented for such group of compounds, bearing in mind that similar N_3-meridional μ-bridged fluoro-copper(II) complexes are very scarce. Attempts to oxidize cyclic (entries 17-19) and allyl (entry 20) secondary alcohols with the most active catalyst **3** proved to be unsuccessful, nonetheless such a situation in copper mediated TEMPO systems is not unprecedented. [51, 55] This may however be perceived as a virtue for selective oxidation of molecules scaffolded with various hydroxyl groups, where some of them must stay intact.

3.4. Proposed reaction mechanism

It has been clearly established that the catalytic cycle of alcohol oxidation is associated with one electron Cu^I/Cu^{II} redox changes [1] and with TEMPO being indispensable for the process to occur (**Table 1** – entry 6). That Cu^I metallic center is necessary is supported by enhanced activity of dinuclear complexes **2-4** (**Table 2** – Entries 1, 2, 4) as well as aforementioned mixed valence (tpy)Cu^ICu^{II} assemblies[51], which would stabilize entities with bridged μ-halide (**3**, **4**) or μ-sulphate groups (**2**). In addition, it was found that the presence of base is mandatory for the reaction to occur.

Although detailed mechanism of Cu/TEMPO oxidation is still debatable, thanks to mechanistic studies on similar systems[24-26],[56,57] , results observed in this paper as well as DFT studies performed herein (**Figs S13, S14, Tables S4, S5**), we propose the following, most plausible reaction mechanism to take place, as shown on compound **3** (**Fig. 3**).

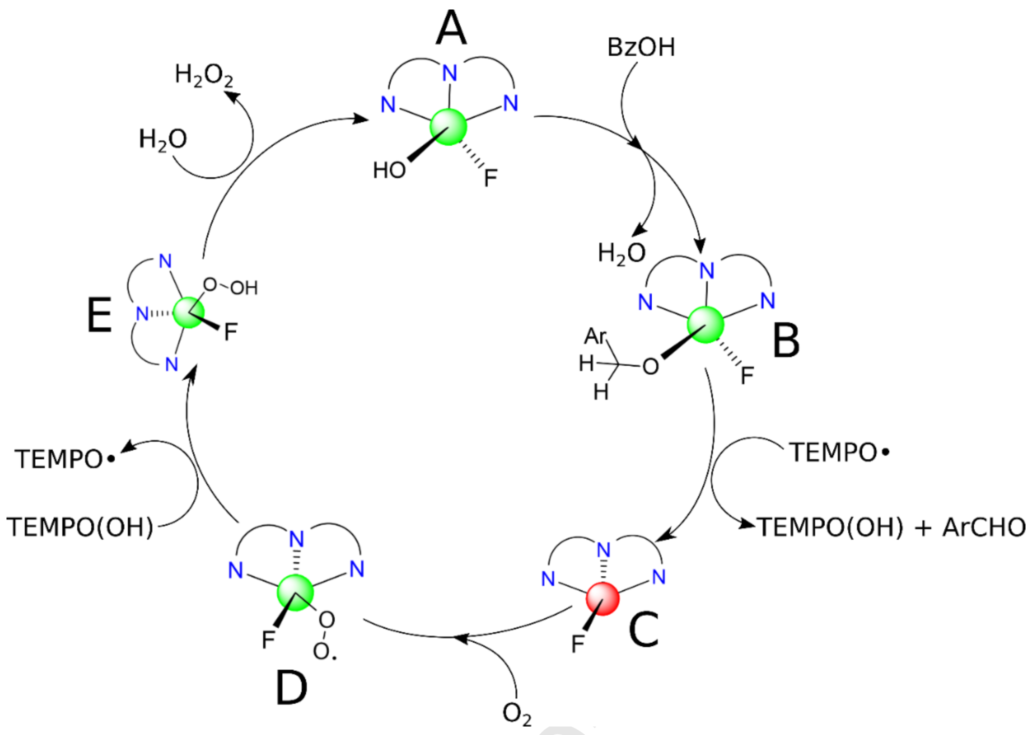


Fig. 3. Schematic representation of mechanistic pathway towards oxidation of benxylic acohols to their corresponding aldehydes for monometallic compounds, as exemplified on **3**. Capital letters denote species that were optimized by DFT methods.

For the sake of clarity and due to computational demand of DFT calculations, the monometallic catalytic pathway is presented, though the one involving the bimetallic **3** [Cu**L**(μ-F)$_2$Cu**L**](BF$_4$)$_2$ can also be constructed and will be referred to as well.

Starting from Cu^{II}-complex, three main stages of the reaction may be distinguished: (i) formation of the [Cu^{II}-alkoxide] complex (**3**→**A**→**B**) and oxidation of the alcohol (**B**→**C**); (ii) oxygen activation (**C**→**D**) and formation of *peroxo*-species (**D**→**E**); (iii) activation of the alcohol to regenerate the alkoxy complex (**E**→**A/B**). [25]

Of relevance for stage (i), one may envisage that mono- and dinuclear structures that are formed in the solid state may interexchange and thus result in a mixture of those in solution, possibly with hydroxyl ligated species (**3**→**A**) - **Fig. S15**. Consequently, coordination of alcohol or its deprotonated form results in equilibrated formation of [Cu^{II}-alkoxide] complexes (**A**→**B**) - **Fig. S16**, which are of reminiscence to the galactose oxidase system.[58, 59] Next step involves oxidation of the above formed intermediate (**B**→**C**) with TEMPO, and is one of the most debated stages of the reaction. Three [TEMPO-Cu^{II}-F-**L**-ArO] transition states of organic radical with copper-alkoxide were thoroughly studied in literature on the seminal [bpy-Cu^{II}-NMI] system and differ in the role of TEMPO on the oxidation step.[17, 23, 25, 26, 56] On that basis, we anticipated the possible interaction modes of organic radical in our system (**Fig. S17**) and since DFT calculations excluded the possible binding of TEMPO to copper ion in our system, we assume that oxidation proceeds *via* intermolecular hydrogen-atom transfer (HAT) to generate TEMPO(OH) and benzaldehyde. Indeed, gas-phase **B**-**C** transition state was calculated and is shown on **Fig. S18** as TS-1. The imaginary vibration (14 *i* cm^{-1}) found for TS-1 corresponds to the simultaneous (i) C-H stretching of one of two hydrogen atoms of benzyl alcohol ligand in the direction of TEMPO oxygen atom (the C-H bond is elongated to 1.190Å in the saddle point structure) (ii) the displacement of the second hydrogen atom in the direction of the aromatic C–C–O plane (enabling formation of benzaldehyde). We found that the kinetic barrier associated with this saddle point to be equal 46.9 kcal/mol (**Fig. S14**). Once the hydrogen transfer is done and TEMPO(OH) is formed, whole complex should spontaneously (*i.e.*, through a negligibly small kinetic barrier) dissociate the benzaldehyde forming **C**. It can be also clearly observed that this is the rate determining step of the whole process. The alternative scenario with hypothesized TEMPO coordinated to the Cu^{II} center is presented on **Fig. S19**. We observed that it causes breaking of two other dative bonds which changes structure of the system altogether. We believe that the main reason for TEMPO not to be coordinated in order for HAT to happen is rather long distance between hydrogen atom to be transferred from benzyloxide ligand to the oxygen atom of coordinated TEMPO ligand. Second reason for that is the steric hindrance caused by methyl substituents in TEMPO ring.

This is an interesting feature, since even though HAT mode was proposed to occur in some other studies [17, 23, 26, 51], it was later shown[25, 56] that oxidation might proceed through direct coordination of TEMPO to copper ion through either five- or six-membered transition state.[24, 25] We ascribe this difference to the fact of ligands denticity, since tridentate character (contrary to the bidentate mode of bpy) of **L** precludes TEMPO from coordination to Cu^{II} ion. It is in line with additional studies on copper-alkoxides, since those intermediates are postulated to influence the αC-H bond strength of deprotonated alcohol[60] and under certain conditions may behave as hydrogen atom acceptors [61], therefore hindering oxidation of non-activated alcohols. This would explain the herein observed catalytic activity with regard to the oxidation of benzylic alcohols and lack of such for compounds with secondary hydroxyl groups.

Next stage (ii) involves regeneration of Cu^{II} catalyst and TEMPO radical, which we propose to proceed *via* oxygen activation and formation of *peroxo*-species (**Fig. S20**). Coordination of dioxygen (**C**→**D**) results in formation of oxidized monometallic complex [$\mathbf{L}Cu^{II}(F)(O_2^{\cdot-})$], which is the global minimum according to our DFT calculations, no matter the phase considered. Step **D**→**E** results in proton transfer from TEMPO(OH) to the dioxygen complexes formed in the previous step and such TEMPO regeneration was also proposed in the literature to occur.[25

According to our computations, the aforementioned process is predicted to require significant amounts of energy from environment to proceed since the Gibbs free energy of the products is significantly higher than that of the substrates. The calculated TS-2 (**Fig. S18**) **D**→**E** transition state (with the imaginary vibration of 513 *i* cm^{-1}) corresponds to the protonation of coordinated O_2 by the TEMPO(OH). Formation of this transition state requires surmounting 32.2 kcal/mol barrier and is associated with elongation of the O-H bond in TEMPO(OH) by the 0.315Å to 1.283Å in the direction of the coordinated oxygen molecule. We anticipate that bimetallic species $[\mathbf{L}Cu^{II}(O_2^{\cdot -})(\mu\text{-}F)(F)Cu^{II}\mathbf{L}]$ would be less stabilized and resulting in higher global energy minimum than for monometallic ones, hence activation energy would be lower to proceed further. All in all, this is in line with experimental observations, since our system necessitates heating. Recently, proton-coupled oxidation of TEMPO(OH) by the chosen Cu^{II} salts could also contribute to the catalyst regeneration under aerobic oxidation conditions. [62]

The last step (iii) involves regeneration of the [Cu^{II}-alkoxide] complex that was the starting point of the catalytic cycle, which can proceed in two ways **(Fig. S21**). One is intramolecular proton transfer to *peroxo* complex **E** from coordinated alcohol, which leads to regenerated **B** and hydrogen peroxide, as was calculated and proposed by Iron et al.[25] The second one differs in that the proton comes from water, which also leads to formation of H_2O_2 and regeneration of active complex in the form of **A**. Given significant excess of water in relation to alcohol, we propose the latter to be more viable, even though **E→A/B** transitions are computed to be thermodynamically unfavorable, and **E→B** being slightly energetically less demanding (**Fig. S22**). This would mean that it is the step, where bimetallic mode of complex would push the reaction further, probably due to additional H-bonding present in **bis-B**.

Finally, tentative proposition of mechanism for bimetallic species is presented in a comparable way (**Fig. S23**), which we propose to be similar to the monometallic one, with eventual energetic hardships being circumvented by additional H-bonding stabilization in **bis-B** and lower overall stability of **bis-D**. Upon initial formation of the alkoxy-Cu^{II} intermediate, oxidation via HAT mechanism is proposed, followed by regeneration of TEMPO and active Cu^{II} complex *via* the *peroxo* route.

4. Conclusions

New hydrazone Schiff base ligand and its five Cu^{II} coordination compounds were synthesized, which form mono- or bimetallic species depending on the chosen counterion. These systems allow for an efficient and selective oxidation of alcohols that are activated by the presence of aromatic substituents. On the basis on experimental results, literature studies and DFT calculations two independent reaction mechanisms were proposed that explain the observed catalytic efficiency, including enhanced activity of the bimetallic species. Inertness towards secondary alcohols may be herein considered as virtue, since such behavior would allow one for selective oxidation of complex molecules that possess multiple oxidizable hydroxyl groups that differ in reactivity.[24] A sacrifice in activity in favour of selectivity seems to be related to the tridentate character of the synthesized ligand. Environmentally benign solvent, presence of air as well as low catalyst loading shall motivate us to study other Schiff base scaffolds[63] so as to gain better insight into the reasons that render efficient oxidation of alcohols possible.

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6. References

[1] S.D. McCann, S.S. Stahl, Copper-Catalyzed Aerobic Oxidations of Organic Molecules: Pathways for Two-Electron Oxidation with a Four-Electron Oxidant and a One-Electron Redox-Active Catalyst, Acc. Chem. Res., 48 (2015) 1756-1766.
[2] S.E. Allen, R.R. Walvoord, R. Padilla-Salinas, M.C. Kozlowski, Aerobic Copper-Catalyzed Organic Reactions, Chemical Reviews, 113 (2013) 6234-6458.
[3] Liquid Phase Aerobic Oxidation Catalysis: Industrial Applications and Academic Perspectives: Industrial Applications and Academic Perspectives, Wiley-VCH Verlag GmbH & Co. KGaA: , Weinheim, Germany, 2016.
[4] T. Punniyamurthy, S. Velusamy, J. Iqbal, Recent Advances in Transition Metal Catalyzed Oxidation of Organic Substrates with Molecular Oxygen, Chem. Rev., 105 (2005) 2329-2364.
[5] R.A. Sheldon, I.W.C.E. Arends, Organocatalytic Oxidations Mediated by Nitroxyl Radicals, Adv. Synth. Catal., 346 (2004) 1051-1071.
[6] R.A. Sheldon, Metal-catalyzed Oxidations of Organic Compounds: Mechanistic Principles and Synthetic Methodology Including Biochemical Processes, Academic Press, 2012.
[7] G. Centi, S. Perathoner, Catalysis and sustainable (green) chemistry, Catal. Today, 77 (2003) 287-297.
[8] Z. Shi, C. Zhang, C. Tang, N. Jiao, Recent advances in transition-metal catalyzed reactions using molecular oxygen as the oxidant, Chem. Soc. Rev., 41 (2012) 3381-3430.
[9] J. E. Nutting, M. Rafiee, S.S. Stahl*, Tetramethylpiperidine N-Oxyl (TEMPO),* Phthalimide N-Oxyl (PINO), and Related N-Oxyl Species: Electrochemical Properties and Their Use in Electrocatalytic Reactions, Chem. Rev. 11*8*, *(2018),* 4834-4885.
[10] H. A. Beejapur, Q. Zhang, K. Hu, L. Zhu, J. Wang, Z. Ye, TEMPO in Chemical Transformations: From Homogeneous to Heterogeneous, ACS Catal., 9 (2019) 2777-2830.
[11] I.E. MarkÓ, P.R. Giles, M. Tsukazaki, I. ChellÉ-Regnaut, A. Gautier, R. Dumeunier, F. Philippart, K. Doda, J.-L. Mutonkole, S.M. Brown, C.J. Urch, EFFICIENT, ECOLOGICALLY BENIGN, AEROBIC OXIDATION OF ALCOHOLS, in: Advances in Inorganic Chemistry, Academic Press, 2004, pp. 211-240.
[12] M.N. Kopylovich, A.P.C. Ribeiro, E.C.B.A. Alegria, N.M.R. Martins, L.M.D.R.S. Martins, A.J.L. Pombeiro, Chapter Three - Catalytic Oxidation of Alcohols: Recent Advances, in: P.J. Pérez (Ed.) Advances in Organometallic Chemistry, Academic Press, 2015, pp. 91-174.
[13] O. Das, T.K. Paine, CHAPTER 2 Copper Catalysts for Aerobic Oxidation of Alcohols, in: Transition Metal Catalysis in Aerobic Alcohol Oxidation, The Royal Society of Chemistry, 2015, pp. 40-69.
[14] M.F. Semmelhack, C.S. Chou, D.A. Cortes, Nitroxyl-mediated electrooxidation of alcohols to aldehydes and ketones, J. Am. Chem. Soc., 105 (1983) 4492-4494.
[15] M.F. Semmelhack, C.R. Schmid, D.A. Cortes, C.S. Chou, Oxidation of alcohols to aldehydes with oxygen and cupric ion, mediated by nitrosonium ion, J. Am. Chem. Soc., 106 (1984) 3374-3376.
[16] G. Patrick, A.I.W.C. E., S.R. A., R. Jan, Room Temperature Aerobic Copper–Catalysed Selective Oxidation of Primary Alcohols to Aldehydes, Adv. Synth. Catal., 346 (2004) 805-811.
[17] E.T.T. Kumpulainen, A.M.P. Koskinen, Catalytic Activity Dependency on Catalyst Components in Aerobic Copper–TEMPO Oxidation, Chem. Eur. J., 15 (2009) 10901-10911.
[18] J.M. Hoover, S.S. Stahl, Highly Practical Copper(I)/TEMPO Catalyst System for Chemoselective Aerobic Oxidation of Primary Alcohols, J. Am. Chem. Soc., 133 (2011) 16901-16910.

[19] J.M. Hoover, J.E. Steves, S.S. Stahl, Copper(I)/TEMPO-catalyzed aerobic oxidation of primary alcohols to aldehydes with ambient air, Nat. Protoc., 7 (2012) 1161.
[20] J.E. Steves, Y. Preger, J.R. Martinelli, C.J. Welch, T.W. Root, J.M. Hawkins, S.S. Stahl, Process Development of CuI/ABNO/NMI-Catalyzed Aerobic Alcohol Oxidation, Org. Process Res. Dev., 19 (2015) 1548-1553.
[21] J.E. Steves, S.S. Stahl, Copper(I)/ABNO-Catalyzed Aerobic Alcohol Oxidation: Alleviating Steric and Electronic Constraints of Cu/TEMPO Catalyst Systems, J. Am. Chem. Soc., 135 (2013) 15742-15745.
[22] X. Boran, L. Jean-Philip, A.B. A., A TEMPO-Free Copper-Catalyzed Aerobic Oxidation of Alcohols, Angew. Chem. Int. Ed., 54 (2015) 4208-4211.
[23] J.M. Hoover, B.L. Ryland, S.S. Stahl, Copper/TEMPO-Catalyzed Aerobic Alcohol Oxidation: Mechanistic Assessment of Different Catalyst Systems, ACS Catal., 3 (2013) 2599-2605.
[24] B.L. Ryland, S.D. McCann, T.C. Brunold, S.S. Stahl, Mechanism of Alcohol Oxidation Mediated by Copper(II) and Nitroxyl Radicals, J. Am. Chem. Soc., 136 (2014) 12166-12173.
[25] M.A. Iron, A.M. Szpilman, Mechanism of the Copper/TEMPO-Catalyzed Aerobic Oxidation of Alcohols, Chemistry – A European Journal, 23 (2017) 1368-1378.
[26] J.M. Hoover, B.L. Ryland, S.S. Stahl, Mechanism of Copper(I)/TEMPO-Catalyzed Aerobic Alcohol Oxidation, J. Am. Chem. Soc., 135 (2013) 2357-2367.
[27] S.D. McCann, S.S. Stahl, Mechanism of Copper/Azodicarboxylate-Catalyzed Aerobic Alcohol Oxidation: Evidence for Uncooperative Catalysis, J. Am. Chem. Soc., 138 (2016) 199-206.
[28] Z. Liu, Z. Shen, N. Zhang, W. Zhong, X. Liu, Aerobic Oxidation of Alcohols Catalysed by Cu(I)/NMI/TEMPO System and Its Mechanistic Insights, Catalysis Letters, 148 (2018) 2709-2718
[29] M.O. Konev, E.R. Jarvo, Nitroxyl Surprise: A Simple Amine Additive Revealed as Copper's Co-Catalyst in the Aerobic Oxidation of Alcohols, ACS Cent. Sci., 3 (2017) 272-274.
[30] S.D. McCann, J.-P. Lumb, B.A. Arndtsen, S.S. Stahl, Second-Order Biomimicry: In Situ Oxidative Self-Processing Converts Copper(I)/Diamine Precursor into a Highly Active Aerobic Oxidation Catalyst, ACS Cent. Sci., 3 (2017) 314-321.
[31] L. Que Jr, W.B. Tolman, Biologically inspired oxidation catalysis, Nature, 455 (2008) 333.
[32] M. Largeron, M.-B. Fleury, Bioinspired Oxidation Catalysts, Science, 339 (2013) 43.
[33] L. Marais, A. J. Swarts, Biomimetic Cu/Nitroxyl Catalyst Systems for Selective Alcohol Oxidation, Catalysts, 9 (2019**)** 395.
[34] M. Fontecave, J.-L. Pierre, Oxidations by copper metalloenzymes and some biomimetic approaches, Coord. Chem. Rev., 170 (1998) 125-140.
[35] E.I. Solomon, D.E. Heppner, E.M. Johnston, J.W. Ginsbach, J. Cirera, M. Qayyum, M.T. Kieber-Emmons, C.H. Kjaergaard, R.G. Hadt, L. Tian, Copper Active Sites in Biology, Chem. Rev., 114 (2014) 3659-3853.
[36] A. Messerschmidt, 8.14 - Copper Metalloenzymes, in: H.-W. Liu, L. Mander (Eds.) Comprehensive Natural Products II, Elsevier, Oxford, 2010, pp. 489-545.
[37] M.A. Fik, M. Kubicki, A.E. Odachowska, J. Karpińska, V. Patroniak, Helicity in Photocatalysis – Advantage or Obstacle? Studies on Silver Complexes – Synthesis, Structure, and Photocatalytic Activity, Eur. J. Inorg. Chem., (2016) 5530-5538.
[38] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, G. Scalmani, V. Barone, G.A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A.V. Marenich, J. Bloino, B.G. Janesko, R. Gomperts, B. Mennucci, H.P. Hratchian, J.V. Ortiz, A.F. Izmaylov, J.L. Sonnenberg, Williams, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V.G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J.A. Montgomery Jr., J.E. Peralta, F. Ogliaro, M.J. Bearpark, J.J. Heyd, E.N. Brothers, K.N. Kudin, V.N. Staroverov, T.A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A.P. Rendell, J.C. Burant, S.S. Iyengar, J. Tomasi, M. Cossi, J.M. Millam, M. Klene, C. Adamo,

R. Cammi, J.W. Ochterski, R.L. Martin, K. Morokuma, O. Farkas, J.B. Foresman, D.J. Fox, Gaussian 09 Rev. D.01, in, Wallingford, CT, 2009.

[39] R. G. Parr, W. Yang, Density Functional Theory of Atoms and Molecular Orbital Theory, New York, 1998.

[40] A.D. Becke, Density-functional exchange-energy approximation with correct asymptotic behavior, Phys. Rev. A, 38 (1988) 3098-3100.

[41] J.P. Perdew, in: P.Z.a.H. Eschrig (Ed.) Electronic Structure of Solids '91, Akademie Verlag, Berlin, 1991, pp. 11.

[42] J.P. Perdew, J.A. Chevary, S.H. Vosko, K.A. Jackson, M.R. Pederson, D.J. Singh, C. Fiolhais, Atoms, molecules, solids, and surfaces: Applications of the generalized gradient approximation for exchange and correlation, Phys. Rev. B, 46 (1992) 6671-6687.

[43] J.P. Perdew, J.A. Chevary, S.H. Vosko, K.A. Jackson, M.R. Pederson, D.J. Singh, C. Fiolhais, Erratum: Atoms, molecules, solids, and surfaces: Applications of the generalized gradient approximation for exchange and correlation, Phys. Rev. B, 48 (1993) 4978-4978.

[44] J.P. Perdew, K. Burke, Y. Wang, Generalized gradient approximation for the exchange-correlation hole of a many-electron system, Phys. Rev. B, 54 (1996) 16533-16539.

[45] Y. I. Cho, M. L. Ward*,* M. J. Rose, Substituent effects of N4 Schiff base ligands on the formation of fluoride-bridged dicobalt(ii) complexes via B–F abstraction: structures and magnetism, Dalton Trans., 45, (2016) 13466-13476

[46] A. R. Stefankiewicz, M. Wałęsa-Chorab, J. Harrowfield, M. Kubicki, Z. Hnatejko, M. Korabi*k,* V. Patroniak, Self-assembly of transition metal ion complexes of a hybrid pyrazine–terpyridine ligand, Dalton Trans., 42 (2013) 1743-1751.

[47] D. L. Reger, A. E. Pascui ,M. D. Smith, J. Jezierska, A. Ozarowski, Dinuclear Complexes Containing Linear M–F–M [M = Mn(II), Fe(II), Co(II), Ni(II), Cu(II), Zn(II), Cd(II)] Bridges: Trends in Structures, Antiferromagnetic Superexchange Interactions, and Spectroscopic Properties, Inorg. Chem., 51 (2012) 11820–11836.

[48] E. Tomat, L. Cuesta, V. M. Lynch, J. L. Sessler, Binuclear Fluoro-Bridged Zinc and Cadmium Complexes of a Schiff Base Expanded Porphyrin: Fluoride Abstraction from the Tetrafluoroborate Anion, Inorg. Chem., 46 (2007) 6224-6226.

[49] S. Alvarez, P. Alemany, D. Casanova, J. Cirera, M. Llunell, D. Avnir, Shape maps and polyhedral interconversion paths in transition metal chemistry, Coord. Chem. Rev., 249 (2005) 1693-1708.

[50] N.W. Johnson, Canad. J. Mathematics, 18 (1966) 169-200.

[51] G. Zhang, E. Liu, C. Yang, L. Li, J.A. Golen, A.L. Rheingold, Copper(II) Complexes of 2,2′:6′,2″-Terpyridine Derivatives for Catalytic Aerobic Alcohol Oxidations – Observation of Mixed-Valence CuICuII Assembles, Eur. J. Inorg. Chem., 2015 (2015) 939-947.

[52] G. Zhang, G. Proni, S. Zhao, E.C. Constable, C.E. Housecroft, M. Neuburger, J.A. Zampese, Chiral tetranuclear and dinuclear copper(ii) complexes for TEMPO-mediated aerobic oxidation of alcohols: are four metal centres better than two?, Dalton Trans., 43 (2014) 12313-12320.

[53] J.U. Ahmad, M.T. Räisänen, M. Leskelä, T. Repo, Copper catalyzed oxidation of benzylic alcohols in water with H2O2, Appl. Catal. A, 411-412 (2012) 180-187.

[54] J. Laugier, J.M. Latour, A. Caneschi, P. Rey, Structural and redox properties of the Tempo adducts of copper(II) halides, Inorg. Chem., 30 (1991) 4474-4477.

[55] Z. Ma, L. Wei, E.C.B.A. Alegria, L.M.D.R.S. Martins, M.F.C. Guedes da Silva, A.J.L. Pombeiro, Synthesis and characterization of copper(ii) 4[prime or minute]-phenyl-terpyridine compounds and catalytic application for aerobic oxidation of benzylic alcohols, Dalton Trans., 43 (2014) 4048-4058.

[56] J. Rabeah, U. Bentrup, R. Stößer, A. Brückner, Selective Alcohol Oxidation by a Copper TEMPO Catalyst: Mechanistic Insights by Simultaneously Coupled Operando EPR/UV-Vis/ATR-IR Spectroscopy, Angew. Chem. Int. Ed., 54 (2015) 11791-11794.

[57] S. Adomeit, J. Rabeah, A.E. Surkus, U. Bentrup, A. Brückner, Effects of Imidazole-Type Ligands in CuI/TEMPO-Mediated Aerobic Alcohol Oxidation, Inorg. Chem., 56 (2017) 684-691.
[58] G. Avigad, D. Amaral, C. Asensio, B.L. Horecker, The d-Galactose Oxidase of Polyporus circinatus, J. Biol. Chem., 237 (1962) 2736-2743.
[59] M.M. Whittaker, J.W. Whittaker, The active site of galactose oxidase, J. Biol. Chem., 263 (1988) 6074-6080.
[60] E.C. Hayes, T.R. Porter, C.J. Barrows, W. Kaminsky, J.M. Mayer, S. Stoll, Electronic Structure of a CuII–Alkoxide Complex Modeling Intermediates in Copper-Catalyzed Alcohol Oxidations, J. Am. Chem. Soc., 138 (2016) 4132-4145.
[61] T.R. Porter, D. Capitao, W. Kaminsky, Z. Qian, J.M. Mayer, Synthesis, Radical Reactivity, and Thermochemistry of Monomeric Cu(II) Alkoxide Complexes Relevant to Cu/Radical Alcohol Oxidation Catalysis, Inorg. Chem., 55 (2016) 5467-5475.
[62] M. C. Ryan, L. D. Whitmire, S. D. McCann, S. S. Stahl, Copper/TEMPO Redox Redux: Analysis of PCET Oxidation of TEMPOH by Copper(II) and the Reaction of TEMPO with Copper(I), Inorg. Chem., 58 (2019) 10194-10200
[63] Aleksandra Bocian, Martyna Szymańska, Daria Brykczyńska, Maciej Kubicki,Monika Wałęsa-Chorab, Giovanni N. Roviello, Marta A. Fik-Jaskółka, Adam Gorczyński, Violetta Patroniak, New Artificial Biomimetic Enzyme Analogues Based on Iron(II/III) Schiff Base Complexes: An Effect of (Benz)imidazole Organic Moieties on Phenoxazinone Synthase and DNA Recognition, Molecules, 24 (2019) 3173-3196.

Author statement

Conceptualization	AG
Methodology	AG, VP, PP, MM
Formal analysis	All authors
Investigation	All authors
Resources	AG, VP, PP, MM
Data Curation	All authors
Writing - Original Draft	AG
Writing - Review & Editing	All authors
Visualization	All authors
Supervision	AG, VP, PP, MM
Project administration	AG
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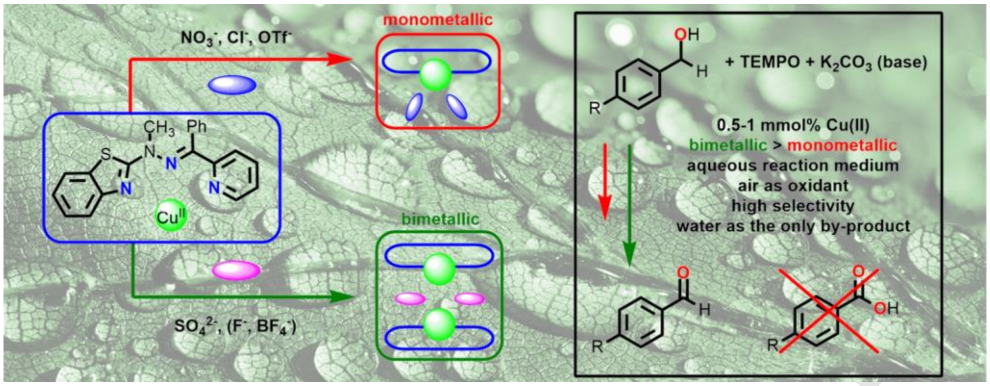
Conflict of Interest

The authors declare no conflict of interest.

Graphical abstract



Highlights

- new benzothiazole Schiff base ligand **L** and its complexes with copper(II) ions
- structures of copper(II) complexes depend on counterion
- selective oxidation of benzylic alcohols with TEMPO
- proposed reaction mechanism with aid of Density Functional Theory calculations
- green chemistry and environmental catalytic process