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Mimicing bromoperoxidase for copper complexes: Synthesis, structures and properties of Cu(II) triazine pyrazolyl complex

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Abstract:

Copper complexes $[Cu_2(\mu_2-C_2O_4)(HC_2O_4)(L_1)] \cdot (H_2C_2O_4)$ (1), $[Cu_2(Bpz^*T-OEt)_2Cl_2CuCl_4]$ (Bpz*T-EtOH = L_2) (2) and [Cu₂(Bpz*T-O)₄]·4pz*·4H₂O (3) (Bpz*T-O = L_3) (L_1 = 2,4-bis(3,5-dimethyl-1Hpyrazol-1-yl)-6-diethylamino-1,3,5-triazine, Bpz*T 2,4,6-tri(3,5-dimethylpyrazol-1-yl)-1,3,5-= s triazine) have been synthesized in the reaction of $Cu(Ac)_2 \cdot 2H_2O$, oxalic acid, L_1 (for 1) or Bpz*T(for 2) and 3) and $CuCl_2 \cdot 2H_2O$ with solution methods. They were characterized by elemental analysis, IR, UV-vis and thermogravimetric analyses (TG), and the single-crystal X-ray diffraction analysis. Structural analysis reveals that centre metal Cu atoms in the complexes 1 and 3 are six-coordination modes, forming distorted octahedron geometries with N2, O2 and N6 donors, respectively. While Cu ¹⁰ atom in the complex **2** is four-coordination and five-coordination modes, forming tetragonal pyramid and tetrahedron geometry with N3 Cl2 and N6, respectively. The complexes exhibit catalytic bromination activity in a single-pot reaction of the conversion of phenol red to bromophenol blue in a mixed system of H₂O-DMF-KBr at the constant temperature of 30 ± 0.5 C with a buffer solution of NaH₂PO₄–Na₂HPO₄ (pH=5.8), indicating that they can be considered as a potential functional model ¹⁵ of bromoperoxidase.

Keywords: Copper complex; Triazine pyrazolyl compound; Crystal structure; Mimicing bromoperoxidase.

1. Introduction

The vanadium haloperoxidases (V-HPOs) from two kinds of the red algal species [1-2], Corallina officinalis and Corallina piluliferahaveave have been studied for a long time owning to the biological and catalytic properties [3]. Structural analysis reveals that they all show a high degree of amino acid homology in their active centres and have nearly identical structural features, with vanadium atom in a proved trigonal-bipyramidal NO4 coordination geometry which is covalently bonded to three oxygen atoms in the equatorial plane, N ε of the histidine and an OH on axial positions [4-7].

Vanadium haloperoxidases are able to accelerate the oxidative halogenation of organic compounds in the presence of hydrogen peroxide, organic hydroperoxides or molecular oxygen. ¹⁰ Among these systems, V-HPOs have received an increasing attention mainly due to their catalytic ability for the oxidation of halides to the corresponding hypohalous acids in the presence of hydrogen peroxide, resulting in the halogenation of certain organic substrates [8, 9] [Reaction(1)]:

 $\mathbf{R-H} + \mathbf{H}_{2}\mathbf{O}_{2} + \mathbf{X}^{-} + \mathbf{H}^{+} \rightarrow \mathbf{R-X} + 2\mathbf{H}_{2}\mathbf{O}(1)$

Though, vanadium haloperoxidases are of great importance in nature, they are not widely used in ¹⁵ catalytic bromination reaction of actual industry. Nature vanadium haloperoxidases are difficult to be extracted, moreover, the application of V-HPOs has been restricted by the disadvantages of lower stability and active, and the catalysis reaction mechanism was not clear yet [10-13]. Based on the points above, we attempted to synthesize efficient metal complexes with organic ligands to mimic the biological activity. To our best knowledge, a number of vanadium complexes have been synthesized ²⁰ with various ligands, including aminoacid-derivatized oxidovanadium complexes [14] (V^VO(salphe)(OMe)(MeOH), V^{IV}O(sal-ala)(2,2'-bipy)·H₂O, V^{IV}O(sal-ala)(1,10-phen)·0.5H₂O), oxovanadium Schiff base complexes [15] ([VO₂(C₉H₇NO₃)](C₁₀H₁₀N₂)_{0.5}, [VO(C₁₀H₈N₂)(C₉H₇NO₃)]₃, [VO(C₁₂H₈N₂)(C₉H₇NO₃)]·2.33H₂O), poly(pyrazolyl)borate and organic carboxylic acid oxo-

vanadium (IV) complexes [16] (Tp*VO(pz*)(CH₃COO), Tp*VO(pz*)(CCl₃COO), Tp*VO(pz*)(m-NO₂-C₆H₄COO)·CH₃CN) and so on, have been so far well developed in the coordination chemistry of vanadium [17-20].

In addition, copper complex is also a kind of bioenzyme [21-24], it has been proven to be an ³ active metal centre in the best studied superoxide dismutase (SOD), which is an important antioxidizing enzyme, might protect cells as a scavenger of superoxide anion free radical that is related to aging, tumours and inflammation[25-29]. Copper SOD model complexes can overcome the disadvantages of natural superoxide dismutase, and get a profound understanding of the enzyme as well as coordination and biological medicinal chemistry [30-32]. However, the catalytic bromination

In order to study on the function properties of copper complexes, here, we synthesized three copper triazine pyrazolyl complexes, $[Cu_2(\mu_2-C_2O_4)(HC_2O_4)(L_1)] \cdot (H_2C_2O_4)$ (1), $[Cu_2(Bpz*T-OEt)_2Cl_2CuCl_4]$ (2) and $[Cu_2(Bpz*T-O)_4] \cdot 4pz* \cdot 4H_2O$ (3) (pz*= pyrazolyl, $L_1 = 2,4$ -bis(3,5-dimethyl-1*H*-pyrazol-1-yl)-6-diethylamino-1,3,5-triazine, Bpz*T = 2,4,6-tri(3,5-dimethylpyrazol-1-yl)-1,3,5-triazine), and studied the bromination reaction activity.

2. Experimental Section

2.1. Reagents and instruments

All the chemicals used were analytical grade and without further purification. L_1 and Bpz*T ($L_1 = 2$, 4-bis(3, 5-dimethyl-1*H*-pyrazol-1-yl)-6-diethylamino-1,3,5-triazine, Bpz*T = 2, 4, 6-tri (3, 5-²⁰ dimethylpyrazol-1-yl)-1,3,5-triazine) were synthesized according to the literature method [33, 34]. Elemental analyses for C, H, and N were carried out on a Perkin Elmer 240C automatic analyzer. The infrared spectra were recorded on a JASCO FT/IR-480 spectrometer with pressed KBr pellets in the

range 200-4000 cm⁻¹. UV-vis spectra were recorded on JASCO V-570 spectrometer (200-2000 nm, in form of solid sample). The X-ray powder diffraction data was collected on a Bruker AXS D8 Advance diffractometer using Cu-K α radiation ($\lambda = 1.5418$ Å) in the 2 θ range of 5–60° with a step size of 0.02° and a scanning rate of 3°/min. Thermogravimetric analyses (TG) were performed under ⁵ atmosphere with a heating rate of 10 °C min⁻¹ on a Perkin Elmer Diamond TG/DTA.

2.2. Synthesis of complexes

Complex $[Cu_2(\mu_2-C_2O_4)(HC_2O_4)_2(L_1)] \cdot (H_2C_2O_4)$ (1): $Cu(Ac)_2 \cdot 2H_2O(0.040 \text{ g}, 0.2 \text{ mmol})$ and $H_2C_2O_4$ (0.045 g, 0.5 mmol) were dissolved in anhydrous ethanol (10mL), and stirred for 1 h at room temperature, then added L_1 (0.034 g, 0.1 mmol) dissolved in 5 mL anhydrous ethanol into the reaction ¹⁰ system dropwise, stirred at room temperature for 3 h. The precipitate was separated by filtration. Then, the solution was placed at room temperature for a few days and green crystals of complex **1** were obtained. Yield: 0.11 g, 71% (Based on Cu(II)). Elemental anal (%) calcd for $C_{42}H_{56}N_{16}O_{16}Cu_2$: C, 43.18; H, 4.83; N, 19.18. Found: C, 43.33; H, 4.60; N, 19.25. IR (KBr, cm⁻¹,v): 3239 (v = c - H), 2980, 2925 (v -CH3), 1631 (v c=0), 1597, 1432, 1323 (v c=c/v c=N), 1141 (v N=N), 492 (v cu=N). UV-vis ¹⁵ (λ_{max} , nm): 258, 288 (π - π *), 368 (LMCT), 774 (d-d*).

Complex [Cu₂(Bpz*T-OEt)₂Cl₂CuCl₄] (**2**): CuCl₂·2H₂O(0.034 g, 0.2 mmol), Bpz*T(0.054 g, 0.15mmol), were dissolved in anhydrous ethanol (15 mL), stirred at room temperature for 3 h, mixed solution was separated by filtration, the green filtrate was stored at room temperature for several days and green precipitate was obtained. Then, the precipitate was dissolved in CH₂Cl₂. After two days, ²⁰ green crystals suitable for X-ray diffraction were obtained. Yield: 0.052 g, 76% (Based on Cu(II)). Elemental anal (%) calcd for C₃₀H₄₂N₁₄O₂Cl₆Cu₃: C, 34.85, H, 4.09, N, 18.96. Found: C, 34.69; H,

4.12; N, 18.87. IR (KBr, cm⁻¹, v): 3275 (v - $_{C-H}$), 2980, 2933 (v - $_{CH3}$), 1570, 1410, 1322 (v $_{C=C}/v _{C=T}$)

N), 1130, 995($\nu_{N=N}$), 477 ($\nu_{Cu=N}$). UV-vis (λ_{max} , nm): 262, 290 (π - π^*), 420 (LMCT), 792 (d-d*).

Complex $[Cu_2(Bpz*T-O)_4] \cdot 4pz* \cdot 4H_2O$ (3): The synthesized method of complex 3 was similar to that of complex 2, $CuCl_2 \cdot 2H_2O$ (0.017 g, 0.1 mmol), Bpz*T (0.072 g, 0.2mmol) were dissolved in s ethanol-water (2:1) mixed solution, stirred at room temperature for 3 h, The precipitate was separated by filtration, the blue filtrate was placed at room temperature for several days and the blue crystals were obtained. Yield: 0.068 g, 78% (Based on Cu(II)). Elemental anal (%) Calcd. for $C_{72}H_{92}N_{36}O_8Cu_2$: C, 50.37; H, 5.84; N, 29.37. Found: C, 50.39; H, 5.86; N, 29.33. IR (KBr, v, cm⁻¹): 3261 (v - c - H), 2972, 2922 (v - cH₃), 1623 (v c=0), 1563, 1416, 1272 (v c=c/v c=N), 1137, 1031 (v N=N), 485 (v Cu=N). UV-vis (λ_{max} , nm): 266, 286 (π - π^*), 348 (LMCT), 712 (d-d*).

2.3 X-ray Crystallographic Determination

The crystals of 1-3 were mounted on glass fibers for X-ray measurement, respectively. Reflection data were collected at room temperature on a Bruker AXS SMART APEX II CCD diffratometer with graphite-monochromatized Mo-K α radiation ($\lambda = 0.71073$ Å) and ω scan mode. All the measured ¹⁵ independent reflections ($I > 2\sigma$ (I)) were used in the structural analyses, and semi-empirical absorption corrections were applied using the SADABS program. The structures were solved by the direct method using the SHELXL-97[35]. All hydrogen atoms of the organic ligands were fixed at calculated positions geometrically and refined by using a riding model. The hydrogen atoms of the lattice water were found in difference Fourier map. The non-hydrogen atoms were refined with ²⁰ anisotropic thermal parameters. Crystallographic data and the structure refinement are given in Table 1. The selected bond lengths and bond angles are listed in Table S1. Hydrogen bonds of the complexes 1-3 are given in Table S2.

Complexes	1	2	3
Formula	$C_{42}H_{56}N_{16}O_{12}Cu_2$	$C_{30}H_{42}N_{14}O_2Cl_6Cu_3\\$	$C_{72}H_{92}N_{36}O_8Cu_2$
$M (g mol^{-1})$	1168.13	1034.10	1716.92
Crystal system	Triclinic	Triclinic	Orthorhombic
Space group	<i>P-1</i>	P-1	<i>pca2(1)</i>
a (Å)	9.799(3)	11.451(2)	31.222(6)
b (Å)	11.493(3)	11.736(2)	15.922(3)
c (Å)	12.815(3)	16.611(3)	16.877(3)
α (°)	72.555(3)	90.351(3)	90
β (°)	89.928(4)	107.008(3)	90
γ (°)	69.314(3)	101.146(3)	90
V (Å ³)	1279.2(6)	2089.9(7)	8390(3)
Z	2	2	4
D_{calc} (Mg m ⁻³)	1.516	1.643	1.359
Crystal size (mm)	0.697×0.207×0.101	0.725×0.144×0.091	0.28×0.06×0.05
F(000)	606	1050	3591
μ (Mo-K α) / mm ⁻¹	0.916	1.944	0.582
θ (°)	2.00 to 25.43	1.95 to 27.46	3.03 to 27.48
Reflections collected	6605	12562	72636
Independent reflections	4611	9084	17706
$(I > 2\sigma(I))$			
Parameters	364	496	1043
Flack			0.011(13)
$\Delta(\rho) \ (e \ \text{\AA}^{-3})$	0.826 and -0.595	0.619 and -0.610	0.947 and -0.499
Goodness-of-fit	1.062	0.997	0.998
\mathbf{R}_{1}^{a}	$0.0599(0.0884)^{b}$	0.0599(0.1189) ^b	$0.0544(0.1005)^{b}$
$\mathrm{wR_2}^\mathrm{a}$	0.1502(0.1678) ^b	0.1281(0.1566) ^b	$0.1324(0.1534)^{b}$

Table 1 Crystallographic data and structure refinement for complexes 1-3

*^a R = $\Sigma ||F_0| - |F_c|| / \Sigma |F_0|$, wR₂ = { $\Sigma [w(F_o^2 - F_c^2)^2] / \Sigma [w(F_o^2)^2]$ }^{1/2}; [F_o> 4 σ (F_o)].

^b Based on all data

2.4 Measurement of bromination activity in solution

Copper complex was dissolved in a mixed solution of 25 mL H₂O-DMF (DMF: 2 mL; H₂O: 23 mL). The bromination reaction activity tests were carried out at the constant temperature of 30 ± 0.5 °C ⁵ with a buffer solution of NaH₂PO₄–Na₂HPO₄ (pH=5.8). Reactions were initiated with the presence of phenol red solution, H₂O₂ and KBr. The copper complex with six different concentrations were placed in six cuvettes, and then put into the constant temperature water bath. The spectral changes were recorded using a 1000 UV-vis spectrophotometer at 5 min intervals, and the resulting data were collected during the reaction. The bromine reaction rate constant of copper complexes can be obtained ¹⁰ according to the method of literatures [36, 37].

3. Results and Discussion

3.1 Synthesis

We have successfully synthesized complexes **1-3** with solution reactions (Scheme 1a). To meet the coordination conditions of the corresponding ligands and copper atom together in the reaction ¹⁵ system, we have endeavored to search for the most optimal reaction parameters. All the synthetic manipulations were carried out at room temperature. We used anhydrous ethanol to synthesize complexes **1** and **2**, while ethanol-water mixed solution for complex **3**. We initially used solution method to synthesize complex **2**, however, we only got the powder of **2**, which was further recrystallized in CH₂Cl₂ to get nice single crystals for X-ray diffraction. This shows that solvent ²⁰ changes affect the crystal growth of the complexes.

In addition, through these experiment results, we surprisingly found that the ligand structures of complex 2 and 3 are different from the ligand used in the starting material. For 2, the 3, 5-dimethylpyrazolyl group in the 2-position of triazine ring from Bpz*T ligand is substituted by an

ethoxy group. For **3**, the reaction result is similar to complex **2**, and the 3, 5-dimethylpyrazolyl is substituted by an oxygen atom forming an unsaturated ketone conjugate species. Through a large number of experiments and analysis, we thought there may be an in *situ* reaction in the process of synthesizing complexes **2** and **3**. The detail reaction mechanism is shown in Scheme 1b.



Scheme 1.: The reaction process of the complexes 1-3 (a); The in situ reaction mechanism routes of complex 2 and 3 (b).

¹⁰ 3.2 IR spectra.

The IR spectra of the complexes 1–3 are examined (Fig. S1-S3). For the complexes 1-3, the spectra have bands at 3239-3275 cm⁻¹ for the complexes assigned to =C-H stretching vibrations, and bands at 2980-2922 cm⁻¹ assigned to -C-H stretching vibrations. The strong peaks in the range of 1597–1272 cm⁻¹ account for the appearance of $v_{C=C}/v_{C=N}$ of the pyrazole and triazine rings, and N-N

⁵ stretching vibration are in the range of 1141-995 cm⁻¹, Cu-N stretching vibration in the range of 428-480 cm⁻¹. In addition, the bands at 1631 cm⁻¹ and 1623 cm⁻¹ for **1** and **3** are assigned to C=O vibrations. The IR spectra data of the complexes **1-3** was listed in Table S3.

3.3 UV-vis spectra.

The UV–vis absorption spectra of complexes 1-3 (Fig. S4-S6) are recorded in the form of solid ¹⁰ sample and their characteristic of the UV-vis bands are listed in Table S4. They have similar absorption patterns. Bands at 258 and 288 nm for 1, 262, 290 nm for 2 and 266, 286 nm for 3 are attributed to the π - π * transition of the ligand. The band at 368 nm for 1, 420nm for 2 and 348 nm for 3 are assigned to the charge transitions from the ligands to Cu(II) atom (LMCT) of N \rightarrow Cu. The broad peak at 774 nm for 1, 792 nm for 2 and 712 nm for 3 can be caused by the d \rightarrow d^{*} transition of Cu²⁺ ¹⁵ cation, respectively.

3.4 Structural Description

Structural analysis shows that complex **1** is crystallized in the triclinic system with *P-1* space group. The molecular structure of **1** consists of two cooper atoms, two L₁ ligands, three coordinated oxalic acid ligands and a free oxalic acid molecule (Fig.1 a). Two copper atoms are crystallographic ²⁰ equivalent, and they are linked by a dianionic oxalate ligand. Cu1 atom displays a distorted octahedra geometry, and it is coordinated by three nitrogen atoms (N4, N6 and N8) from L₁ ligand, one oxygen atom (O2) from coordinated oxalic acid and two oxygen atoms (O5, O6) from bridging oxalic acid.

For L₁ ligand, it adopts terminal tridentate chelating coordination mode, the bond length of Cu–N is in the range of 1.944(3)-2.176(4) Å. And for the coordinated oxalic acid group, it adopts terminal monodentate coordination mode, the lengths of Cu–O is in the range of 1.949(3)-2.312(3) Å. The angles of the N-Cu-O and N-Cu-N are in the range of 89.11(14)-168.76(12) ° and 75.95(13)-5151.95(13) °, respectively. The angle of the O-Cu-O is 87.37(12) °.

In addition, there are two kinds of inter-hydrogen bonds in the structure of the complex **1**, (i) the hydrogrn bonds of C–H···O(C4–H4C···O3^{#1}: 3.352(6) Å, 141.3°; C6–H6A···O7^{#2}: 3.398(8) Å, 159.7°, #1: 2-x, -y, z-2, #2: 1+x, y, z) are between the carbon atom from L₁ ligand and the oxygen atom from the coordinated oxalic acid ligand (O7) and free oxalic acid (O3); (ii) hydrogen bonds of O– H···O(O3–H3···O1^{#1}: 2.666(8) Å, 136.4°; O8–H8···O5: 2.777(6) Å, 172.2°) are between two oxygen atoms from the coordinated oxalic acid and free oxalic acid. The molecules are connected to 1D chains structure by the hydrogen interactions of C4–H4C···O3 and O3–H3···O1 (Fig.1 b). Then, the neighbour chains are connected to 2D sheets structure by hydrogen interactions of O8–H8···O5 (Fig.1 c). Finally, the hydrogen bond C6–H6A···O7^{#2} linked these layers to construct a 3D packing ¹⁵ framework (Fig.S9).





с

⁵ Fig 1. a: The molecular structure of 1; b: an infinite helical chain structure of 1; c: a view of a 2D supermolecular network structure formed by the hydrogen bonds;

Single crystal X-ray diffraction analysis reveals that complex 2 is crystallized in the triclinic system with *P-1* space group. The molecular structure of 2 consists of three copper atoms, two L_2 ligand (Bpz*T-EtOH = L_2), six chlorine ions (Fig.2 a). Cu1 may be best described as tetragonal pyramid geometry, and it is coordinated by three nitrogen atoms (N3, N5 and N7) from L_2 ligand, two chlorine ions (Cl1, Cl2). The coordination environment of Cu2 is the same as Cu1. The central atom Cu3 can be described as tetrahedra geometry, it is coordinated by four chlorine ions (Cl2, Cl4, Cl5 and Cl6). Adjacent [Cu₂(Bpz*T-EtO)₂Cl₂] unit are connected by CuCl₄ unit. For L₂ ligand, it adopts a terminal tridentate chelating coordination mode, the bond lengths of Cu–N is in the range of 1.931(4)–

2.118(4) Å. By comparison, it is found that the Cu–N_{pz*} bond length is longer than that of Cu–N_{triazine}. Therefore, the coordination ability of nitrogen from triazine ring is stronger than that from pyrazolyl ring. For chlorine ions, it adopts the terminal monodentate coordination mode, the lengths of Cu–Cl is in the range of 2.1893(16)–2.5665(16) Å. Similarly, the bond distance of bridging chlorine with ⁵ copper atom (Cu–Cl_b) is slightly longer than that of terminal chlorine (Cu–Cl_t), the coordination ability of terminal chlorine is stronger than that of bridging chlorine. The angles of the N-Cu-N and N-Cu-Cl are in the range of 76.53(17)-152.65(17)° and 87.84(13)-160.26(14)°, respectively. Furthermore, the angle of Cl(1)-Cu(1)-Cl(2) is 101.85(6)°, and Cl-Cu(3)-Cl is in the range of 97.68(6)-133.73(7)°.

In addition, in the molecular packing of the complex **2**, there is a kind of hydrogen bonds of C-¹⁰ H…O, which comes from between carbon atoms (C6) and oxygen atom (O2) of L₂ ligand, (C6– H6A…O2^{#3}, 3.292(8) Å, 137.5°, #3: 1+x, y, z). Adjacent molecules are linked forming a 1D chain structure via the hydrogen bond (Fig.2 b).





Fig 2. a: The molecular structure of 2. b: A view of a 1D chain by hydrogen bonding interaction in 2. The complex 3 crystallizes in the Orthorhombic system with space group Pca2(1). The asymmetric unit of complex 3 contains two Cu atoms, four coordinated L₃ ligands, four free 3,5 dimethylpyrazole ligands (Bpz*T-O = L₃) and four lattice water molecules. Cu1 may be described as distorted octahedron, and it is coordinated by six nitrogen atoms (N1, N5, N7, N8, N12 and N14) from two L₃ ligands. For L₃, it adopts a terminal tridentate chelating coordination mode, the bond lengths of Cu–N is in the range of 1.931(4)–2.258(4) Å. The angles of the N-Cu-N are in the range of 74.54(15)–176.46(15) °.

In the molecular packing of the complex **3**, the hydrogen bonds can be divided into three kinds: (i) the inter-hydrogen bonds of O–H···O (O4W–H4WA···O2W: 2.694(8) Å, 125.7°. O1W– H10A···O3W^{#5}: 2.698(7) Å, 143.9°. #5: x, y, 1+z.) between two free water (O2W, O4W, O1W, O3W) and (O2W–H2WA···O1^{#4}: 2.768Å, 143.99°. #4: 1+x, y, -1+z.) between a free water (O2W) and an oxygen atom (O1^{#4}) from complex molecule form two chain-bonds, which are specified as C_{2}^{2} ²⁰ (6) and C_{1}^{1} (6) [38]. (ii) the bond of O–H···N (O3W–H10C···N17: 3.405(6) Å, 138.3°) between oxygen atom from free water and a nitrogen atom from L₃ ligand also forms a chain-hydrogen bond.

(iii) intra-hydrogen bonds C–H···N (C48–H48A···N23: 2.957(6) Å, 133.1°; C17–H17A···N10: 2.957(6) Å, 132.9°) between the carbon atom and nitrogen atom from L₃ ligand, would be specified as S(6) [38], six atoms forming two closed hexatomic rings. In addition, two inter-hydrogen bonds of C–H···N (C34-H34C···N31^{#6}: 3.370(7) Å, 155.8°; C34–H34C···N32^{#7}: 3.361(7) Å, 140.8°. #6: 1.5-x, - 5 1+y, -0.5+z, #7: 1.5-x, -1+y, -0.5+z.) form a bifurcated hydrogen bond.



Fig 3. a: The molecular structure of 3. b: a view of the intramolecular hydrogen bonds in 3

3.5 Thermal properties

To examine the thermal stability of complexes 1-3, thermogravimetric analysis (TG) was carried out at a heating rate of 10 °C/min under nitrogen in the temperature range of 30–1000 °C (Fig. S7). In 1, the results show that the initial weight loss of 31.93% before 220 °C is due to the release of a lattice s oxalic acid and coordinated oxalic acid, two 3,5-dimethyl pyrazolyl moieties (calc. 31.94%). The second weight loss occurs in the temperature range of 220-1000 °C, which is ascribed to the release of the framework of the triazine ring of the L_3 ligand, and the final residue corresponds to copper oxide. In 2, the first weight loss of 13.56% before 221 °C is attributed to the reduction of a 3, 5-dimethyl pyrazolyl and a C_2H_5O moiety (calc.13.81%). The second weight loss of 37.12% was attributed to the 10 release of two 3,5-dimethyl pyrazolyl moieties, two coordinated chlorine ions, a triazine ring and a C₂H₅O moiety (calc. 37.12%) in the temperature range of 221–479 °C. The final residue corresponds to a copper dichloride and two copper oxides (obsd. 28.5%; calc. 25.69%). In 3, the first weight loss of 9.78% before 235 °C is attributed to the reduction of four free water and a free 3, 5-dimethyl pyrazolyl moiety (calc.9.62%). The second weight loss of 16.93% was attributed to the release of 15 three free 3, 5-dimethyl pyrazolyl moieties (calc. 16.38%) in the temperature range of 235–302 °C. In the temperature range of 302–324 °C, the weight loss equaled to 16.56%, ascribed to the release of organic ligands (calc. 16.93%). The final residue corresponded to two copper oxide molecules and the residual carbon.

3.6 Mimicking bromination reaction.

²⁰ We found copper complexes are able to mimic a reaction in which copper complex could catalyze the phenol red in the presence of H_2O_2 and bromide potassium to bromophenol blue through experiments. Herein, the bromination reaction activity of complexes **1**, **2** and **3** using phenol red as an organic substrate, which is shown by the conversion of phenol red to bromophenol blue have been

investigated. The reaction is rapid and stoichiometric, producing the halogenated product by the reaction of oxidized halogen species with the organic substrate, and the reactive process is shown in Scheme 2.



Scheme 2 The reactive process of bromination reaction for the complexes.

The addition of solution of complex **2** to the standard reaction system of bromide potassium in a phosphate buffer with phenol red as a trap for oxidized bromine resulted in the visible colour change of the solution from yellow to blue. The electronic absorption recorded a decrease in absorbance of the peak at 443 nm with the loss of phenol red and an increase of the peak at 592 nm with production of the bromophenol blue (shown in Fig. 4), investigating that complex **2** possesses better catalytic activity [39, 40].



Fig 4. Oxidative bromination of phenol red catalyzed by **2**. Spectral changes at 10 min intervals. The reaction mixture contained phosphate buffer (pH 5.8), KBr (0.4 mol·L⁻¹), phenol red (10^{-4} mol·L⁻¹) and complex **2** (0.1 µmol·L⁻¹).

Take complex **2** as an example to carry out kinetic studies of mimicking bromination reaction. A series of *dA/dt* data were obtained by changing the concentration of the copper complex, then the plot of -log (*dc/dt*) vs -log*c* for complex **2** was depicted according to the data of Fig. 5, obtaining a straight line (Fig. 6) with a slope of 1.0965 and an intercept of 0.646. The former confirms the first-order reaction is close dependent on concentration of copper. Based on the equation of "*b*=*log k* + *ylog c*₂ + *zlog c*₃", the reaction rate constant, k, is determined by the concentrations of KBr and phenol red (*c*₂ and *c*₃), the reaction orders of KBr and phenol red (*y* and *z*), as well as *b*. While in the experiment, considering that the reaction orders of KBr and phenol red (*y* and *z*) are 1 according to the literature; *c*₂ and *c*₃ are known to be 0.4 mol/L and 10⁻⁴ mol/L, respectively, so the reaction rate constant (*k*) for complex **2** can be calculated as 5.648×10³ (mol/L)⁻² s⁻¹.

Similar plots for **1**, **3** and $Cu(NO_3)_2$ were generated in the same way (Fig. S8). The values of the ¹⁵ slope and the intercept are 1.0820, 1.2033 and 1.0823, 1.3181 for **1** and **3**, respectively, 1.1409, 0.6327 for starting material of $Cu(NO_3)_2$.



Fig 5. A series of linear calibration plots of the absorbance at 592 nm dependence of time for different concentration of the complex **2**. Condition used: pH=5.8, c(KBr)=0.4 mol·L⁻¹, c(H₂O₂₎=1 mol·L⁻¹, c(phenol red)=10⁻⁴ mol·L⁻¹. c(complex 0.5/mmol·L⁻¹)= a: 1.5×10^{-3} ; b: 3.6×10^{-3} ; c: 4×10^{-3} ; d: 7.3×10^{-3} ; e: 8.4×10^{-3} , f: 1.15×10^{-2} .



Fig 6. $-\log (dc/dt)$ dependence of $-\log c$ for 2 in DMF-H₂O at 30±0.5°C (c is the concentration of the complex 2)

The cyclic catalytic brominated reaction mechanism is shown in Scheme 3, (1): the copper ¹⁰ complex (CuLL') is easily to form an transitional intermediate species of [CuLL'O₂H] with H₂O₂ as an oxidation regent; (2): the transitional intermediate species is transformed to copper radicals species [CuLO₂] and H₂L' rapidly; (3): Br⁻ is oxidized by the [CuLO₂], at the same time, Br⁺ and CuLL' are formed. It is found that the catalytic reaction rate would be mainly based on the stability of the formed copper radical species [CuLO₂].



Scheme 3. The cyclic catalytic brominated reaction mechanism

The experiment results showed that: (i) the reaction orders of the copper complexes in the ⁵ bromination reaction are all close to 1, confirming appreciatively the first-order dependence on copper; (ii) the reaction rate constants of the three complexes is 2>1>3(Table 2). Although the reaction rate constant of starting material of Cu(NO₃)₂ is slightly larger than those of the complexes, concentration of Cu in the complexes(7-18%) is much lower than that of starting material of Cu(NO₃)₂(34%), this is much more decreasing environment pollution in the catalytic reaction system, to be in favor of the implementation of the green catalytic reaction.

	Complexes	m	b	$k(mol L^{-1})^{-2}s^{-1}$
\mathbf{O}	1	1.08(2)	1.20(3)	$1.56(5) \times 10^3$
	2	1.09(6)	0.64(6)	$5.64(8) \times 10^3$
	3	1.08(2)	1.31(3)	$1.20(1) \times 10^3$

Table 2 Kinetic data for the complexes in DMF–H₂O at 30 ± 0.5 °C*

* Conditions used: $c(phosphate buffer) = 50 \text{ mmol} \cdot L^{-1}$, pH = 5.8, $c(KBr) = 0.4 \text{ mol} \cdot L^{-1}$, $c(phenol red) = 10^{-4} \text{mol} \cdot L^{-1}L^{-1}$. "x" is the reaction order of the copper complex; "b" is the intercept of the line; "k" is the reaction rate constant for the copper complex.

Analysis results found that Cu(II) complexes show high catalytic activity. The order of the reaction rate constant for complexes is 2>1>3. As we can see, there are similar ligands in the structure

of complexes, they just have different coordination patterns leading to the different intermediate species, which can also influenced the catalytic activity. Three Cu atoms adopt four-coordination and five-coordination respectively, while **1** and **3** adopt six-coordination, therefore, it is easier to form a transitional intermediate species of [CuLL'O₂H] owing to steric hindrance, thus its catalytic activity is the highest. For **1** and **3**, both of them have two Cu atoms, but complex **3** adopts six-coordination sandwich structure, and the center Cu atom is surrounded by two L_3 ligands tightly, so it is difficult to form an transitional intermediate to play a catalytic role. All these phenomena above showed that the catalytic activity of the complexes may have great connection with their structural characterization.

With the reaction process, it was surprising to find that the color of brominated reaction by ¹⁰ catalysis of copper complex changed slowly with reaction time. The color of bromophenol blue turned gradually into a kind of light yellow species whose absorbance is stronger than that of bromophenol blue. As shown in Fig. 7, the absorbance of the peak at 592 nm which was characteristic of the bromophenol blue product was decrease and an increase in the absorbance of the peak at 420 nm was observed. Through a large number of experimental studies, we thought that the change of color might ¹⁵ rise from photodegradation: under the action of Cu complex, the bromophenol blue was catalysised and degraded tardily into new species which structure was similar to the phenol red. In general, Cu complex not only can be used as the catalyst of brominated reaction, but also have an effect on the photocatalysis.



Fig 7. Bromophenol blue was changed by the degraded of complexes 1 - 3

4. Conclusion

⁵ Three new copper complexes, supported by pincer-N-heterocyclic ligands, have been successfully synthesized for the first time. The single-crystal X-ray diffraction analysis reveals that centre metal atoms Cu in complexes **1**, **3** are six-coordination modes, forming distorted octahedron geometries. Cu atoms in complexes **2** are four-coordination and five-coordination modes, forming tetragonal pyramid and tetrahedron geometry. We tested the catalytic bromination reaction activities with phenol red as an organic substrate in the presence of H_2O_2 , KBr and a phosphate buffer solution and finally found high catalytic activity, which indicated that copper complexes can be considered as potential functional models of bromoperoxidase.

Supporting Information Available

The selected bond lengths and angles of complexes **1-3** are listed in Table S1; their hydrogen ¹⁵ bonds are shown in Table S2. IR data and UV-vis absorption bands of the complexes **1-3** are shown in Table S3 and Table S4. Figure S1-S3 and Figure S4-S6 presented the infrared spectra, UV–vis spectra of the complexes **1-3**, respectively. Tables of atomic coordinates, isotropic thermal parameters, and complete bond distances and angles have been deposited with the Cambridge Crystallographic Data Center. Copies of this information may be obtained free of charge, by quoting the publication citation

and deposition numbers CCDC 1013924 (1), 1013980 (2) and 1013925 (3), from the Director, CCDC, 12 Union Road. Cambridge, CB2 1EZ, UK (Fax+44-1223-336033; e-mail deposit@ccdc.cam.ac.uk; http://www.ccdc.cam.ac.uk

Acknowledgments

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