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Mn(II) complexes with bipyridine, phenanthroline and benzoic acid: Biological and catalase-like activity

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Abstract. Five mononuclear Mn(II) complexes, $[Mn(phen)_2(ClO_4)_2]$ (**1**), $[Mn(phen)_3](ClO_4)_2(H_2CO_3)_2$(**2**), $[Mn(bipy)_2(ClO_4)_2]$ (**3**), $[Mn(bipy)_3](ClO_4)_2$) (**4**), and $Mn(phen)_2(ba)(H_2O)](ClO_4)(CH_3OH)$ (**5**), where bipy = 2,2'-bipyridine, phen = 1,10-phenanthroline, and ba = benzoic acid were prepared and characterized by X-ray, IR and UV-Vis spectroscopies, and their catalase-like and biological activities were studied. The presence of two different types and the number of chelating NN-donor neutral ligands allowed for analysis of their effects on the catalase and biological activities. It was observed that the presence and number of phen ligands improved the activity more than the bipy ligand. Complexes **1** and **2**, which contain more basic phen ligands, disproportionate H_2O_2 faster than complexes **3** and **4**, which contain less basic bipy ligands. The *in vitro* antimicrobial activities of all the complexes were also tested against seven bacterial strains by microdilution tests. All the bacterial isolates demonstrated sensitivity to the complexes and the antifungal (anticandidal) activities of the Mn(II) complexes were remarkably higher than the reference drug ketoconazole.

Keywords. Manganese complex; catalase; biological activity; hydrogen peroxide; bipyridine; phenanthroline

1. Introduction

The synthesis of transition metal complexes that exhibit antimicrobial and catalase activities has gained interest in recent years due to their potential for application as inorganic pharmaceuticals in clinical therapy and diagnostics.[1–7] An increasing number of mono- and dinuclear Mn(III/II) complexes with catalase activity have been reported in the literature, most of them with Schiff base ligands. Following the first publication of the bipy and phen ligands of Mn(II) complexes by Fukuda and Sone in 1970, a large number of such compounds have been reported with different metals using mainly the same ligands with various anions.[8–11] Because of their potential use as catalytic scavengers of H_2O_2 against oxidative stress, several mono- and dinuclear complexes involving different types of ligands have been synthesized and characterized in an attempt to mimic the active sites and catalytic activities of enzymes.[12–19] While numerous Mn complexes have been synthesized, few systematic studies have explored the effect of the N-N chelating coordination of neutral bipy and phen ligands on catalase and biological activity.[20–22]

To investigate the catalase and antimicrobial activities of complexes in this class, we synthesized five Mn(II) complexes using bidentate bipy/phen and benzoic acid (ba) ligands and perchlorate as a counter anion with the general formulae [Mn(N-N)(O)(O)], $[Mn(N\text{-}N)_2]^{2+}$ where N,N represents the bidentate diimine ligands bipy and phen; (O)(O) represents the counter ion perchlorate for complexes **1** and **3** and benzoate for complex **5**.[23,24] The complexes obtained with these ligands had the following compositions: $[Mn(phen)_2(ClO_4)_2)]$ (**1**), $[Mn(phen)_3](ClO_4)_2(H_2CO_3)_2$ (**2**), $[Mn(bipy)_2(ClO_4)_2)]$ (**3**), $[Mn(bipy)_3](ClO_4)_2$ (**4**) and $Mn(phen)_2(ba)(H_2O)](ClO_4)(CH_3OH)$ (**5**), where bipy = 2,2′-bipyridine, phen = 1,10-phenanthroline, and ba = benzoic acid. In addition to crystallographically characterizing these compositions, spectral studies were also carried out. In this work, we examined the chelating effects of phen and bipy with two coordinations of NN chelating atoms in complexes **1** and **3** and four coordinations of NN atoms in complexes **2** and **4**, respectively. In addition to NN chelation, the effect of the second ligand coordination of ba was also tested. Herein, we report the reactivity of complexes **1**– **5** with H_2O_2 (catalase activity) studied by measuring the volume of the evolved oxygen. Promising results were obtained against the antimicrobial activity of different sets of microorganisms for complexes **1**, **2** and **5**, which may have the potential to be an alternative antifungal drug to ketoconazole.

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2. Experimental

2.1 *Materials and Methods*

All chemicals were purchased from Aldrich and were used as received. FT-IR spectra of compounds were recorded on a Jasco FT/IR-300 E spectrophotometer. FT-IR spectra were recorded on a JASSCO FT/IR-300E spectrophotometer using the KBr pellet technique in the range 4000–400 cm^{-1}. The electronic spectra were recorded on a SHIMADZU UV-2450 spectrophotometer.

2.2 *Synthesis of Compounds*

2.2a *[Mn(phen)$_2$(ClO$_4$)$_2$], (**1**)*: A mixture of Mn$(ClO_4)_2.6(H_2O)$ (0.100 g, 0.276 mmol) with phen (0.099 g, 0.552 mmol) in methanol (1:2) were stirred for 12 h at r.t.. The mixture was filtered over celite and the solvent was evaporated to dryness. Yellow crystals were obtained by slow cooling of methanol solution at room temperature. Yield: 47% (color light yellow, decompose 223-298°C. Significant IR bands (KBr, cm^{-1}): 3085 (s), 1997 (s), 1612 (s), 1550 8w), 1461 (s), 1103 (vs), 821 (s), 605 (s). Found (%): N: 9,09; C: 48,05; H: 3.25; Calc. (%): N: 9,11; C: 48,17; H: 3.06). The complex is soluble in DMF, MeOH, EtOH, $(CH_3)_2CO$, MeCN and slightly soluble in CH_2Cl_2.

2.2b *[Mn(phen)$_3$](ClO$_4$)$_2$(H$_2$CO$_3$), (**2**)*: A mixture of $Mn(ClO_4)_2.6(H_2O)$ (0.100 g, 0.276 mmol) with phen (0.149 g, 0.828 mmol) in methanol (1:3) were stirred for 12 h at r.t.. The mixture was filtered over celite and the solvent was evaporated to dryness. The yellow product was recrystallized from methanol by ether diffusion. Yield: 61% (color light yellow, M.p. 310°C. FTIR bands (KBr, cm^{-1}): 3097 (w), 1978 (w), 1608 (w), 1465 (w), 1091 (vs), 821 (s), 605 (s). Found (%) N: 9,42; C: 47,12; H: 2.83; Calc. (%): N: 9.12; C: 46.92; H: 2.63); The complex is soluble in DMF, MeOH, EtOH, $(CH_3)_2CO$, MeCN, and slightly soluble in CH_2Cl_2.

2.2c *[Mn(bipy)$_2$(ClO$_4$)$_2$], (**3**)*: A mixture of Mn$(ClO_4)_2.6(H_2O)$ (0.100 g, 0.276mmol) with bipy (0.0862 g, 0.552 mmol) in the molar ratio 1:2 and methanol (20 mL) was placed in a Schlenk vessel (50 mL). The mixture was refluxed for 4 h. The resulting solution was allowed to stand in air and crystals of the complex **3** were deposited after a week (color: green, M.p. 336°C, 0.91 g, yield 90%). FTIR (KBr pellet, cm^{-1}): 3081 (s), 1997 (m), 1596 (s), 1454 (s), 1280 (w), 1087 (vs), 740 (s), 613 (s). Found (%) N: 9.64; C: 42.01; H: 3.05; Calc. (%): N: 9.89; C: 42.42; H: 2.85). The complex is soluble in MeOH, EtOH, MeCN, $(CH_3)_2CO$, and slightly soluble in CH_2Cl_2.

2.2d *[Mn(bipy)$_3$](ClO$_4$)$_2$), (**4**)*: A mixture of Mn$(ClO_4)_2.6(H_2O)$ (0.100 g, 0.276 mmol) with bipy (0.129 g, 0.828 mmol) in the molar ratio 1:3 and methanol (20 mL) was placed in a Schlenk vessel (50 mL). The mixture was refluxed for 4 h. The mixture was filtered over celite and the solvent was evaporated to dryness. The yellow product was recrystallized from methanol by ether diffusion. Yield: 86% (color light yellow, M.p. 315°C. FTIR bands (KBr, cm^{-1}): 3073(s), 1994 (s), 1585 (s), 1450 (s), 1280 (w), 1087 (vs), 740 (s), 609 (s). Found (%) N: 12.04; C: 49.98,05; H: 3.25; Calc. (%): N: 11.63; C: 49.88; H: 3.35). The complex is soluble in DMSO, DMF, MeOH, EtOH, $(CH_3)_2CO$, MeCN, and slightly soluble in CH_2Cl_2.

2.2e *[Mn(ba)(phen)$_2$(H$_2$O)](ClO$_4$)$_2$(CH$_3$OH), (**5**)*: A solution of manganese(II) perchlorate, $Mn(ClO_4)_2.6(H_2O)$, 0.144 g, 0.398 mmol) in methanol (10 mL) was added to a neutralized solution of benzoic acid (0.515 g, 0.422 mmol) with NaOH (0.1 M solution). The reaction mixture was stirred for 1 h at room temperature and then the solution of phen (0.143 mg, 0.796 mM) in methanol (2 mL) was added to the mixture. The final solution was refluxed for 5 h. The solvent was removed by evaporation and the crude product was washed with diethyl ether, and then dried under vacuum (0.1954 g, 69%). The yellow product was recrystallized from methanol by ether diffusion. M.p. (Dec).190–192°C. IR (KBr pellet, cm^{-1}): 3050 (vs), 1990 (s), 1581 (vs), 1396 (s), 1307 (s), 1083 (vs), 825(s), 694 (s). Found (%) N: 8.64; C: 58.05; H: 3.25; Calc. (%): N: 8,17; C: 56.03; H: 3.97). The complex is soluble in polar solvents, and slightly soluble in CH_2Cl_2 and $CHCl_3$.

2.3 *Antimicrobial activity*

Antimicrobial activities of the compounds against a few bacteria namely, *Staphylococcus aureus* NRRL B-767, *Pseudomonas aeruginosa* ATCC 254992, *Klebsiellapneumoniae* NRRL B-4420, *Escherichia coli* NRRL B-3704, *Enterococcus faecalis* ATCC 29212, *Proteus vulgaris* NRRL B-123, *Listeria monocytogenes* ATCC 7644, and *Candida* species, namely, *Candida tropicalis* NRRL Y-12968, *Candida krusei* NRRL Y-7179, *Candida zeylanoides* NRRL Y-1774, *Candida parapsilosis* NRRL Y- 12696, *Candida albicans* ATCC 90028 and *Candida globrata* NRRL Y-17815, were expressed as

the minimum inhibitory concentration (MIC). The test strains were obtained from the American Type Culture Collection (ATCC) and Agricultural Research Service Culture Collection (ARS).

The minimal inhibitory concentration (MIC) values of the compounds were determined by the micro dilution testing protocol.[25] The stock solutions of the compounds were prepared in DMSO. Chloramphenicol was used as the standard antibacterial agent whereas ketoconazole was used as an antifungal agent. The antimicrobial activity of the compounds and control drugs were recorded as MIC values, in μg/mL.

2.4 *Hydrogen peroxide disproportionation studies*

Volumetric measurements of the oxygen evolved during the reaction of the Mn(II) complexes with H_2O_2 was carried out as follows: A 50 mL, two-necked round-bottom flask containing a solution of the complex in solvent was placed in a water bath (±0.2°C). One of the necks was connected to a graduated burette filled with water and the other was stoppered with a rubber septum. The solution was stirred for 10 min to reach a stable temperature. While the solution was stirring, a chosen volume of H_2O_2 stock solution was injected into the flask through the rubber septum using a syringe, and the volume of evolved oxygen was measured with the burette as a function of time.

2.5 *X-ray crystallography*

Diffraction data for the complex were collected with Bruker AXS APEX CCD diffractometer equipped with a rotating anode at 296(2) K using graphite monochromated Mo Kα radiation at $\lambda = 0.71073$ Å. Diffraction data were collected over the full sphere and were corrected for absorption. Unit cell dimensions were determined by least-squares refinement of the complete data set and an empirical absorption correction was made based on psi-scans. The data reduction was performed with the Bruker SMART program package.[26] For further crystal and data collection details, see table 1. Structure solution was found with the SHELXS-97[27] package using the direct methods and were refined SHELXL-97[28] against F^2 using first isotropic and later, anisotropic thermal parameters for all non-hydrogen atoms. Hydrogen atoms were added to the structure model at calculated positions. Geometric calculations were performed with PLATON.[29]

3. Results and Discussion

3.1 *Synthesis of the complexes*

The synthesis of the complexes is shown in scheme 1. X-ray analysis and spectral data confirm the assigned compositions of the complexes. The electronic spectra of the complexes were taken in methanol. The same ligand and metal give different complexes because the structure of the complexes depends strongly on the mole ratio of metal to ligand in the reaction medium. Only harvested crystals of the complexes were used for catalase and the biological activity studies to exclude the effects of impurities.

3.2 *Spectroscopic study of the complexes*

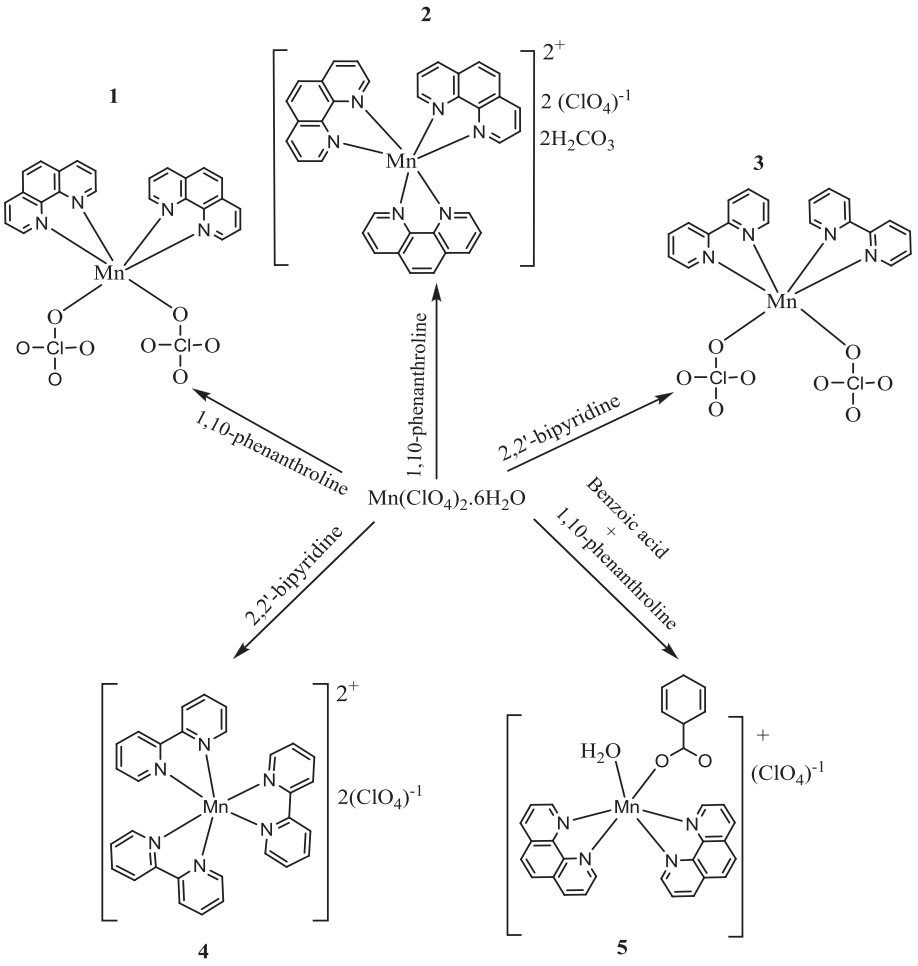
Complexes **1–5** share some similar features in the IR spectra resulting from the skeletal vibrations of aromatic rings, exhibiting a strong band at approximately 1599-1576 cm^{-1} (C = N and C = C stretches), 1476–1048 cm^{-1} (C – C and C – N vibrations), and 920-737 cm^{-1} (aromatic C–H deformation vibrations) (figure S1 in Supplementary Information). The coordination of bipy / phen to the manganese through the nitrogen atoms is indicated by the positive shift of the (C = C) and (C = N) ring stretching frequencies, which are 8–25 cm^{-1} (~1600 and 1550 cm^{-1}) lower in the free ligand (1586 cm^{-1} and 1454 cm^{-1}), respectively. The strong non-splitting absorption band of uncoordinated perchlorate anions (at approximately 1100 cm^{-1} and 620 cm^{-1}) is distinctly split into 2 components, which are observed at approximately 1029 and 1138 cm^{-1} and 624-630 cm^{-1}. These features indicate monodentate coordination of the perchlorate group.[30–32] In the case of complexes **2** and **4**, the observed broad unsplit bands at ca. 1100 $cm^{-1}$and 630 cm^{-1} are indicative of the presence of uncoordinated perchlorate ions.

The coordination of deprotonated benzoic acid to manganese was observed by the shifting of ν_{C-O} from 1682 cm^{-1} and 1453 cm^{-1} in the free ligand to 1581 cm^{-1} and 1396 cm^{-1}, which are assigned to the asymmetrical and symmetrical COO vibrational modes, respectively. Moreover, the difference between these two bands (185 cm^{-1}) indicates that the carboxylate is acting in unidentate mode. The decrease in the ν_{C-O} frequency in complex **5** clearly indicated that the binding of deprotonated ligand to the metal center, and the decreases in ν_{C-O} were due to the generation of partial double bond character in the carbonyl moiety after complex formation.

The UV-Vis spectroscopic data are very similar for all of the complexes, indicating that the Mn(II)

Table 1. Crystal data and structure refinement parameters of complexes **1 – 5**.

	$[Mn(phen)_2(ClO_4)_2]$	$[Mn(phen)_3](ClO_4)_2(H_2CO_3)_2$	$[Mn(bipy)_2(ClO_4)_2]$	$[Mn(bipy)_3](ClO_4)_2$	$[Mn(phen)_2(ba)(H_2O)].(ClO_4)(CH_3OH)$
Empirical formula	C24 H16Cl2MnN4O8	C18.50 H14 Cl Mn0.50 N3 O7.50	C20H16Cl2MnN4O8	C30 H24 Cl2 Mn N6 O8	C32 H27 Cl Mn N4 O8
Formula weight	614.25	461.25	566.21	722.39	685.97
Temperature	108(2) K	107(2) K	100(2) K	100(2) K	106(2) K
Wavelength	0.71073 Å	0.71073 Å	0.71073 Å	0.71073 Å	0.71073 Å
Crystal system, space group	Orthorhombic, Pbcn	triclinic, P-1	Monoclinic, $P21/n$	Monoclinic, P21/c	Monoclinic, P121/c1
Unit cell dimensions (Å, °)	a = 13.3753(14) $\alpha = 90$ b = 9.2068(9) $\beta = 90$ c = 19.320(2) $\gamma = 90$	a = 12.6685(10) $\alpha = 86.341(10)$ b = 12.9049(2) $\beta = 74.337(10)$ c = 13.2145(10) $\gamma = 73.701(10)$	a = 8.2272(5) $\alpha = 90$ b = 13.3691(9) $\beta = 100.1(3)$ c = 21.0132(14) $\gamma = 90$	a = 18.6642(10) $\alpha = 90$ b = 7.9312(4) $\beta = 102.9(10)$ c = 21.4812(11) $\gamma = 90$	a = 11.6192(3) $\alpha = 90$ b = 16.0932(6) $\beta = 109(10)$ c = 16.9741(6) $\gamma = 90$
Volume	2379.1(4) $Å^3$	1996.39(4) $Å^3$	2275.8(3) $Å^3$	3099.3(3) $Å^3$	3004.26(17) $Å^3$
Z, Calculated density	4, 1.715 Mg/m^3	4, 1.535 Mg/m^3	4, 1.653 Mg / m^3	4, 1.548 Mg/m^3	4, 1.517 Mg/m^3
Absorption coefficient	0.840 mm^{-1}	0.543 mm^{-1}	0.871mm^{-1}	0.660 mm^{-1}	0.589 mm^{-1}
F(000)	1244	942	1148	1476	1412
Crystal size	0.54 x 0.51 x 0.34 mm	0.40 x 0.30 x 0.20 mm	0.41 x 0.29 x 0.21 mm	0.73 x 0.33 x 0.17 mm	0.27 x 0.24 x 0.23 mm
Theta range for data collection	2.11 to 24.73°.	1.60 to 28.28°.	1.81 to 28.38°.	1.12 to 28.31°.	1.85 to 28.45 deg.
Limiting indices	−13 <=h<=15, −10<=k<=10, −18<=l<=22	−16<=h<=16, −15<=k<=17, −17 <=l<=17	−10<=h<=11, −17<=k<=17, −28<=l<=25	−24<=h<=23, −5<=k<=9, −27<=l<=28	−15<=h<=15, −21<=k<=21, −16<=l<=22
Reflections collected / unique	20318 / 2095 [R(int) = 0.0294]	27915 / 9821 [R(int) = 0.0255]	31590 / 5689 [R(int) = 0.0467]	18129/7039 [R(int) = 0.0344]	29294 /7586 [R(int) = 0.029]
Completeness to theta	99.3%	99.1%	99.3%	93.3%	99.1%
Absorption correction	Integration	Integration	Integration	Integration	Integration
Max. and min. transmission	0.751 and 0.641	0.899 and 0.812	0.893 and 0.797	0.893 and 0.797	0.876 and 0.857
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Data / restraints / parameters	2025 / 0 / 179	9821 / 0 / 554	5652 / 0 / 316	7725 / 0 / 424	7522 / 0 / 425
Goodness-of-fit	1.007	1.035	1.062	1.025	0.999
Final R indices on F^2	R1 = 0.0989,	R1 = 0.0611,	R1 = 0.062,	R1 = 0.0421,	R1 = 0.0372,
[I>2sigma(I)]	wR2 = 0.2015	wR2 = 0.1666	wR2 = 0.213	wR2 = 0.0966	wR2 = 0.0917
R indices (all data)	R1 = 0.1017, wR2 = 0.2028	R1 = 0.0754, wR2 = 0.1776	R1 = 0.0730, wR2 = 0.2782	R1 = 0.0651, wR2 = 0.1101	R1 = 0.0491, wR2 = 0.0984
Largest diff. peak and hole	1.194 and −1.165 $e.A^{-3}$	0.803 and −1.257 $e.A^{-3}$	1.148 and −1.099 $e.A^{-3}$	0.947 and −0.401 $e.A^{-3}$	0.787 and −0.456 $e.A^{-3}$



Scheme 1. Synthesis of Mn(II) complexes **1** – **5**.

complexes are behaving as a high spin octahedral d^5 system (See figures in SI). The absorption bands in the UV region at 235, 280, 229 and 264 nm are assigned to ligand-centered $\pi \rightarrow \pi^*$ or $n \rightarrow \pi^*$ transitions in the bipy and phen ligands, respectively. Due to the d^5 configuration of the Mn^{2+} ion, no absorption is expected in the visible region of the spectrum.

3.3 *Description of Crystal Structures*

The crystal data, selected bond lengths/angles and hydrogen bonding interaction parameters for complexes **1**-**5** are listed in tables 1, 2 and 3.

3.3a *[Mn(bipy)$_2$(ClO$_4$)$_2$] (**3**) and [Mn(phen)$_2$(ClO$_4$)$_2$] (**1**)*: Complexes **1** and **3** crystallize in the orthorhombic space group Pbcn (Z = 4) and the monoclinic space group P21/n (Z = 4), respectively. The X-ray crystal structures of **1** (figure 1a) and **3** (figure 1b) are discussed together below. The similarity between the structure of complex **3**[33–37] and complex **1**[38,39] has been reported previously by others. Our group has reported detailed structure analysis of complex **1** and has also worked with it as a catalyst for alcohol oxidation.[40]

In each structure, the manganese ion is six-coordinated, but the geometry is far from octahedral, principally due to the bite angle of the bipy and phen ligands. The manganese ion in *cis*-Mn(bipy)(ClO$_4$)$_2$ (**3**) sits on a two-fold axis, whereas *cis*-Mn(phen)$_2$ (ClO$_4$)$_2$ (**2**) has no internal crystallographic symmetry. In spite of this result, the geometries of the two complexes are very similar (figure 1). The 5-membered chelating rings of Mn(II) and N atoms of phen exhibit nearly perfect coplanarity; the N1 – C5 – C6 – N2 torsion angle is 0(1)° for complex **1**. The mean planes of the two phen molecules are inclined at 69.51° (N2···N1 and N5···N6), 80.44° (N3···N4 and N5···N6) and 70.33° (N2···N1 and N3···N4) with respect to one another. The 5-membered chelating rings of Mn(II) and N atoms of bipy are considerably planar for complex **3**; the N1 – C5 – C6 – N2 and N4 – C15 – C16 – N4 torsion angles are 2.3(5)° and 6.4(4)°, respectively.

Table 2. Selected bond lengths (Å) and angles (°) for the complexes **1** – **5**.

1			
Mn1 - O1	2.2019	O1 - Mn1- N1	94.28
Mn1 - N1	2.2446	O1 - Mn1- N2	88.93
Mn1 - N2	2.2307	N1 - Mn1- N2	94.87
Cl1 - O1	1.4586	Mn1-O1- Cl1	135.90
Cl1 - O2	1.4078	Mn1- N1- C2	127.40
N1 - C2	1.3357	Mn1- N2 - C6	114.73
		Mn1- N2 - C7	128.56
2			
N(2) - Mn(1)	2.248(2)	N(6) - Mn(1) - N(1)	162.52(9)
N(4) - Mn(1)	2.249(2)	N(1) - Mn(1) - N(2)	74.64(9)
Mn(1) - N(6)	2.237(2)	N(2) - Mn(1) - N(4)	157.87(9)
Mn(1) - N(1)	2.242(2)	N(6) - Mn(1) - N(5)	73.85(9)
Mn(1) - N(5)	2.273(2)	N(1) - Mn(1) - N(3)	103.41(9)
Mn(1) - N(3)	2.291(2)	N(4) - Mn(1) - N(3)	73.62(9)
3			
Mn1 - O8	2.193 (3)	O8 - Mn1 -O1	77.26 (10)
Mn1 - N4	2.205 (3)	O8 - Mn1 - N2	156.84 (10)
Mn1 - N2	2.206 (3)	N2 - Mn1 - O1	87.89 (9)
Mn1 - N3	2.218 (3)	N3 - Mn1 - O1	168.74 (9)
Mn1 - N1	2.219 (3)	N4 - Mn1 - N1	169.12 (10)
Mn1 - O1	2.279 (2)	N4 - Mn1 - N3	74.21 (10)
4			
Mn(1) - N(5)	2.214(2)	N1 - Mn1 - N5	164.48
Mn(1) - N(3)	2.214(2)	N1 - Mn1 -N2	73.08
Mn(1) - N(4)	2.215(2)	N3 - Mn1 - N4	74.61
Mn(1) - N(1)	2.235(2)	N3 - Mn1 -N5	101.36
Mn(1) - N(6)	2.277(2)	N3 - Mn1 - N6	175.13
Mn(1) - N(2)	2.277(2)	N5 - Mn1 -N6	73.92
5			
Mn(1) - O(1)	2.1078(12)	O(1) - Mn(1) - O(8)	86.51(5)
Mn(1) - O(8)	2.1623(14)	O(8) - Mn(1) - N(3)	163.19(5)
Mn(1) - N(3)	2.2618(15)	O(1) - Mn(1) - N(4)	103.45(5)
Mn(1) - N(4)	2.2686(15)	N(3) - Mn(1) - N(4)	73.38(5)
Mn(1) - N(2)	2.2693(15)	O(8) - Mn(1) - N(1)	102.83(5)
Mn(1) - N(1)	2.2776(14)	N(4) - Mn(1) - N(1)	161.21(5)

The phen ligands show no unusual features. The variations in the C − N and C − C lengths (table 2) are closely parallel in each ring and follow the pattern observed in other phen and bipy complexes. The N(1)− Mn(l)− N(2) chelating angle is equal to 74.7(2)° and is similar to those observed in Mn(II)-phen complexes. In addition, in both cases of these non-covalent interactions, a $\pi - \pi$ interaction is also observed between parallel bipy/phen rings on adjacent chains with a separation of 3.68 Å for complex **1** and 3.984 Å for complex **3**.[41] The analysis indicates that the crystal packing of **1** and **3** are formed *via* hydrogen bonding and weak C − H$\cdots\pi$ interactions. In nitrogen-containing molecules, the inductive effect of neutral or charged N atoms decreases the electron density in adjacent CH groups (C atoms) and enhances the facility with which they participate in C − H$\cdots$X hydrogen bonds because, in general, they are the shortest ones. In the present case, all C atoms participate in hydrogen bonds with oxygen atoms of the perchlorate ion, some of which are presented in table 3.

Nonclassical C_{bipy}− H$\cdots$O hydrogen bonds (average C − O distance = 3.280(9) Å) link adjacent columns to form the resulting 3D network. The shortest $\pi\cdots$H distance is 3.140 Å for **3**. The shortest Mn$\cdots$Mn interaction is 7.864 (8) Å for **3**.

3.3b *Structure of [Mn(phen)$_3$](ClO$_4$)$_2$)$_2$(H$_2$CO$_3$) (**2**)*: Complex **2** crystallizes in the triclinic space group P-1 (Z = 4). Complex **2** consists of the $[Mn(phen)_3]^{2+}$ complex cation, two uncoordinated carbonic acids and two perchlorate molecules as counter ions (figure 2a). In the cation, the Mn(II) atom is coordinated by six N atoms from three phen molecules to complete a distorted ZnN6 octahedral geometry. All of the Mn − N bond distances are almost equal and in good agreement with previous reports. The Mn − N bond lengths are in the range of 2.238 (3)–2.291 (2) Å (table 2). The phen groups exhibit their usual acute N$\cdots$N bite distances (N1$\cdots$N2 = 2.722(4) Å, N3$\cdots$N4 = 2.721(4) Å, and N5...N6 = 2.710(4) Å) and N − Mn − N bite angles (N1 − Mn 1 − N2 = 74.63(9)°, N3 − Mnl − N4 = 73.63(9)° and N5 − Mnl − N6 = 73.85(9)°). The 5-membered chelating rings of Mn(II) and the N atoms of phen exhibit nearly perfect coplanarity; the N1 − C12 − C11 − N2 and N3 − C24 − C23 − N4 and N5 − C35 − C36 − N6 torsion angles are 3.5(4)°, 0.1(4)°, and −2.3(4)°, respectively. The mean planes of the two phen molecules are inclined at 69.51° (N2$\cdots$N1 and N5$\cdots$N6), 80.44° (N3$\cdots$N4 and N5$\cdots$N6) and 70.33° (N2$\cdots$N1 and N3$\cdots$N4) with respect to one another. The bond distances of the three phen molecules are normal within the range 1.326(4)− 1.363(4) Å for aromatic N − C bonds.

No classical hydrogen bonding was found in the crystal structure. Furthermore, the host perchlorate anion stabilizes the structure via C − H$\cdots$O hydrogen bonds (table 3). The perchlorate group acts as a 4-hydrogen-bond acceptor for the phen hydrogen. The closest intermolecular contact is observed between the carbon atom (C8) of phen and the oxygen atoms of perchlorate O5 (3.276 Å). C_{bipy}− H$\cdots$O hydrogen bonds [average C − O distance = 3.370 Å] link adjacent columns to form the resulting 3D network. The shortest centroid-centroid distance of two parallel phen ligands is 3.740 Å.

3.3c *[Mn(bipy)$_3$](ClO$_4$)$_2$) (**4**)*: Complex **4** crystallizes in the monoclinic space group P21/c (Z = 4). Complex **4** consists of a $[Mn(bipy)_3]^{2+}$ complex cation and a water molecule (figure 2b). In the cation, the

Table 3. Selected hydrogen parameters (Å, °), for complexes **1**- **5**.

D - H···A	D - H	H···A	D···A	D - H···A
1				
C3 – H3···O3^{i}	0.95	2.433	3.381	176
C12 – H12···O2^{i}	1.08	2.486	3.421	168
C11 – H11···O3^{ii}	1.08	2.519	3.344	145
Symmetry codes: (i) x,-y,+z+1/2 (ii) x-1/2, +y−1/2, −z+1/2				
2				
C13 – H13···N2	0.95	2.710	3.289	119
C33 – H33···O8	0. 95	2.354	3.216	150
C15 – H15···O3^{i}	0.95	2.540	3.448	160
C8 – H8···O5^{ii}	0.95	2.335	3.276	170
C6 – H6···O8^{ii}	0.95	2.481	3.402	163
C29 – H29···O6^{iii}	0.95	2.499	3.354	149
Symmetry codes: (i) -x+1,-y+2,-z+1 (ii) x, +y,+z+1 (iii) x+1, +y,+z				
3				
C1 – H1···O7	0.95	2.65	3.506	149
C1 – H1···O8	0.95	2.66	3.179	114
C14 – H1···O4^{i}	0.95	2.68	3.613	166
C17 – H17A···O4^{i}	0.95	2.52	3.465	172
C10 – H10···O7^{ii}	0.95	2.59	3.349	136
C3 – H3···O8^{iii}	0.95	2.64	3.277	124
C13 – H13···O3^{iv}	0.95	2.69	3.231	116
C18 – H18···O6^{v}	0.95	2.41	3.238	145
C19 – H19···O5^{v}	0.95	2.69	3.418	133
C7 – H7A···O3^{vi}	0.95	2.46	3.384	162
Symmetry codes: (i) x+1/2,- y+1/2,+z+1/2 (ii) –x+1/2, +y+1/2, –z+1/2 (iii) –x,–y,–z (iv) x–1 /2, –y+1/2, +z+1/2 (v)–x+1/2, +y +1/2, -z+1/2 (vi) x-1, +y,+z				
4				
C14 – H14···O1	0.95	2.381	3.322	170
C30 – H30···O7^{i}	0.95	2.556	3.329	121
C13 – H13···O1^{ii}	0.95	2.501	3.101	118
C10– H10···O4^{iii}	0.95	2.352	3.147	141
C8 – H8···O6^{iv}	0.95	2.349	3.287	169
Symmetry codes: (i) x,-y+1/2,+z-1/2 (ii) -x+1, +y+1/2, –z+1/2 (iii) –x,–y+1,–z+1 (iv) x,+y+1, +z				
5				
O8 – H8A···O2	0.80	1.851	2.617	159
O8 – H8B···O7	0.90	1.825	2.724	173
C27 – H27···O2	0.95	2.492	2.794	98
C31 – H31···O1	0.95	2.489	2.788	98
O7 – H7···O6	0.84	2.748	1.940	161
C3 – H3···O2^{i}	0.95	2.695	3.642	174
C10 – H10···O1^{i}	0.95	2.583	3.441	150
C6 – H6···O4^{i}	0.95	2.477	3.383	160
C16 – H16···O2^{ii}	0.95	2.512	3.439	165
Symmetry codes: (i) x,-y+1/2,+z-1/2 (ii) x,-y+1/2,+z+1/2				

Mn(II) is coordinated by six N atoms from three phen molecules to complete a distorted ZnN6 octahedral geometry. The Mn – N bond lengths are in the range 2.238(3) – 2.291(2) Å and in good agreement with previous reports (table 2). The ligands form a distorted octahedral coordination sphere around Mn(II), with the bipy groups exhibiting their usual acute N···N bite distances (N1···N2 = 2.686(3) Å, N3···N4 = 2.684(3) Å, and N5···N6 = 2.701(3) Å) and N – Mn – N bite angles (N1 – Mn 1 – N2 = 73.07(8)°, N3 – Mnl – N4 = 74.61(8)° and N5 – Mnl – N6 73.92 (8)°). The values are very close to those

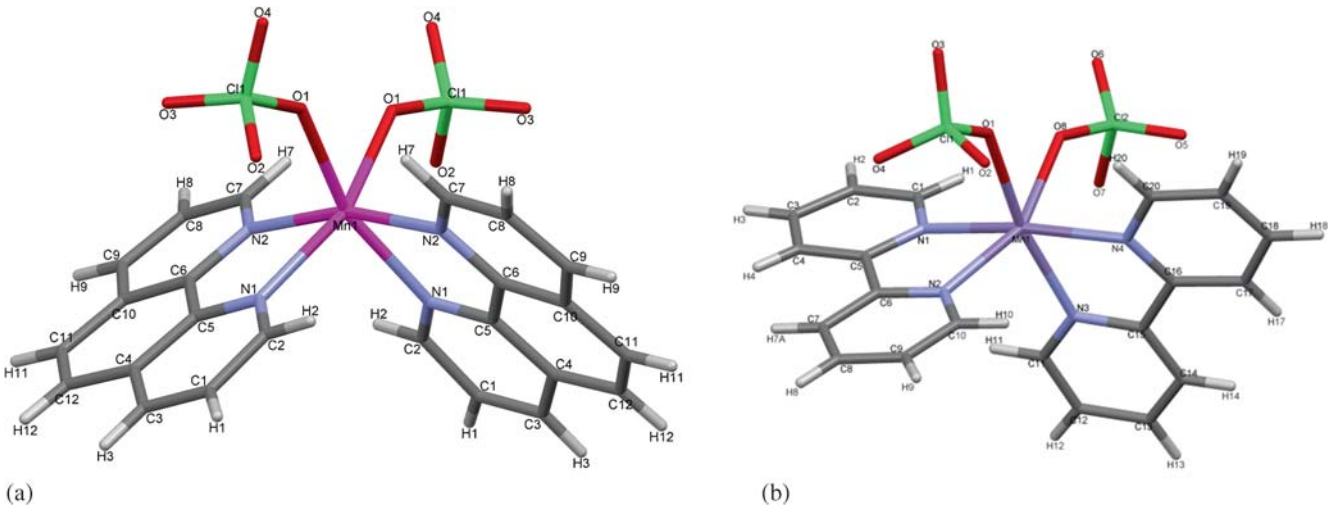


Figure 1. a) Molecular structure of complex **1**. b) Molecular structure of complex **3**.

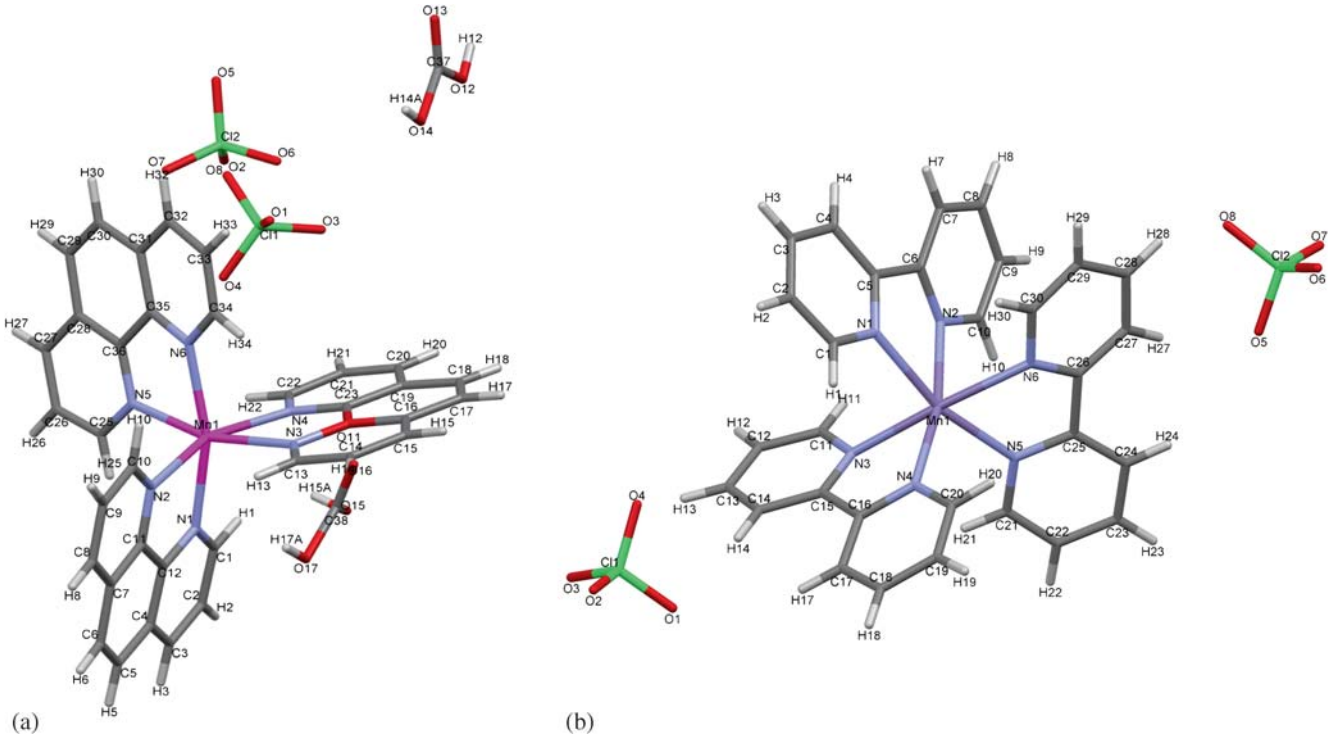


Figure 2. a) Molecular structure of complex **2**. b) Molecular structure of complex **4**.

found in $[Mn(bipy)_2C1_2]$,[42,43] $[Mn(bipy)_2(NCS)_2]$[44] and $[Mn(phen)_2(H_2O)(ClO_4)]$.[39] The deviations from ideal octahedral bond angles (table 1) are a consequence of chelate ring formation: cisoidal angles (73.07 - 106.80(8)°) and transoid angles (164.48°, 168.40°, and 175.13(8)°). The 5-membered chelating rings of Mn(II) and bipy N atoms are not planar. The N1 − C5 − C6 − N2, N3 − C15 − C16 − N4 and N5 − C25 − C26 − N6 torsion angles are 20.6(3)°, 13.8(3)°, and 24.4(3)°, respectively. The aromatic bond distances of the three bipy molecules are normal, within the range 1.336(3)−1.360(3) Å for aromatic N − C bonds.

No classical hydrogen bonding was found in the crystal structure (table 3). $C_{bipy}-H\cdots O$ hydrogen bonds between the oxygen atoms (O1, O4, O6 and O7) of uncoordinated perchlorate anions and the hydrogen atoms of coordinated bipy are in the range 2.349 Å to 2.556 Å. The closest intermolecular contact is observed between the carbon atom (C13) of bipy and the oxygen atoms of perchlorate O1 (3.101 Å; −x + 1, +y + 1/2). The shortest centroid-centroid distance of parallel bipy ligands is 4.665 Å. The existence of these stacking interactions confirms the formation of a 3D molecular network. The shortest metal-metal distance is 7.931 Å.

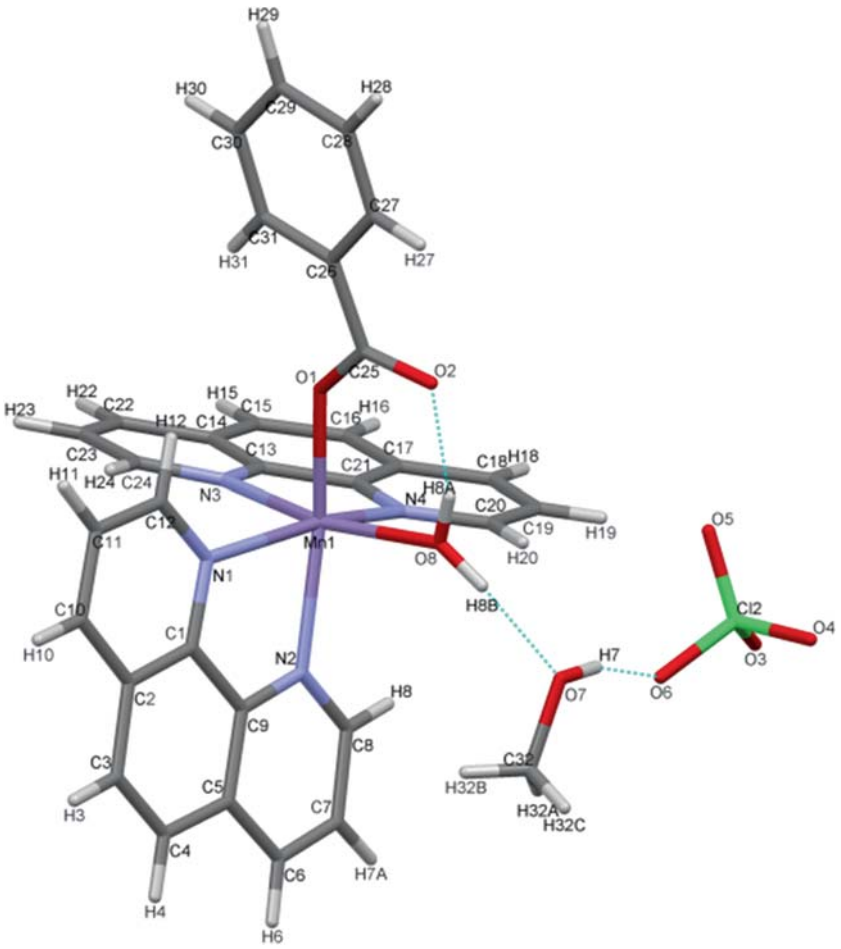


Figure 3. Molecular structure of complex **5**.

3.3d *[Mn(phen)$_2$(ba)(H$_2$O)](ClO$_4$), (**5**)*: Complex **5** crystallizes in the monoclinic space group P121/c1 (Z = 4). The X-ray structure for **5** is shown in figure 3. The asymmetric unit consists of [Mn(ba)(phen)$_2$(H$_2$O)] (figure 3). The two phen ligands are coordinated to the Mn(II) in a bidentate manner, while the benzoate anion is bound to the metal through only one carboxylate oxygen in a monodentate mode. A water molecule occupies the sixth coordination site.

The Mn–O bond lengths are 2.162(2) Å and 2.108(1) Å whereas the Mn—N distances are in the range 2.262(2) – 2.278(1) Å; these distances are comparable to those reported elsewhere.[36,42–44] The deviation from the ideal octahedral geometry is revealed by the range of angles observed around the metal center (73.10(5)°– 103.45(5)°) and by the transoid bond-angles (160.93(5)°, 161.21(5)° and 163.19°(6)) (table 3). The phen groups exhibit their usual acute N···N bite distance [N1···N2 = 2.708(2) and N3···N4 = 2.707(2) Å,] and N – Mn – N bite angles (N1 – Mn l – N2 = 73.10(8)° and N3 – Mnl – N4 = 73.38(8)°). The phen ligands are perfectly planar. The 5-membered chelating rings of Mn(II) and N atoms of phen are not planar; the N1 – C1 – C9 – N2 and N3 – C13 – C21 – N4 torsion angles are – 0.7(2)° and 1.3(2)°, respectively. The angles between the two planes on which the two phen ligands lie are 74.57° and 71.07° and 88.54° for the benzoate ring and phen ligands, respectively.

Within the crystal lattice of **5**, carboxylate oxygen (O1), coordinated water oxygen (O8), lattice perchlorate (O3–O5), and methanol oxygens (O7) are all involved in hydrogen bonding (table 3). The oxygen atoms (O4 and O6) of uncoordinated perchlorate and the carboxylate group of ba (O1 and O2) show the C – H···O intermolecular interactions with hydrogen atoms of coordinated phen molecules in the range of 2.583 Å to 2.748 Å (table 3). The shortest $\pi \cdots \pi$ distance between 2 parallel phen ligands is 3.533 Å.

3.4 *Catalase Activity*

The catalytic activities of complexes **1** – **5** toward H_2O_2 disproportionation were investigated in acetonitrile, acetone and water (table 4 and figure 4). The initial solution of Mn(II) complexes is colorless, and after the

Table 4. H_2O_2 disproportionation with **1 – 5** in different solvents.

Complex	Acetone ($\times 10^{-5}$ M.s^{-1})	TOF (h^{-1})	Acetonitrile ($\times 10^{-5}$ M.s^{-1})	TOF (h^{-1})	Water ($\times 10^{-5}$ M.s^{-1})	TOF (h^{-1})
1	39.3	1518	5.08	195	4.06	366
2	39.2	1511	8.74	337	6.63	256
3	21.9	822	2.84	110	9.47	366
4	25.8	979	3.79	146	7.96	307
5	57.4	2193	20.3	728	8.74	366

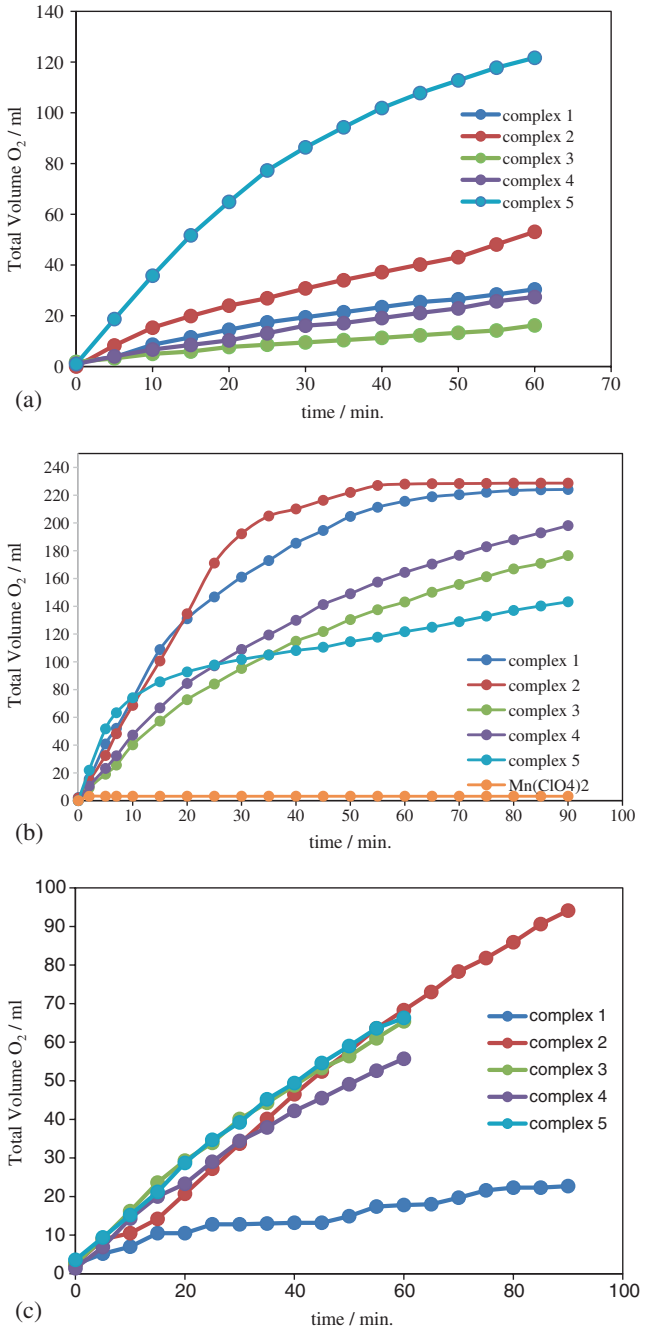


Figure 4. Time dependence of O_2 evolution upon reaction of complexes **1**-**5** with H_2O_2 in different solvents. a) acetonitrile, b) acetone and c) water. Reaction conditions: catalyst = 8.83×10^{-3} mol; H_2O_2 = 1.94×10^{-2} mol; solvent = 10 mL; T = r.t.

addition of H_2O_2, it becomes yellow or colorless and immediate evolution of oxygen was observed for all the complexes. Volumetric measurements of the evolved O_2 show that these complexes are able to catalytically disproportionate H_2O_2 into H_2O and O_2. The degree of conversion is different for each compound. The catalytic activity of $Mn(ClO_4)_2$ towards H_2O_2 disproportionation was also investigated under the same conditions as those used for the Mn(II) compxesl. In this case, as shown in figure 4b, 100% (TOF = 1511) of the H_2O_2 decomposed using complex **2** whereas ~1% of the H_2O_2 decomposed using the simple salt ($Mn(ClO_4)_2$).

We observed that the presence of bidentate chelating NN donor ligands, bipy and phen in the coordination sphere of the metal not only significantly enhances the ability of the manganese to disproportionate H_2O_2 but also inhibits the formation of insoluble manganese oxide in acetone. The activities of complexes **1** and **3,** which have four N atom coordinations, are $v_o = 39.3 \times 10^{-5}$ M.s^{-1}, TOF = 1518 h^{-1} and $v_o = 21.0 \times 10^{-5}$ M.s^{-1}, TOF = 822 h^{-1}, respectively, and for complexes **2** and **4**, which have six N atom coordinations, they are $v_o = 39.2 \times 10^{-5}$ M.s^{-1}, TOF = 1511 h^{-1} and $v_o = 25.8 \times 10^{-5}$ M.s^{-1}, TOF = 979 h^{-1}, respectively (table 4). Furthermore, we observed that the nature of the ligands has a greater effect on the catalase activity. Complexes **1** and **2,** which have more basic phen ligands, are more active in the disproportionation of H_2O_2 (TOF 1511 and 1518 h^{-1}, respectively) than the bipy complexes of **3** and **4** (TOF 822 and 979 h^{-1}, respectively), which have less basic bipy ligands. In addition, the disproportionation of H_2O_2 is almost two times faster for three coordinations than two coordinations of corresponding ligands (table 5). These results suggested that the number of σ-donors at the metal center is important to activate the hydrogen peroxide.[45] Furthermore, complex **1** which contains benzoate and phen ligands has the highest TOF with 2193 h^{-1}.

When the reaction was carried out at 37°C in Tris-HCl buffer solution, which corresponds to the physiological conditions of the cell environment, the catalase activity of **2** gave an oxygen evolution rate of 1.26×10^{-4} M.s^{-1}. Thus, we suggest that complex **2** would also be an active catalyst *in vitro*.

3.4a *Solvent effect*: The examination of the solvent effects was performed using acetone, acetonitrile and water to better understand the reaction. We observed that the decomposition rate of H_2O_2 by complexes **1**-**5** was found to depend strongly on the solvent. No induction period was observed in any of the studied solvents. The observed initial rates (under the same conditions) are given in table 4, while figure 4 illustrates the data obtained in acetonitrile, acetone and water. The results showed that as the solvent polarity increased, the rate of disproportionation decreased (table 4). While H_2O_2 was disproportionated slowly in water, the reaction in acetone gave the best results for all complexes. The rates for **1**, **2, 3, 4** and **5** were in the range of 2.3 to 10 times faster than in water. The highest activity was observed at 39.7% disproportionation ($9.47\times\ 10^{-4}$ M.s^{-1} and TOF = 366 h^{-1}) over 90 min for complex **2** in water. Based on the solvent studies, it can be concluded that the rate of disproportionation decreases with the coordinating capacity of the solvent; the poorly coordinating acetone results in a higher rate than the strongly coordinating water or acetonitrile. We assume that this effect would indicate the presence of coordinatively saturated species within the catalytic cycle and that these intermediate species are probably stabilized by the coordination of solvent molecules, which are in a competition with the substrate for a vacant coordination site. In contrast to other complexes, complex **5**, which is coordinated with one benzoate, two phen, and one water ligand, has the best activity (TOF = 728 h^{-1}) in acetonitrile (table 4).

3.5 *Biological activity*

MICs were recorded as the minimum concentration of a compound that inhibits the growth of the tested microorganism. The antimicrobial and antifungal (anticandidal) activity of complexes **1**-**5**, the metal-free ligands and a simple manganese salt were investigated. In this study, it was observed that benzoic acid and the simple salt ($Mn(ClO_4)_2$ do not exhibit antimicrobial activities in the studied concentration range. Furthermore, the coordination of the acid to the metal (complex **5**) does not result in any significant improvement in their activity.

When the antimicrobial activity of the metal complexes was investigated, the following factors should be considered: (i) the chelating effect of the ligands, (ii) the nature of donor ligands, (iii) the charge of the complex, (iv) the existence and the nature of the counter ion, and (v) the oxidation state of the metal in the complex. For complexes **1**–**5**, only the first of these factors is present.[46] Examination of the structure-activity relationships of the studied complexes indicates that the presence and number of chelating NN ligand and the oxygen donor ligand effect were the likely contributing factors to the activities of the compounds.

3.5a *Antifungal activity*: The antifungal activity of the complexes were tested on six different *Candida* species that are pathogenic to humans. Complexes **1** – **5** showed higher inhibitory levels (7.81 μg/ml) than both the ligands (bipy, ba and salt) and the reference drug ketoconazole (table 5).

In contrast to the remarkable activity of 1,10-phenanthroline and its metal complexes, metal-free bipy and the majority of its metal complexes had no inhibitory effect on the growth of the studied microorganisms with the exception of complex **3** for *C. krusei*. Complexes **1** and **2** incorporating the phen ligand dramatically inhibit the growth of the fungus. Metal-free phen showed very high anti-Candidal activity, which was surpassed by the activity of phen complex **2** for

Table 5. Minimum inhibitory concentration (*MIC*, μg/ml) shown by studied compounds against the test fungi.

Fungi / chemical	*Candida tropicalis*	*Candida krusei*	*Candida zeylanoides*	*Candida parapsilosis*	*Candida albicans*	*Candida globrata*
$[Mn(phen)_2(ClO_4)_2)]$, **1**	15.625	7.8125	62.5	15.625	15.625	7.8125
$[Mn(phen)_3](ClO_4)_2)_2$ (H_2CO_3), **2**	7.8125	7.8125	31.25	15.625	7.8125	15.625
$[Mn(2,2'\text{-bipy})_2(ClO_4)_2]$, **3**	62.5	31.25	250	62.5	62.5	62.5
$[Mn(2,2'\text{-bipy})_3](ClO_4)_2)$, **4**	62.5	31.25	250	62.5	62.5	125
$[Mn(ba)(phen)_2(H_2O)](ClO_4)_2$ (CH_3OH), **5**	7.8125	7.8125	31.25	62.5	15.625	15.625
bipy	62.5	62.5	250	62.5	62.5	31.25
phen	7.8125	7.8125	15.625	31.25	15.625	15.625
ba	125	62.5	250	125	250	250
Salt, $(Mn(ClO_4)_2$	125	125	250	250	250	250
Ketoconazole	125	125	250	15.625	62.5	62.5

C. tropicalis and *C. zeylanoides*. In addition to this result, increasing the number of chelating phen from 2 to 3 increases the inhibition effect for *C tropicalis*, *C. zeylanoides* and *C. albicans* but does not affect the activity for *C. krusei* and *C. parapsilosis*. Furthermore, compared with the activity of complex **1**, which has two chelating phen ligands, the addition of a second oxygen donor ligand ba does not affect the inhibition of metal complex **5** for *C. krusei* and *C. albicans* but increases inhibition for *C. tropicalis* and *C. zeylanoides* and decreases the inhibition of *C. parapsilosis* and *C. glabrata*.

The order of the antifungal activities of the compounds toward *C. tropicalis* was **2** = **5**= phen >**1**>**3**= **4**= bipy > ba = salt = ketoconazole. *C. krusei* was more sensitive to the tested compounds than the other *Candida* species, and complexes **1**, **2** and **5** had the same inhibitory concentration for the yeast. *C. zeylanoides* was more resistant to all of the compounds tested, but ligands **2** and **5** showed the highest concentrations. For *C. parapsilosis*, complexes **1** and **2** had the same activity as the reference drug, and the order of activity was the reference drug ketoconazole = **1** = **2** > phen > **3**= **4**= **5**= bipy >ba >salt. Complex **2** showed the highest MIC (7.81 μg/mL) toward *C. albicans,* while complexes **1**, **5** and phen inhibited the growth of the fungus at 15.62 μg/mL. The antifungal activity of the compounds toward *C. glabrata* was in the order of **1** > **2**= **5**= phen > **3**= ketoconazole > **4** > ba= salt.

It is possible that the differences in the activities of $[Mn(bipy)_2(ClO_4)_2]$ and $[Mn(bipy)_3]^{+2}$ and also $[Mn(phen)_2(ClO_4)_2]$ and $[Mn(phen)_3]^{+2}$ against bacteria are greatly influenced by the differences in the abilities of these two species to traverse cell walls and/or membrane construction. It is expected that the more extensive aromatic ring system of the phen ligand, compared to bipy would confer greater lipophilicity to $[Mn(phen)_2(ClO_4)_2]$ and $[Mn(phen)_3]^{+2}$ and enable it to penetrate the cell wall and promote adverse intracellular interactions. The toxicity increase may be considered in the light of Tweedy's chelation theory.[46] Chelation considerably reduces the polarity of the metal ion because of partial sharing of its positive charge with oxygen and nitrogen donor atoms and possible π-electron delocalization over the entire chelate ring. Such a chelation could enhance the lipophilic nature of the complex, which subsequently favors its permeation through the lipid cell membrane, thus enhancing its antibacterial and antifungal activities.[47–50]

3.5b *Antibacterial activity*: The antibacterial experimental data (table 6) indicate that *P. aeroginosa* and *P. vulgaris* were the most resistant bacteria against all of the compounds tested, including the reference drug, and the MIC values of all of the compounds were found to be in the range 125-250 μg/mL. However, other bacteria tested were moderately sensitive to the compounds at 15.62 and 31.25 μg/mL. The antibacterial activities of the compounds toward *S. aureus* were found to follow the order **1** > **2** = **5** > **3** > **4** = bipy = ba = salt. *K. pneumonia* was the most sensitive to phen, and complexes **1**, **2** and **5** showed the same level of antibacterial activity. The antibacterial activity of the compounds toward *E. coli* were found to follow the order standard chloramphenicol >**2** = phen > **1** = **5** > bipy > **3** = **4** > ba = salt. For *L. monocytogenes*, the order of activity can be arranged in the following order: standard chloramphenicol > phen > **1** = **2** = **5** > **4** > bipy = ba = salt > **3**. It can be concluded that derivatization of the ligands resulted in the higher antibacterial activations of complexes **1**, **2** and **5**. Although there are sufficient increases in the antibacterial activities of the

Table 6. Minimum inhibitory concentration (*MIC*, μg/mL) shown by studied compounds against the test bacteria.

Bacterium / chemical	*S. aureus*	*P. aeroginosa*	*K. pneumonie*	*E. coli*	*E. feacalis*	*Proteus vulgaris*	*L. Monocytogenes*
$[Mn(phen)_2(ClO_4)_2]$, **1**	31.25	250	31.25	31.25	31.25	250	31.25
$[Mn(phen)_3](ClO_4)_2)_2$ (H_2CO_3), **2**	62.5	250	31.25	15.625	31.25	125	31.25
$[Mn(2,2'\text{-bipy})_2(ClO_4)_2)]$, **3**	125	250	125	125	125	250	250
$[Mn(2,2'\text{-bipy})_3](ClO_4)_2)$, **4**	250	250	125	125	62.5	250	62.5
$[Mn(ba)(phen)_2(H_2O)](ClO_4)_2$ (CH_3OH), **5**	62.5	250	31.25	31.25	62.5	250	31.25
bipy	250	250	125	62.5	62.5	250	125
phen	31.25	250	15.625	15.625	15.625	125	15.625
ba	250	250	250	250	250	250	125
salt, $(Mn(ClO_4)_2$	250	250	250	250	250	250	125
Chloramfenicol	3.906	125	7.812	7.812	7.812	15.625	3.906

manganese complexes compared to free phen ligands, it could not reach the effectiveness of the conventional chloramphenicol.

It would appear that bipy, whether coordinated or uncoordinated to manganese, does not improve anti-*Candidal* properties. Furthermore, the presence and number of NN-donor phen significantly improves the activity of the complex. The phen molecule is a potent anti-Candidal agent and, upon reaction with Mn(II), yields complexes with comparable fungi-toxic activities. Finally, complexes **1**, **2** and **5** have the potential as alternative antifungal drugs to ketoconazole for the treatment of *Candida* infections. All of the synthesized complexes have reasonable antimicrobial activities. However, a different set of microorganisms could be involved in further antimicrobial activity tests because different genera and species, or even strains, could have different degrees of sensitivity to these antimicrobials.

4. Conclusions

In this study, the syntheses, crystal structures and biological/catalase-like activities of five Mn(II) complexes with two or three neutral ligands are presented. Complexes **1** and **3** contain two 1,10-phenanthroline/2,2′-bipyridine ligands, and complexes **2** and **4** contain three 1,10-phenanthroline/2,2′-bipyridine ligands, while complex **5** contains 1,10-phenanthroline and benzoic acid. The effects of NN chelating neutral ligands with Mn(II) on biological and catalase-like activities were investigated. All complexes have higher activities in acetone than in acetonitrile and water. Complex **5** showed the maximum TOF followed by **1**, **2**, **4** and **3** in acetone. Complexes containing phen ligands (i.e., **1** and **2)** are more active in the disproportionation of H_2O_2 than bipy complexes (**3** and **4**). The rate of reaction was 1.5 times faster for three-coordinated phen than bipy and 1.8 times faster for two-coordinated phen than bipy ligands. Biological activity studies showed that bipy containing complexes (**3** and **5**) are less active than phen containing complexes (**1**, **2** and **5**) and the latter complexes have the potential to be alternative antifungal drugs to ketoconazole for the treatment of *Candida* infections.

Supplementary Information (SI)

CCDC 808526, 848864, 848417, 798813 and 827692 contain the supplementary crystallographic data for complexes **1** – **5**, respectively. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk. FTIR spectra and UV-Vis spectra are available in Supplementary Information at www.ias.ac.in.chemsci.

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