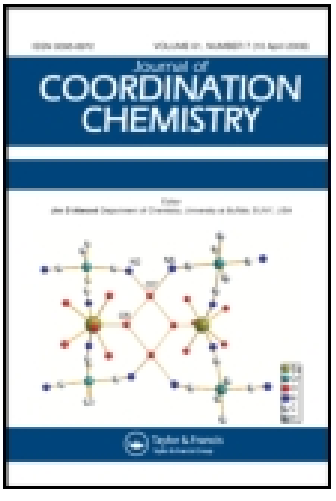

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New acyclic Schiff-base copper(II) complexes and their electrochemical, catalytic, and antimicrobial studies

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New acyclic Schiff-base copper(II) complexes and their electrochemical, catalytic, and antimicrobial studies

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A new series of acyclic mononuclear copper(II) complexes have been prepared by Schiff-base condensation derived from 5-methylsalicylaldehyde, diethylenetriamine, tris(2-aminoethyl) amine, triethylenetetramine, *N*,*N*-bis(3-aminopropyl)ethylene diamine, *N*,*N*-bis(aminopropyl) piperazine, and copper perchlorate. All the complexes were characterized by elemental and spectral analyses. Electronic spectra of the complexes show a d–d transition in the range 500–800 nm, electrochemical studies of the complexes show irreversible one-electron-reduction process around −1.10 to −1.60 V. The reduction potential of the mononuclear copper(II) complexes shifts toward anodic direction upon increasing the chain length of the imine compartment. ESR spectra of the mononuclear copper(II) complexes show four lines, characteristic of square-planar geometry, with nuclear hyperfine spin 3/2. The copper(II) complexes show a normal room temperature magnetic moment value $\mu_{eff} = 1.72$–1.76 BM, close to the spin-only value of 1.73 BM. Electrochemical and catalytic studies of the complexes were compared on the basis of increasing the chain length of the imine compartment. All the complexes were screened for antifungal and antibacterial activities.

Keywords: Schiff-base ligands; Copper(II) complexes; Cyclic voltammetry; Catecholase activity; Antimicrobial activity

1. Introduction

Coordination metal complexes have long been recognized as materials with unusual properties. The ability of transition metals to possess a variety of coordination geometries is largely responsible for their unique biological actions [1]. Study of certain transition metals containing compounds relate to the crucial roles of metal ions in nature; looking at the known structures of metallobiosites and then designing analogues can initiate new areas of coordination chemistry.

Acyclic compounds are important and powerful ligands, ubiquitous in transition metal coordination chemistry. They mimic important biological ligands [2]. The chemistry of compartmental ligands capable of forming acyclic complexes with similar

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or dissimilar metal ions [3] has grown rapidly. Acyclic ligands can impose high degree of preorganization on metal complex formation and are used as models [4] for protein–metal binding sites in biological systems, as synthetic ionophores, as therapeutic reagents in chelate therapy for the treatment of metal toxication, in catalysis, and to investigate the mutual influence of metal centers on their physicochemical properties [5]. Schiff bases are easily prepared by condensation between aldehydes and amines. Stereogenic centers of chirality (planes, axes) can be introduced in the synthetic design. Schiff-base ligands are able to coordinate [6–10] and stabilize various oxidation states. Schiff bases can be used to obtain optical materials and conducting polymers [11]. Thus, new optical and conducting materials can be produced by these compounds. Schiff-base ligands have been used in the construction of membrane sensors [12–19] and as models for biological systems [20, 21]. Schiff bases have been often used as chelating ligands of transition metals, as radiopharmaceuticals for cancer targeting, as agrochemicals, as catalysts, and as dioxygen carriers. Copper is an important trace element for plants and animals and is involved in a number of biological processes. Copper complexes containing Schiff bases are of great interest since they exhibit numerous biological activities, such as antitumor [22], anticandida [23], antibacterial [24], and antimicrobial [25] activities. Structure–activity relationships of the metal complexes are determined by the oxidation state of metals, the type and number of donors, and the relative disposition within the ligand [26]. Parashar *et al*. [27] reported that copper(II), cobalt(II), and nickel(II) complexes of Schiff-base ligands obtained from 2-substituted anilines and salicylaldehyde exhibit good antifungal and antibacterial activities.

This work deals with the influence of ligand modification on spectral, electrochemical, magnetic, and catalytic studies, reporting the synthesis and characterization of acyclic mononuclear copper(II) complexes.

2. Experimental

2.1. *Physical measurements*

Elemental analyses of the complexes are obtained using a Haereus CHN rapid analyzer. Conductivity measurements of the complexes are obtained using an Elico digital conductivity bridge model CM-88 using freshly prepared solution of the complex in DMF. IR spectra were recorded on a Perkin Elmer FT-IR 8300 series spectrophotometer on KBr discs from 4000 to 400 cm^{-1}. ^1H NMR spectra were recorded using a JEOL GSX 400 MHz NMR spectrometer. Mass spectra were obtained on a JEOL DX-303 mass spectrometer. Electronic spectral studies were carried out on a Perkin Elmer 320 spectrophotometer from 200 to 1100 nm. Cyclic voltammograms were obtained on a CHI-600A electrochemical analyzer under oxygen-free conditions using a three-electrode cell in which a glassy carbon electrode was the working electrode, a saturated Ag/AgCl electrode was the reference electrode, and a platinum wire was the auxiliary electrode. A ferrocene/ferrocenium couple was used as an internal standard and $E_{1/2}$ of the ferrocene/ferrocenium (Fc/Fc^+) couple under the experimental condition was 470 mV. Tetra(*n*-butyl)ammonium perchlorate (TBAP) was used as the supporting electrolyte. Room temperature magnetic moments were measured on a PAR vibrating sample magnetometer (VSM) Model-155. X-band EPR spectra were recorded

at 25°C on a Varian EPR-E 112 spectrometer using diphenylpicrylhydrazine (DPPH) as the reference. Catalytic oxidation of catechol to *o*-quinone by the copper complexes was studied in 10^{-3} mol L^{-1} DMF solutions. The reactions were followed spectrophotometrically with the strongest absorption of *o*-quinone at 390 nm and monitoring the increase in absorbance. A plot of log $(A_\alpha/A_\alpha - A_t)$ *versus* time was made for each complex and rate constants for the catalytic oxidations were calculated.

2.2. *Chemical and reagent*

5-Methylsalicylaldehyde [28] was prepared following the literature method. Analytical grade methanol, acetonitrile, and DMF were purchased from Qualigens. TBAP, used as supporting electrolyte in electrochemical measurements, was purchased from Fluka and recrystallized from hot methanol. *N*,*N*-bis-(3-aminopropyl) piperazine, *N*,*N*-bis-(3-aminopropyl) ethylene diamine, and tris-(2-aminoethyl)amine were purchased from Aldrich. Triethylenetetramine and diethylenetriamine were purchased from Qualigens.

2.3. *Synthesis of ligands*

2.3.1. Synthesis of bis(5-methylsalicylaldehyde)diethylenetriamine, L^1 [29]. An absolute methanol solution (10 mL) containing diethylenetriamine (0.1030 g, 1 mmol) was added dropwise to a stirred solution of 5-methylsalicylaldehyde (0.2720 g, 2 mmol) and the solution was refluxed for 7 h. The resulting yellow solution was cooled in ice. The yellow precipitate was filtered, washed with hexane, and dried under vacuum. The crude product on recrystallization from THF gave yellow crystals. Yield (54.8%). m.p.: 163°C. Anal. Calcd for $C_{20}H_{25}N_3O_2$ (%): C, 70.77; H, 7.42; N, 12.38. Found (%): C, 70.72; H, 7.31; N, 12.30. ESI MS: (*m*/*z*) 339.19, Calcd av. *m*/*z* 338.10. IR data (KBr) (ν, cm^{-1}): 3405 ν [b, (OH)], 1637 [s, ν(C=N)], ^{1}H NMR (ppm in $CDCl_3$ 400 MHz): 2.94(2CH_3, s, 6H), 3.24(N–CH_2, d, 8H, $J = 12$ Hz), 6.84(Ar–H, t, 6H, $J = 8$ Hz), 7.81(N–H, d,1H, $J = 8$ Hz), 8.29(–CH=N, d, 2H, $J = 12$ Hz), 9.78(2Ar–OH, s, 2H).

Ligands L^2, L^3, L^4, and L^5 were synthesized by following the above procedure using tris-(2-aminoethyl)amine (0.1490 g, 1 mmol), triethylenetetramine (0.1420 g, 1 mmol), *N*,*N*-bis-(3-aminopropyl)ethylenediamine (0.1740 g, 1 mmol), and *N*,*N*-bis-(3-aminopropyl)piperazine (0.2000 g, 1 mmol) instead of diethylenetriamine.

2.3.2. Synthesis of L^2. Yield (35.2%). m.p.: 138°C. Anal. Calcd for $C_{22}H_{30}N_4O_2$ (%): C, 69.08; H, 7.91; N, 14.65. Found (%): C, 69.01; H, 7.34; N, 14.61. ESI MS: (*m*/*z*) 382.24, Calcd av. *m*/*z* 382.10. Selected IR data (KBr) (ν, cm^{-1}): 3485[b, ν(OH)], 1635[s, ν(C=N)], ^{1}H NMR (ppm in $CDCl_3$ 400 MHz): 2.35(2CH_3, s, 6H), 3.49(N–CH_2, d, 10H, $J = 8$ Hz), 5.82(NH_2, s, 2H), 6.94(Ar–H, t, 6H, $J = 8$ Hz), 7.93(2CH_2, s, 4H), 8.24(–CH=N, d, 2H, $J = 12$ Hz), 9.89(2Ar–OH, s, 2H).

2.3.3. Synthesis of L^3. Yield (41.5%). m.p.: 125°C. Anal. Calcd for $C_{22}H_{30}N_4O_2$ (%): C, 69.08; H, 7.81; N, 15.65. Found (%): C, 69.01; H, 7.64; N, 15.61. ESI MS: (*m*/*z*) 383.24, Calcd av. *m*/*z* 383.10. Selected IR data (KBr) (ν, cm^{-1}): 3445 ν(OH), 1630[s, ν(C=N)], ^{1}H NMR (ppm in $CDCl_3$ 400 MHz): 2.32(2CH_3, s, 6H), 3.77(2N–$(CH_2)_2$, d,

12H, $J = 12$ Hz), 6.94(Ar–H, t, 6H, $J = 8$ Hz), 7.98(2N–H, d, 2H, $J = 8$ Hz), 8.32(–CH=N, d, 2H, $J = 8$ Hz), 9.87(2Ar–OH, s, 2H).

2.3.4. Synthesis of L^4. Yield (29.5%). m.p.: 141°C. Anal. Calcd for $C_{24}H_{34}N_4O_2$ (%): C, 70.21; H, 8.34; N, 13.69. Found (%): C, 70.13; H, 8.29; N, 13.53. ESI MS: (m/z) 410.30, Calcd av. m/z 410.10. Selected IR data (KBr) (ν, cm^{-1}): 3475 ν(OH), 1637 [s, ν(C=N)]. ^{1}H NMR (ppm in $CDCl_3$ 400 MHz): 2.60($2CH_3$, s, 6H), 3.71(N–$(CH_2)_2$, d, 4H, $J = 8$ Hz), 5.32(2N–H, d, 2H, $J = 8$ Hz), 7.09(Ar–H, s, 6H), 7.81(CH_2, s, 12H), 8.16(–CH=N, s, 2H), 9.81(2Ar–OH, s, 2H).

2.3.5. Synthesis of L^5. Yield (29.5%). m.p.: 171°C. Anal. Calcd for $C_{26}H_{36}N_4O_2$ (%): C, 71.53; H, 8.32; N, 12.80. Found (%): C, 71.41; H, 8.24; N, 12.77. ESI MS: (m/z) 436.35, Calcd av. m/z 435.20. Selected IR data (KBr) (ν, cm^{-1}): 3435 ν(OH), 1631[s, ν(C=N)]. ^{1}H NMR (ppm in $CDCl_3$ 400 MHz): 2.28($2CH_3$, s, 6H), 3.54(2N–$(CH_2)_2$, d, 8H, $J = 12$ Hz), 5.71(CH_2, s, 12H), 7.24(Ar–H, s, 6H), 8.25(–CH=N, s, 2H), 9.79(2Ar–OH, s, 2H).

2.4. *Synthesis of metal complexes*

An absolute methanol solution containing $Cu(ClO_4)_2 \cdot 6H_2O$ (0.037 g, 0.1 mmol) was added dropwise to a stirring solution of L^1 (0.0339 g, 0.1 mmol) in 20 mL of absolute methanol and refluxed for 8 h. On cooling the solution, green microcrystals formed, were filtered, washed with methanol followed by diethyl ether, and dried in vacuum. The crude product was recrystallized from methanol and acetonitrile (1 : 3, v/v). [Cu(II)L^2], [Cu(II)L^3], [Cu(II)L^4], and [Cu(II)L^5] were synthesized by following the above procedure using L^2 (0.038 g, 0.1 mmol), L^3 (0.0382 g, 0.1 mmol), L^4 (0.0426 g, 0.1 mmol), and L^5 (0.0468 g, 0.1 mmol).

2.4.1. Synthesis of [Cu(II)L^1]. Yield: (65%). m.p.: 322°C (dec). Anal. Calcd for $C_{20}H_{23}CuN_3O_2$ (%): C, 59.91; H, 5.78; N, 10.49; Cu, 15.85. Found (%): C, 59.69; H, 5.72; N, 10.22; Cu, 15.61 ESI MS: (m/z) 400.12, Calcd av. m/z 400.02. Conductance (Λ $Scm^2\,mol^{-1}$) in DMF: 65. Selected IR data (KBr) (ν, cm^{-1}): 3375 ν(NH), 1624 [s, ν(C=N)], 616 [s, ν(M–N)], 436 [s, ν(M–O)], UV-Vis [λ_{max}, nm (ε,$(mol\,L^{-1})^{-1}\,cm^{-1}$)] in DMF: 585 (140), 355 (16,450).

2.4.2. Synthesis of [Cu(II)L^2]. Yield: (81%). m.p.: 331°C (dec). Anal. Calcd for $C_{22}H_{28}CuN_4O_2$ (%): C, 59.51; H, 6.36; N, 12.62; Cu, 14.31. Found (%): C, 59.32, H, 6.25; N, 12.49; Cu, 14.26. ESI MS: (m/z) 443.15, Calcd av. m/z 442.10. Conductance (Λ $Scm^2\,mol^{-1}$) in DMF: 71. Selected IR data (KBr) (ν, cm^{-1}): 3417 $\nu(NH_2)$, 1614 [s, ν(C=N)], 426 [ν(M–N)], 441 [s, ν(M–O)], UV-Vis [λ_{max}, nm (ε,$(mol\,L^{-1})^{-1}\,cm^{-1}$)] in DMF: 600 (123), 360 (18,000).

2.4.3. Synthesis of [Cu(II)L^3]. Yield: (71%). m.p.: 325°C (dec). Anal. Calcd for $C_{22}H_{28}CuN_4O_2$ (%): C, 59.51; H, 6.36; N, 12.62; Cu, 14.31. Found (%): C, 59.42; H, 6.20; N, 12.43; Cu, 14.21. ESI MS: (m/z) 443.15, Calcd av. m/z 445.02.

Conductance (Λ $Scm^2 mol^{-1}$) in DMF: 75. Selected IR data (KBr) (ν, cm^{-1}): 3360 ν(NH), 1620 [s, ν(C=N)], 567 [ν(M–N)], 446 [s, ν(M–O)], UV-Vis [λ_{max}, nm (ε, $(mol\,L^{-1})^{-1}\,cm^{-1}$)] in DMF: 680 (138), 381 (18,400).

2.4.4. Synthesis of [Cu(II)L^4]. Yield: (79%). m.p.: 335°C (dec). Anal. Calcd for $C_{24}H_{32}CuN_4O_2$ (%): C, 61.06; H, 6.84; N, 11.86; Cu, 13.45. Found (%): C, 61.01; H, 6.76; N, 11.73; Cu, 13.31. ESI MS: (m/z) 475.21, Calcd av. m/z 473.18. Conductance (Λ $Scm^2 mol^{-1}$) in DMF: 79. Selected IR data (KBr) (ν, cm^{-1}): 3330 ν(NH), 1628 [s, ν(C=N)], 560 [ν(M–N)], 430 [s, ν(M–O)], UV-Vis [λ_{max}, nm (ε, $(mol\,L^{-1})^{-1}\,cm^{-1}$)] in DMF: 630 (128), 390 (19,600).

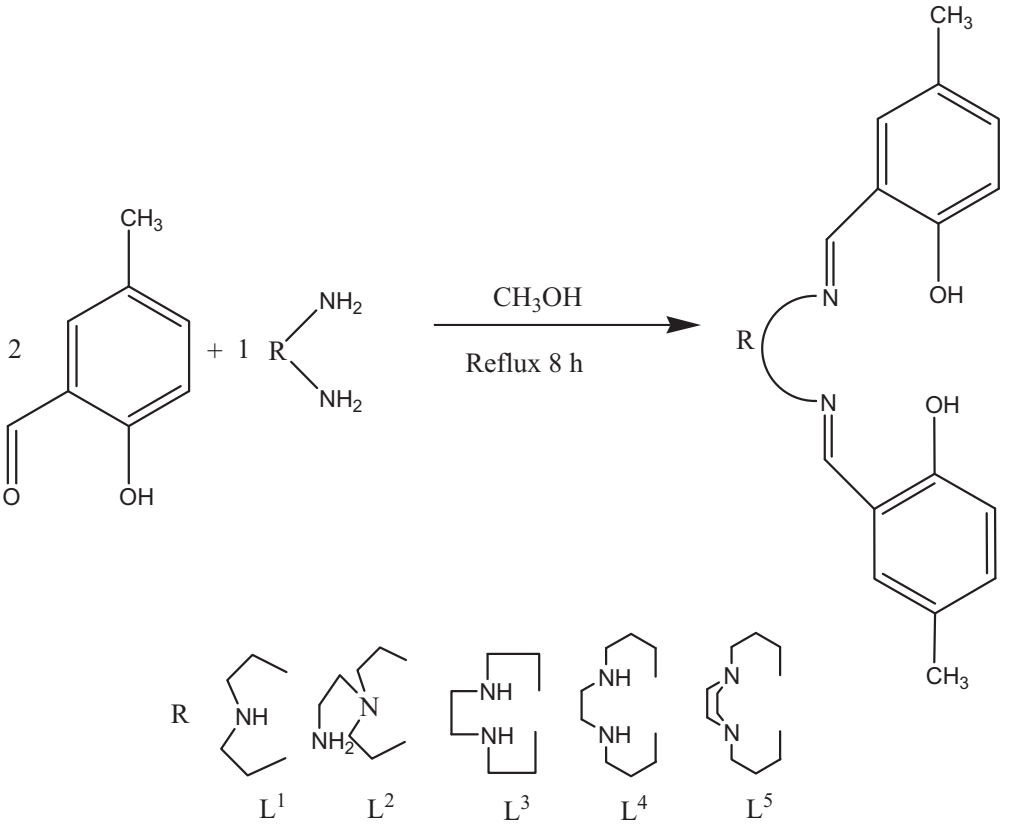
2.4.5. Synthesis of [Cu(II)L^5]. Yield: (61%). m.p.: 341°C (dec). Anal. Calcd for $C_{26}H_{34}CuN_4O_2$ (%): C, 62.69; H, 6.87; N, 11.25; Cu, 12.74. Found (%): C, 62.58; H, 6.80; N, 11.17; Cu, 12.69. ESI MS: (m/z) 499.25, Calcd av. m/z 497.12. Conductance (Λ $Scm^2 mol^{-1}$) in DMF: 82. Selected IR data (KBr) (ν, cm^{-1}): 3113 ν(N–CH_2), 1626 [s, ν(C=N)], 569 [s, ν(M–N)], 455 [s, ν(M–O)], UV-Vis [λ_{max}, nm (ε, $(mol\,L^{-1})^{-1}\,cm^{-1}$)] in DMF: 730 (130), 340 (18,200).

3. Results and discussion

A series of acyclic mononuclear copper(II) complexes were synthesized by Schiff base condensation of the precursor compounds with diamines in the presence of copper as shown in schemes 1 and 2. Conductivity measurements (Λ 73–97 $Scm^2 mol^{-1}$) show they are 1 : 1 electrolytes in DMF [30]. All attempts to grow single crystals of the complexes (e.g. by the diffusion of diethyl ether vapor into DMF solutions or recrystallization of the complexes from acetonitrile) have failed and only green powder or microcrystals were obtained. Spectral, electrochemical, catalytic, and antimicrobial studies of the complexes were carried out.

3.1. *Spectroscopic studies*

The FT-IR spectrum of 5-methy1salicylaldehyde shows a peak at 1655 cm^{-1} corresponding to (–CHO). The ligands as well as 5-methy1salicylaldehyde show a band at 3400 cm^{-1} corresponding to (–OH). Ligands and complexes show a sharp band at 1620–1640 cm^{-1} due to C=N. The presence of this new peak and the absence of (C=O) and (–OH) in the complexes indicate Schiff-base condensation [31–36]. For the complexes, bands at 430–466 cm^{-1} could be assigned to –(M–O) bond. Other weak bands at lower frequency could be assigned to –(M–N) [37]. The spectra of all the complexes are dominated by bands at 3150–3070 cm^{-1} due to the aromatic C–H stretching vibration. A strong band at 1260 cm^{-1} in the free Schiff bases has been assigned to phenolic C–O stretch. Upon complexation, this band shifts to higher frequency (1300 cm^{-1}) showing coordination through phenolic oxygen [38]. The presence of uncoordinated perchlorate anions in all the mononuclear complexes are inferred from a single broad band around 1100 cm^{-1} (ν_3-antisymmetric stretch) which is



Scheme 1. Schematic diagram for the synthesis of ligands.

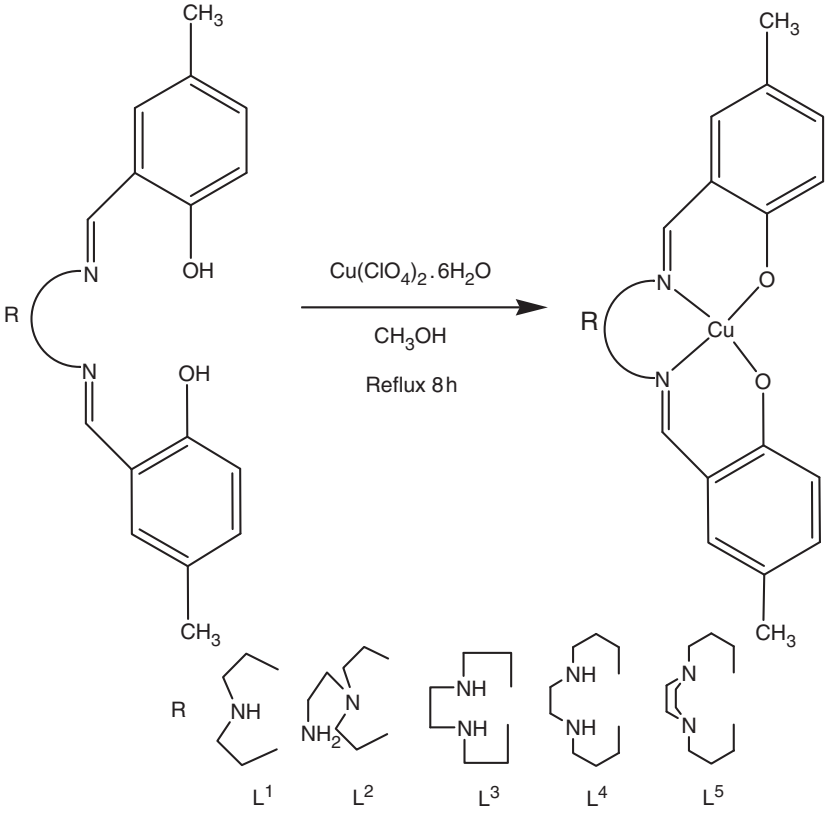
not split and a band around 650 cm^{-1} (ν_4-antisymmetric bending). The band around 930 cm^{-1} (ν_2-symmetric stretching) due to coordinated perchlorate is not observed and this indicates that no perchlorate ions are coordinated in the complexes.

3.2. *Electronic spectra*

Electronic spectra of all the complexes obtained in DMF show a single weak d–d band at 450–800 nm due to $^2B_{1g} \rightarrow {}^2A_{1g}$ associated with square-planar [39] geometry around [Cu(II)L]. A red shift in the λ_{max} value of d–d band [40] with increase in the chain length between imine nitrogen has been observed. This red shift may be due to distortion from planar geometry as the chain length increases. Moderately intense band at 280–450 nm is associated with ligand to metal charge transfer. An intense band observed at 220–260 nm is associated with intra ligand transition.

3.3. *ESR spectra*

Solid-state ESR spectra of the copper(II) complexes recorded in the X-band region at room temperature show four lines [41] due to hyperfine splitting (nuclear spin 3/2).



Scheme 2. Schematic diagram for the synthesis of complexes.

Table 1. ESR and magnetic moment data of mononuclear copper(II) complexes.

		ESR		
Complexes	Magnetic moment μ_{eff} BM	$g_{\|\|}$	$g_{\perp}$	$A_{\|\|}$
[Cu(II)L^1]	1.72	2.31	2.09	160
[Cu(II)L^2]	1.73	2.28	2.10	169
[Cu(II)L^3]	1.73	2.30	2.12	171
[Cu(II)L^4]	1.75	2.21	2.14	180
[Cu(II)L^5]	1.76	2.19	2.16	186

The observed g values are less than 2.3 indicating considerable covalent character in the M–L bonds [42]. The ESR data of [Cu(II)L] complexes are given in table 1. $g_{||}$ and $g_{\perp}$ values indicate square-planar geometry. The absence of the half-field signal at 1600 G, corresponding to $DM = \pm 2$ transition, ruled out Cu–Cu interaction [43], consistent with mononuclear complexes. The hyperfine $A_{||}$ splitting falls in the range $150–165 \times 10^{-4}\,cm^{-1}$, indicative of an electron interacting with only one copper nucleus. The relation $g_{||} > g_{\perp}$ is typical of d^9 copper(II) complexes in a ground state

Table 2. Electrochemical[a] reduction (cathodic potential) and catecholase[b] activity data for the complexes.

Complexes	E_{pc}(*V vs.* Ag/AgCl)	Rate constant (k) $\times 10^3\,min^{-1}$ Catecholase activity
[Cu(II)L^1]	−1.55	3.66
[Cu(II)L^2]	−1.50	3.83
[Cu(II)L^3]	−1.43	4.29
[Cu(II)L^4]	−1.38	4.75
[Cu(II)L^5]	−1.15	5.22

[a]Measured by CV at $50\,mV\,s^{-1}$. *E vs.* Ag/AgCl condition, GC working electrode, and Ag/AgCl. Reference electrode: supporting electrolyte TBAP, concentration of complexes is $1\times10^{-1}\,mol\,L^{-1}$.
[b]Measured spectrophotometrically in DMF. Concentration of the complexes is $1\times10^{-3}\,mol\,L^{-1}$.

doublet with the unpaired electron in a d_{x2-y2} orbital [44–47]. The order $g_{||} > g_{\perp} > 2$ and the ESR parameters coincide with related systems, suggesting square-planar geometry [46]. In the axial spectra, the g values are related to the exchange interaction term G by the expression

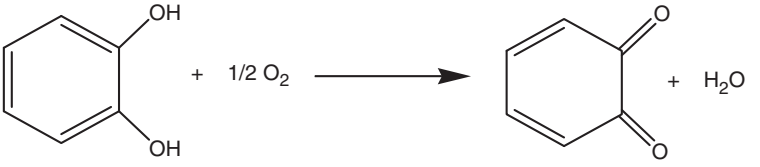
$$G = (g_{||} - 2.0023)/(g_{\perp} - 2.0023).$$

According to Hathaway and Tomlinson [46] if $G > 4.0$, exchange is negligible because the local tetragonal axes are aligned parallel or slightly misaligned. If $G < 4.0$, exchange is considerable and the local tetragonal axes are misaligned. The observed G values for the complexes are higher than 4.0.

Room temperature (at 298 K) magnetic moments of the complexes, determined by VSM, show μ_{eff} from 1.72 to 1.76 BM, close to the spin-only value of copper(II) [48]. The room temperature magnetic data of the copper(II) complexes do not provide conclusive evidence for the geometry; however, the electronic spectral data coupled with magnetic moment values indicate square-planar geometry for the copper(II) complexes.

3.4. *Electrochemistry of the complexes*

Electrochemical properties of the mononuclear complexes were studied by cyclic voltammetry in DMF containing TBAP as supporting electrolyte in the potential range −0.4 to −2.0 V. The electrochemical data of copper(II) complexes are given in table 2. Generally the electrochemical properties depend on chelate ring/size, axial ligation degree, distribution of unsaturation, and substitution pattern in the chelate ring. Each voltammogram shows a one electron irreversible reduction wave at −1.10 to −1.60 V. Controlled potential electrolysis carried out at 100 mV, more negative than the reduction wave, shows the consumption of one electron per molecule. The reduction potential shifts in the anodic direction for [Cu(II)L^1] to [Cu(II)L^5] from −1.55 V to −1.15 V, as the number of methylene groups increases [49, 50]. This shows that, as the number of methylene groups between the imine nitrogen (chain length) increases, the entire acyclic ring becomes more flexible, causing a distortion of the complexes, which stabilizes Cu(I).



Scheme 3. Oxidation of catechol.

4. Kinetic studies

4.1. *Oxidation of pyrocatechol (catecholase activity)*

The catecholase activity of the copper(II) complexes was carried out using pyrocatechol as the model substrate for the identification of functional models for metalloenzymes (scheme 3) [51]. For this purpose, 10^{-3} mol dm^{-3} solutions of complexes in DMF were treated with 100 equivalents of pyrocatechol in air. The course of the reaction was followed spectrophotometrically at 390 nm for 45 min at regular time intervals of 5 min. The slope was determined by the method of initial rates by monitoring the growth of the 390 nm band of the product *o*-quinone. A linear relationship for initial rate and the complex concentration obtained for the copper(II) complexes shows a first-order dependence on the complex concentration.

The plots of log $(A_\alpha/A_\alpha - A_t)$ *versus* time for catecholase activity of the copper(II) complexes are shown in figure 1. The inset of figure 1 shows the time-dependent growth of *o*-quinone chromophore in the presence of [Cu(II)L^5]. The observed initial rate constants for copper(II) complexes are given in table 2. [Cu(II)L^5] has higher catalytic activity (5.22×10^{-3} min^{-1}) than [Cu(II)L^4] (4.75×10^{-3} min^{-1}) which in turn is higher than [Cu(II)L^1] (3.66×10^{-3} min^{-1}). The order of activity of the complexes is shown below.

$$[Cu(II)L^5] > [Cu(II)L^4] > [Cu(II)L^3] > [Cu(II)L^2] > [Cu(II)L^1].$$

The rate of oxidation of catecholase to *o*-quinone increases as the chain length increases, due to the flexibility resulting from the distortion of the coordination sphere. Increase in the chain length causes a greater distortion of the geometry of the complexes, which favors the reaction.

4.2. *Antimicrobial activity*

4.2.1. Microorganisms. Microorganisms, *Staphylococcus aureus* (ATCC 12600), *Micrococcus luteus*, *Bacillus subtilis* (ATCC 6633), *Escherichia coli* (ATCC 11775), *Klebsiella pneumonia* (ATCC 13883), and *Candida albicans* (ATCC TW10637) were stored in a refrigerator at the microbiology lab, Centre for Herbal Sciences, and used for the antimicrobial study.

4.2.2. Reference and control. Tetracycline was chosen as the reference compound for all the bacterial species used, *S. aureus*, *M. luteus*, *B. subtilis*, *E. coli*, and *K. pneumonia*.

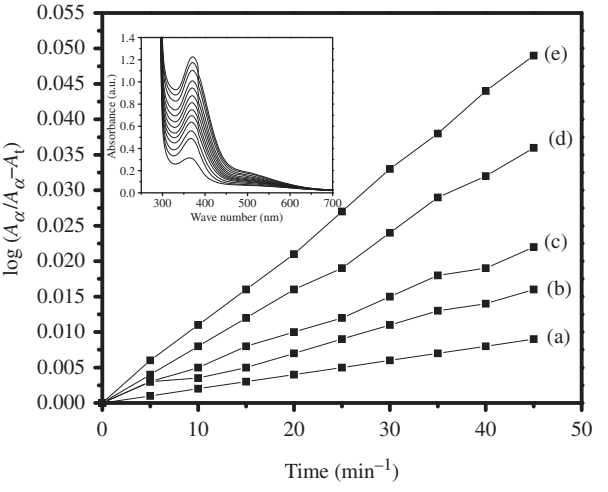


Figure 1. Catecholase activity of the copper(II) complexes: (a) [Cu(II)L^1], (b) [Cu(II)L^2], (c) [Cu(II)L^3], (d) [Cu(II)L^4], and (e) [Cu(II)L^5]. The inset is the time-dependent growth of the *o*-quinine chromophore in the presence of [Cu(II)L^5].

Itraconazole was chosen as the reference compound for *C. albicans*. The control consists of plates of solidifying agar onto which pure solvent was placed.

4.2.3. Agar preparation. Two types of agar were used, Mueller Hinton agar (MHA), (HIMEDIA-M173-500G) to make up the medium for bacteria and Sabouraud dextrose agar (SDA), (HIMEDIA-M063-500G) to make up the medium for fungi.

4.2.4. MHA (bacteria). MHA was purchased from HiMedia Laboratories Pvt. Ltd., Mumbai. MHA of 60.8 g was suspended in 1600 mL of distilled water in a 2 L flask, stirred, boiled to dissolve, and then autoclaved at 15 lbs and at 121°C for 15 min. The pH range was maintained between 7.0 and 7.5. Incubation was maintained at 37°C for 24 h.

4.2.5. SDA (fungi). SDA was purchased from HiMedia Laboratories Pvt. Ltd., Mumbai. SDA of 9.75 g was suspended in 150 mL of distilled water in a 250 mL flask, stirred, boiled to dissolve, and then autoclaved at 15 lbs and at 121°C for 15 min. The pH range was between 6.0 and 6.5. Incubation was maintained at 37°C for 24 h [52].

4.2.6. Results. The data for antimicrobial activity of the copper(II) complexes against six microorganisms are shown in table 3. [Cu(II)L^5] showed maximum zone of inhibition against *E. coli*, [Cu(II)L^2] showed maximum zone of inhibition against *M. luteus*, [Cu(II)L^4] showed maximum zone of inhibition against *B. subtilis*, [Cu(II)L^3] showed maximum zone of inhibition against *K. pneumoniae*, [Cu(II)L^4] showed maximum zone of inhibition against *S. aureus*, and [Cu(II)L^3] showed maximum zone of inhibition against *C. albicans*. All compounds inhibited the growth of

Table 3. Antibacterial and antifungal activities data of copper(II) complexes.

	Zone of inhibition (mm)																	
	E. coli			*M. luteus*			*B. subtilis*			*K. pneumoniae*			*S. aureus*			*C. albicans*		
Compound	250 μg	500 μg	750 μg	250 μg	500 μg	750 μg	250 μg	500 μg	750 μg	250 μg	500 μg	750 μg	250 μg	500 μg	750 μg	250 μg	500 μg	750 μg
[Cu(II)L^1]	–	12 ± 0.6	12 ± 0.8	12 ± 0.4	17 ± 0.4	19 ± 0.4	05 ± 0.2	22 ± 0.4	28 ± 0.4	–	16 ± 0.6	17 ± 0.2	–	22 ± 0.2	28 ± 0.4	–	05 ± 0.4	15 ± 0.4
[Cu(II)L^2]	11 ± 0.4	14 ± 0.4	16 ± 0.4	18 ± 0.4	20 ± 0.4	22 ± 0.4	–	25 ± 0.4	28 ± 0.8	–	15 ± 0.4	18 ± 0.4	03 ± 0.2	20 ± 0.4	25 ± 0.4	–	20 ± 0.4	22 ± 0.4
[Cu(II)L^3]	09 ± 0.4	13 ± 0.4	16 ± 0.3	11 ± 0.4	18 ± 0.4	20 ± 0.5	–	24 ± 0.5	28 ± 0.4	–	14 ± 0.4	20 ± 0.4	–	23 ± 0.4	28 ± 0.4	10 ± 0.4	20 ± 0.4	25 ± 0.4
[Cu(II)L^4]	11 ± 0.4	13 ± 0.5	18 ± 0.4	04 ± 0.4	05 ± 0.3	08 ± 0.3	–	25 ± 0.6	30 ± 0.5	–	08 ± 0.3	10 ± 0.4	05 ± 0.2	25 ± 0.4	30 ± 0.6	–	13 ± 0.4	20 ± 0.4
[Cu(II)L^5]	12 ± 0.5	17 ± 0.4	21 ± 0.5	12 ± 0.3	12 ± 0.4	18 ± 0.4	03 ± 0.2	20 ± 0.5	25 ± 0.4	05 ± 0.3	12 ± 0.4	15 ± 0.5	04 ± 0.2	20 ± 0.4	25 ± 0.5	–	18 ± 0.4	23 ± 0.4
Std-1		22 ± 0.5			22 ± 0.4			35 ± 0.8			21 ± 0.4			35 ± 0.8			–	
Std-2		–			–			–			–			–			27 ± 0.4	

Std-1 = tetracycline (40 μg), Std-2 = itraconazole (40 μg).

microorganisms with values ranging between 250 and 750 $\mu g\,mL^{-1}$ [53]. This difference in inhibition may be due to the differences between the cell structures of bacteria and does not depend upon the number of alkyl group present in the complex. While the cell walls of fungi contain chitin, the cell walls of bacteria contain murein [54]. In addition, fungi contain ergosterol in their cell membranes instead of the cholesterol found in the cell membranes of animals [55, 56]. The difference in antibacterial activity of copper complexes probably is associated with ligand type and its space distribution around the complex core [57].

5. Conclusion

Five Schiff-base copper(II) complexes have been synthesized and their coordination chemistry and antibacterial activity have been investigated. The electronic spectra of [Cu(II)L] indicate square-planar geometry, and there is a red shift due to the increase in chain length. Cyclic voltammograms exhibit one-electron quasi-reversible process with reduction potential shifting anodically on increasing chain length. All [Cu(II)L] complexes show good catecholase activity. Increase in chain length causes a greater distortion of the geometry of the complexes which favors higher rate of reaction. The complexes showed remarkable activity against all microorganisms tested. [Cu(II)L^4] has the highest activity against *B. subtilis* and *S. aureus*. [Cu(II)L^5] has the highest activity against *C. albicans*. All these studies of the complexes agree well with established trends.

Supplementary material

The ESR spectrum of complex CuL^1 and the cyclic voltammograms of complexes CuL^1, CuL^2, CuL^3, CuL^4, and CuL^5 are given as supplementary material.

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