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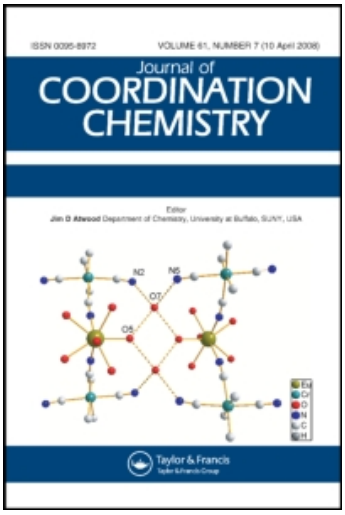

Journal of Coordination Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455674

Synthesis, characterization, and biological activity studies on (*E*)-*N*′-[2-hydroxy-1,2-di(pyridin-2-yl)ethylidine]aroyl hydrazides and their copper(II) complexes

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Online publication date: 08 March 2010

To cite this Article Karbouj, Reem , El-Dissouky, Ali , Jeragh, Bakir and Al-Saleh, Esmaeil(2010) 'Synthesis, characterization, and biological activity studies on (*E*)-*N*′-[2-hydroxy-1,2-di(pyridin-2-yl)ethylidine]aroyl hydrazides and their copper(II) complexes', Journal of Coordination Chemistry, 63: 5, 868 — 883
To link to this Article: DOI: 10.1080/00958971003645946
URL: http://dx.doi.org/10.1080/00958971003645946

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Journal of Coordination Chemistry
Vol. 63, No. 5, 10 March 2010, 868–883

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Synthesis, characterization, and biological activity studies on (*E*)-*N*′-[2-hydroxy-1,2-di(pyridin-2-yl)ethylidine]aroyl hydrazides and their copper(II) complexes

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(*Received 18 June 2009; in final form 21 October 2009*)

The reaction of copper(II) salts with (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)aroyl hydrazide (H_2L^1, H_2L^2, H_3L^3) or (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene) isonicotinohydrazide (H_2L^4) afforded the complexes $[(L)Cu(H_2O)_3]$, $[(H_2L)Cu(OAc)(H_2O)]$, $[(HL)Cu(OAc)]_n$, $[(H_2L)Cu(H_2O)](ClO_4)_2$ and $[(H_2L)Cu(OAc)(H_2O)]$, where $n = 1$ or 2 and L is the dinegative ion of the ligands. The ligands and their complexes are characterized by elemental analyses, spectral (IR, NMR, electronic, and ESR) and magnetic studies. The FT-IR indicates that the ligands are neutral or anionic polydentate. The number of the coordinating centers depends on the nature of the metal used and the reaction conditions. The room temperature magnetic moment values, electronic spectra and ESR data indicate square planar, trigonal bipyramidal, square pyramidal, and distorted octahedral ligand fields around copper(II). Thermal decomposition of the complexes was monitored by TG and DTG under N_2 and the thermal decomposition mechanisms are given. The compounds were screened for their antimicrobial activities on some Gram-positive and Gram-negative bacterial species. The free ligands are inactive against all studied bacteria. The complexes have variable activity with the most active $[(H_2L)Cu(H_2O)](ClO_4)_2$, where H_2L is H_2L^1 or H_2L^2. The minimum inhibition concentrations for these two complexes were determined. These biological activity results are related to the structures of the compounds.

Keywords: Aroyl hydrazones; Pyridoin; Complexes; Spectra; Thermal analysis; Biological activity

1. Introduction

Hydrazones are extensively used for synthetic and analytical chemistry, employed in polymer industry (as plasticizing agents, antioxidants, and polymerization inhibitors) and also in the pharmaceutical industry [1–3] with interesting biological properties [4, 5] as anti-inflammatory [6], analgesic [7], and antipyretic [8, 9]. Hydrazones have also been found useful as anti-malaria drugs [10] and for macrophage migration inhibitory factor

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ISSN 0095-8972 print/ISSN 1029-0389 online © 2010 Taylor & Francis
DOI: 10.1080/00958971003645946

tautomerase activity [11]. N-(phenylpyridin-2-yl methylene)-N′-pyridin-2-ylhydrazine and radical scavengers have been reported as promising inhibitors of RR, which is also reported to inhibit the proliferation of the hormone-dependent human mammary tumor cell line MDA-MB231. 2′-Quinolinyl-hydrazones have inhibitory effects on proliferation of Burkitt's lymphoma cells. If metal ions are combined with active drugs, new powerful, multitherapic agents may be obtained as in case of $[Cu_2(indomethacin)_4(DMF)_2]$. Hydrazones are polydentate heterocycles containing Schiff bases with different donors toward various metal ions [12–18]. Their complexes have oxygen uptake [19], oxidative catalysis [20], magnetic behavior [21–28], and biological activities [29–35]. Copper(II) compounds containing heterocyclic bases have diverse applications following the discovery of the chemical nuclease activity of $[Cu(phen)_2]^{2+}$ [31]. The antimicrobial and antiproliferative activities of Schiff base Cu(II) complexes are not attributed to the properties of the metal center or to coordinated ligand alone [34–41] but to the physicochemical, structural, and electronic properties that arise due to the coordination. In continuation of our research on polydentate chelates containing heterocyclic nitrogen of copper(II), we (1) synthesize and characterize and (2) study the thermal decomposition and biological activity of some aroyl hydrazones of α-pyridoin and their copper(II) complexes.

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2. Experimental

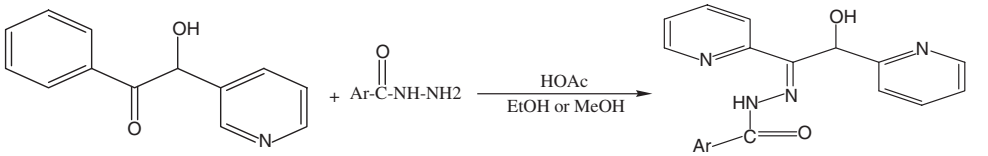
2.1. *Synthesis of the organic compounds*

2.1.1. (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)benzohydrazide (H_2L^1), (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)methylbenzohydrazide, (H_2L^2), (*E*)-2-hydroxy-N-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)benzohydrazide (H_3L^3), and (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene) isonicotinohydrazide (H_2L^4). A methanolic solution (30 mL) of α-pyridoin (0.214 g, 1.0 mM) was added to a solution (25 mL) of benzoylhydrazide (0.136 g, 1.0 mM) or 4-methylbenzoylhydrazide (0.15 g, 1.0 mM), 2-hydroxybenzoylhydrazide (0.15 g, 1.0 mM of isonicotinoylhydrazide (0.137 g, 1.0 mM) in methanol or ethanol. The mixture was stirred for 1 h, then 10 drops of acetic acid were added and stirred for 48–72 h at room temperature. The cream-colored precipitates of H_2L^3 and H_2L^4 were filtered off, washed with cold methanol, diethyl ether, recrystallized from EtOH and dried *in vacuo* over anhydrous $CaCl_2$.

For H_2L^1 and H_2L^2, the solvent was evaporated with a rotavap until dryness and methanol (15 mL) was added, poured on a water–ice mixture with stirring and the resultant solution was kept overnight in a refrigerator. The cream-colored precipitate formed in each case was filtered off, washed several times with cold methanol, diethyl ether, recrystallized from CH_2Cl_2 and MeOH, respectively, and dried *in vacuo* over anhydrous $CaCl_2$. The syntheses of the aroyl hydrazones are shown in scheme 1.

2.2. *Synthesis of copper(II) complexes*

The copper(II) complexes were synthesized according to the following general method: a mixture of ethanolic or methanolic solution (25 mL) of (benzoyl-, *p*-methylbenzoyl,



Ar = C_6H_5- (H_2L^1), *p*-MeC_6H_4- (H_2L^2), *o*-OH-C_6H_4- (H_3L^3) or C_5H_4N-(H_2L^4)

Scheme 1. Synthesis of the aroyl hydrazones of α-pyridoin. Ar = C_6H_5–(H_2L^1), *p*-MeC_6H_4–(H_2L^2), *o*-OH–C_6H_4–(H_3L^3) or C_5H_4N–(H_2L^4).

o-hydroxybenzoyl, or isonicotinoyl hydrazide) and $Cu(OAc)_2 \cdot H_2O$ or $Cu(ClO_4)_2 \cdot 6H_2O$ (1.0 or 0.5 mM) was refluxed under stirring for 15–20 min. To this mixture α-pyridoin (1.0 mM) in the same solvent (15 mL) was added dropwise with stirring. The resultant solution in some cases was filtered off to remove the insoluble reactants and the filtrate was refluxed under stirring for 5–6 h and then cooled to room temperature. The solid precipitate was then isolated by filtration, washed with hot methanol, diethyl ether and dried *in vacuo* over P_4O_{10}.

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2.3. *Biological activity studies*

The biological activity of the ligands and their complexes are tested by two methods as given in following sections.

2.3.1. Well diffusion method. The inhibitory effects were examined by the well diffusion method [42]. Preliminary experiments were conducted using five bacteria methicillin resistant *Staphylococcus aureus* (MRSA), *Bacillus* sp., *E. coli* DH5α, *Pseudomonas aeruginosa*, and *Salmonella* sp. as a quick method to examine the inhibitory effects of the synthesized chemical compounds on all bacterial genera. Different well diameters were used by Bennett *et al.* [43] and Lachica *et al.* [44]. The diameter of the well is a factor of the volume of the test substrate, usually ranging between 50 and 100 µL. We used 50 µL of test substrate to be placed in 0.2 cm diameter well with height of 7.5 mm. This test was expected to show which bacterial genera were likely to be inhibited and consequently, growth, and minimum inhibitory concentration (MIC) will be used to test the susceptible bacterial genera.

2.3.2. Growth studies and determination of minimum inhibitory concentration. The effects of the synthesized chemical compounds on the growth of 19 strains of MRSA that showed inhibition with the well diffusion method were determined spectrophotometrically. Fresh bacterial cultures were prepared by growing bacteria on nutrient agar (NA) plates. After 24 h incubation at $37.0 \pm 0.1^{\circ}C$, grown bacterial biomass was collected in sterile tubes containing sterile phosphate buffer (pH 7). The optical density (OD) of the bacterial suspension was adjusted to 1.0 (600 nm). Growth experiments were conducted using a bioscreen automated system. Samples were transferred to the wells of honeycomb plates. Each well contained bacterial suspension (50 µL), sterile nutrient broth (50 µL), test chemical compound (100 µL), and the total volume was adjusted to 400 µL with sterile water. For the controls, no chemical compound

was added; instead 50 μL of sterile phosphate buffer was added. Plates were placed in the bioscreen system, temperature was adjusted to 37 ± 0.10°C and the experiments were run. All experiments were conducted in triplicate. The mean and standard deviation of all experiments were calculated, growth curves were plotted, and growth rates were calculated. The MIC for chemical compounds was determined as the lowest concentration that inhibited the growth of the bacteria. The slope of the linear part of the bacterial growth curve was calculated and considered as the growth rate of the bacteria. It is not possible to determine the standard deviations of MIC values because according to the method used, different concentrations of test chemical were tested and the lowest concentration that completely inhibited the bacterial growth was the MIC value. Thus, the MIC value is a concentration of a test compound that inhibits the bacterial growth, so, even when the experiment is repeated, the same MIC value will be determined, thus, statistical analysis cannot be applied.

2.4. *Elemental analysis and physical measurements*

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CHNS analyses were obtained using a LECO CHNS-932 Elemental Analyzer. FT-IR spectra of KBr discs of the organic ligands and their complexes were performed using a Perkin–Elmer System 2000 FT-IR spectrophotometer. Calibration of wave numbers was made with a polystyrene film. Nuclear magnetic resonance (NMR) spectra of organic ligands were performed with a Bruker DPX 400, 400 MHz super-conducting NMR spectrometer with TMS as a standard. Electronic spectra of the ligands and their complexes either as Nujol mull or solution were accomplished with a Varian Cary-5 double beam spectrophotometer. Thermal analyses (TG and DTG) were carried out on Shimadzu Thermal system 50 consisting of TGA-50 and DTA-50 from room temperature to 1000°C under dinitrogen with heating rate of $10°C\,min^{-1}$. ESR spectra for samples of copper complexes were measured on a Radiopan Varian spectrometer T 100.0000 kHz and at different G modulation amplitude with a rectangular TE 102 cavity and 100 kHz modulation field. Resonance conditions were found at *ca* 9.7 GHz (X-band) at room temperature. The field was calibrated with a powder of diphenylpicrylhydrazyl free radical (DPPH; $g = 2.0037$) [45]. The room temperature magnetic susceptibility values were determined by a Faraday balance and diamagnetic corrections were made using Pascal's constants. The molar conductivities were measured for 1.00×10^{-3} DMSO solutions at 25 ± 1°C using a Jenway 4020 conductivity meter.

3. Results and discussion

Reaction of 2-hydroxy-1,2-(dipyridine-2-yl)ethane-1-one, (α-pyridoin), with benzoylhydrazine, 4-methylbenzoylhydrazine, 2-hydroxy-benzoylhydrazine or isonictonoyl-hydrazine in presence of few drops of acetic acid (scheme 1) gave (*E*)-N-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)benzohydrazide, (*E*)-N-(2-hydroxy-1,2-di (pyridin-2-yl)ethylidene)methylbenzohydrazide, (*E*)-2-hydroxy-N-(2-hydroxy-1-,2-di (pyridin-2-yl)ethylidene)benzohydrazide and (*E*)-N-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)isonicotinohydrazide abbreviated as H_2L^1, H_2L^2, H_3L^3, or H_2L^4, respectively.

H_2L^1, H_2L^2, H_3L^3, or H_2L^4 are air stable with various solubility in most organic solvents but insoluble in water. (1) H_2L^1 is soluble in DMF, DMSO, and CH_2Cl_2, but sparingly soluble in ethanol and methanol, (2) H_2L^2 is soluble in EtOH, MeOH, DMF, DMSO, and slightly soluble in CH_2Cl_2, (3) H_3L^3 is soluble in DMF, DMSO and sparingly soluble in EtOH, MeOH, and CH_2Cl_2 and (4) H_2L^4 is soluble in DMF, DMSO and slightly soluble in MeOH and CH_2Cl_2.

Reaction of these ligands with $Cu(OAc)_2 \cdot H_2O$ or $Cu(ClO_4)_2 \cdot 6H_2O$ in either 1 : 1 or 1 : 2 (Cu(II):H_nL, $n = 2$ or 3) gave products similar to those synthesized by *in situ* (mixture of α-pyridoin, corresponding aroyl hydrazine and the corresponding metal salt in the appropriate solvent as given in the experimental section). The reaction products are dependent on the nature of the ligand, metal salt, and mole ratio. The complexes are air stable and insoluble in most organic solvents and water but soluble in coordinating solvents such as Py, DMF, or DMSO. The purity of the ligands and complexes are proved utilizing TLC, melting point, and elemental analysis. The formulation of the complexes was based on their elemental analyses and molar conductivity values (Supplementary material).

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3.1. *Characterization of the organic ligands*

3.1.1. Infrared spectra of organic ligands. The main IR bands with their tentative assignments in "Supplementary material" displays a medium-strong band at 3162–3216 cm^{-1} due to $\nu_{(NH)}$ of the hydrazone, which may be involved in NH···O hydrogen bonding [46–49]. This is confirmed by a medium intensity band at 1475–1489 cm^{-1} characteristic of $\delta_{(NH)}$. The spectra of all ligands show a medium-weak broad band at 3422–3464 cm^{-1}, assigned to $\nu_{(OH)}$ of the −CH–OH which is confirmed by weak and medium bands at 1210–1212 and 1040–1080 cm^{-1} due to $\delta_{(OH)}$ and $\nu_{(C-O)}$. The broad band at 3422–3464 cm^{-1} is evidence for O–H···N hydrogen bonding. Spectra of H_3L^3 exhibit additional bands at 1236 and 646 cm^{-1} assigned as $\nu_{(C-O)}$ of phenol and hydrogen bonded out of plane, $\delta_{(OH)}$, respectively. The very strong bands at 1645–1684 and 1578–1607 cm^{-1} in spectra of the hydrazones are assigned to $\nu_{(C=O)}$ and $\nu_{(C=N)}$. The relative lower energy of these bands could be taken as evidence for C=O and C=N hydrogen bonding. The lower energy of $\nu_{(C=N)}$ could also be attributed to conjugation with the neighboring pyridine [47–49]. The medium-strong band at 1522–1545 cm^{-1} is assigned to $\nu_{(C=N)}$ of pyridine. The pyridine ring breathing is a weak band at 602–612 cm^{-1} [50–53]. Spectra of all ligands display a weak band at 992–996 cm^{-1} due to $\nu_{(N-N)}$ [50–53]. IR data suggest keto-form with hydrogen bonding in the solid state.

3.1.2. ^{1}H-NMR spectra of the ligands. ^{1}H-NMR spectra of the free ligands as d_6-DMSO solutions in presence and absence of D_2O are given in "Supplementary material". A weak signal at δ 15.94–16.14 (1H) ppm for all ligands disappeared in presence of D_2O and is assigned to NH involved in hydrogen bonding. The spectra exhibit a signal (disappearing in presence of D_2O) at δ 11.87 (1H), 11.79 (1H), and 12.00 ppm (1H) for H_2L^1, H_2L^2, and H_2L^4, respectively. The spectrum of H_3L^3 exhibits two signals (disappearing in the presence of D_2O) at δ 14.89 (1H) and 12.03 (1H) ppm. Accordingly, these signals are assigned to the hydrogen bonded −OH protons. The aryl

protons appeared in their usual position at δ 6.86–7.97 ppm and pyridine protons at δ 7.46–8.69 ppm. The spectrum of H_2L^2 exhibits additional signal δ 2.52 ppm (3H) characteristic of methyl. Signals at δ 5.23(1H), 4.26(1H), 5.70(1H), and 5.35(1H) ppm in the spectra of H_2L^1, H_2L^2, H_3L^3, and H_2L^4, respectively, are assigned to $-CH-$. The number of protons assigned from the ^1H NMR is consistent with the formula and elemental analysis.

3.2. *Characterization of the complexes*

3.2.1. Infrared spectra. The FT-IR spectra of the complexes are recorded as KBr discs and main infrared bands with their tentative assignments are given in "Supplementary material".

3.2.1.1. *$[L^1Cu(H_2O)_3]$, $[(H_2L^3)Cu(OAc)(H_2O)]$, $[(HL^3)Cu(H_2O)]\cdot 0.5H_2O$, $[(HL^4)Cu(OAc)]$ and $[(HL^4)Cu(OAc)]_2$.* Very strong absorptions at 1645–1684 cm^{-1} due to $\nu_{(C=O)}$ and medium-strong bands at 1578–1607 cm^{-1} due to $\nu_{(C=N)}$ of azomethine in the free ligands disappear in the complexes and two new bands at 1622–1630 and 1343–1410 cm^{-1} due to the conjugate system, $\nu_{(-C=N-N=C-}$and $\nu_{(C-O)}$, appear [54, 55]. The band due to $\nu_{(C=N)}$ undergoes a bathochromic shift and $\nu_{(N-N)}$ exhibits a hypsochromic shift, indicating coordination of one azomethine-N and a deprotonated enolato-O to copper [54, 55]. Pyridine bands at 1522–1545 cm^{-1} due to $\nu_{(C=N)}$ and at 602–612 cm^{-1} due to $\delta_{(py)}$ shift to higher wave numbers in some cases, indicating coordination and/or their nitrogens are involved in inter- and/or intramolecular hydrogen bonding. Bands of $\nu_{(NH)}$ (3176–3216 cm^{-1} in the free ligands) disappear supporting formation of the conjugate system –C=N–N=C– and enolization of the hydrazone carbonyl during complex formation. Absorptions at 3336–3458 cm^{-1} in all complexes could be attributed to H_2O and/or intra- or intermolecular hydrogen bonds. For $[(HL^3)Cu(H_2O)]\cdot 0.5H_2O$ and $[L^1Cu(H_2O)_3]$, the ligands are dibasic tridentate, bonded to copper through one pyridine nitrogen, one azomethine nitrogen, and enolato oxygen. The spectrum of $[(H_2L^3)Cu(H_2O)(OAc)]$ displays bands at 1602 and 1364 cm^{-1} characteristic of acetato ν_{asym} and ν_{sym}, respectively, with $\Delta\nu = 237\ cm^{-1}$ consistent with monodentate acetate. Bands at 1533 and 1374 cm^{-1} for $[(HL^4)Cu(OAc)]$ and at 1492 and 1373 cm^{-1} for $[(HL^4)Cu(OAc)]_2$ are due to acetato ν_{asym} and ν_{sym}, with $\Delta\nu = 159$ and $119\ cm^{-1}$, respectively, characteristic of a bidentate and bidentate bridging acetate, respectively [55, 56]. The spectral data suggest tridentate monobasic ligand bonded to the copper(II) *via* one pyridine nitrogen, azomethine nitrogen and enolato oxygen for $[(HL^4)Cu(OAc)]$, while monobasic bidentate without pyridine bonding to copper(II) for $[(HL^4)Cu(OAc)]_2$.

3.2.1.2. *$[(H_2L^1)Cu(H_2O)](ClO_4)_2$, $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ and $[(H_3L^3)Cu(H_2O)](ClO_4)_2$.* The infrared spectra of perchlorate containing complexes display a very strong split band at 1055–1142 cm^{-1} in addition to a weak one at 931–936 cm^{-1} due to ν_3 and ν_4, characteristic of ionic perchlorate [49–51]. The strong absorption due to $\nu_{C=O}$ in the free ligands shifts to lower wave number by *ca* 15–35 cm^{-1}, suggesting bonding to copper; $\nu_{(C=N)}$ of azomethine and of pyridine are shifted to higher wave number by *ca* 5–19 cm^{-1} and *ca* 7–11 cm^{-1}, respectively,

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indicating they may or may not bond to copper and that the conjugate system –C=N–N=C– is not formed. This is supported by the medium band at 3169–3237 cm^{-1} characteristic of $\nu_{(NH)}$ of the amide.

3.3. *Electronic ESR spectra and magnetic data for copper(II) complexes*

The room temperature magnetic moments of copper(II) complexes (Supplementary material) are in the range 1.81–2.37 μB, except $[(HL^4)Cu(OAc)]_2$ with 1.48 μB. These values are characteristic of magnetically dilute copper(II) complexes. The high magnetic moment values greater than the spin only value of 1.73 μB imply the presence of a low lying excited term which is able to mix orbital angular momentum with the spin angular momentum of the ground state [57–60], quite common for copper(II) complexes with distorted ligand fields.

The lower magnetic moment value for $[(HL^4)Cu(OAc)]_2$ (1.48 BM) indicates a magnetic exchange interaction between copper centers attributed to two Cu(II) ions within 6 Å of each other. IR of $[(HL^4)Cu(OAc)]_2$ show the acetates to be bidentate bridging, therefore, reduction of the magnetic moment can be explained on the basis of formation of a dimer through acetate bridge.

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The electronic spectral data of the copper(II) complexes either as Nujol mull and/or DMF solutions are collected in table 1. The electronic spectrum of $[(HL^4)Cu(OAc)]$ displays two bands at 749 and 989 nm (13350 and 10110 cm^{-1} with $\Delta\nu = 3240\ cm^{-1}$). The spectral features and the separation energy between these two bands could be accounted for by trigonal bipyramidal copper(II) [61, 62]. Accordingly, these two bands are assigned to $d_{xz(yz)} \rightarrow d_{z^2}$ and $d_{x^2y^2} \rightarrow d_{z^2}$ transitions, respectively [52–55]. The electronic spectrum of $[(HL^4)Cu(OAc)]$ as DMF solution displays bands at 617 and 805 nm characteristic of copper(II) in a distorted square pyramidal ligand field. This means there is geometrical change from trigonal bipyramidal structure in solid state to square pyramidal in solution and both geometrical shapes exist in equilibrium in solution. Assuming approximately C_{4v} symmetry for this complex, the absorption at 617 nm can be considered to consist of two bands due to $^2B_1 \rightarrow {}^2E_1$ and $^2B_1 \rightarrow {}^2B_1$ transitions, while the absorption at 805 nm is due to $^2B_1 \rightarrow {}^2A_1$ [61–64]. The X-band ESR spectrum of polycrystalline sample at room temperature (Supplementary material) exhibits axial shape with $g_\perp > g_\parallel$ (table 1), suggesting d_{z^2} ground state. Accordingly, the ESR data support the trigonal bipyramidal structure in accord with the electronic spectral data. Therefore, the structure in figure 1 could be assumed for the complex in the solid state.

The electronic spectra of $[(HL^4)Cu(OAc)]_2$ display a broad band at 702 and 755 nm as nujol mull and DMF solution, respectively. The spectral shape and energy are consistent with data reported for square-planar copper(II) complexes. Based on the magnetic moment of 1.48, the bidentate bridging nature of the acetato group ($\Delta\nu = 119\ cm^{-1}$) and the monobasic bidentate ligand, the square-planar structure (figure 2), can be attained through bridging acetate leading to magnetic exchange interaction.

The X-band ESR spectrum at room temperature has $g_\parallel = 2.29$ and $g_\perp = 2.07$ in accord with $d_{x^2-y^2}$ ground state. In addition the spectrum exhibits a weak signal at half field with $g = 4.19$, characteristic of dimeric copper(II) complexes, supporting the IR and electronic spectral and magnetic data.

Table 1. Electronic (λ_{max}, nm) and ESR spectral data of copper(II) complexes.

Complex	State	Electronic spectral data	$g_{parallel;}$	$g_{\perp}$	$g_{av.}$	G	g^a
$[(L^1)Cu(H_2O)_3]$	Nujol DMF	410, 718 324, 791	2.26	2.06	2.13	4.33	
$[(H_2L^1)Cu(H_2O)](ClO_4)_2$	Nujol DMF	524, 793 388, 412, 531, 803	2.25	2.06	2.12	4.16	
$[(H_2L^2)Cu(H_2O)](ClO_4)_2$	DMF	390, 410, 671, 826	2.25	2.06	2.12	4.16	
$[(H_2L^3)Cu(OAc)(H_2O)]$	Nujol DMF	369, 501, 825 447, 525, 794			2.11		
$[(HL^3)Cu(H_2O)].0.5H_2O$	Nujol DMF	458, 551, 825 361, 451, 525, 794			2.10		
$[(H_3L^3)Cu(H_2O)](ClO_4)_2$	Nujol DMF	550 372, 519	2.28	2.06	2.30	4.67	
$[(HL^4)Cu(OAc)]^b$	Nujol DMF	749, 989 617, 805	2.02	2.23	2.16		
$[(HL^4)Cu(OAc)]_2^d$	Nujol DMF	410, 702 388, 775	2.29	2.07	2.14	4.14	4.19

[a]molar conductivity ($\Omega^{-1}\,cm^2\,mol^{-1}$) of 1.00×10^{-3} M DMSO solution.
[b] and [c] have the same stochiometry but different structures.

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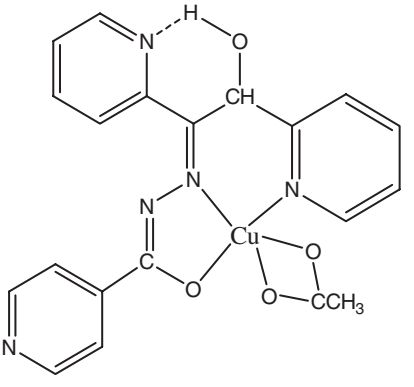

Figure 1. Structure of $[(HL^4)Cu(OAc)]$.

The electronic spectrum of $[(H_2L^3)Cu(OAc)(H2O)]$ displays d–d bands at 551 and 825 nm in Nujol mull and at 525 and 794 nm as DMF solution, similar to data reported for five-coordinate copper(II) complexes in a square pyramidal environment [57–61]. The square-based pyramidal structure (figure 3) is assumed rather than the trigonal bipyramidal, because of the band position and band separation $\Delta\nu = 6050$ and $6400\,cm^{-1}$ in solid and solution, respectively (the value of $\Delta\nu$ for trigonal bipyramidal is less than $3000\,cm^{-1}$) [56–61]. The higher energy positions of the bands in solution could be attributed to solvation of the complex and/or solvent substitution with H_2O and/or OAc.

The X-band ESR spectrum of the solid complex at room temperature shows only one broad signal with g of 2.11 (table 1). This broad unresolved signal could be

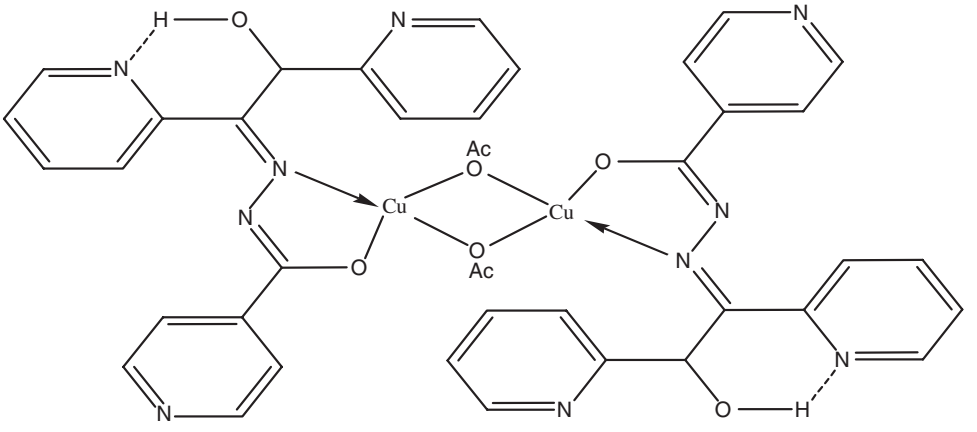

Figure 2. Structure of $[(HL^4)Cu(OAc)]_2$.

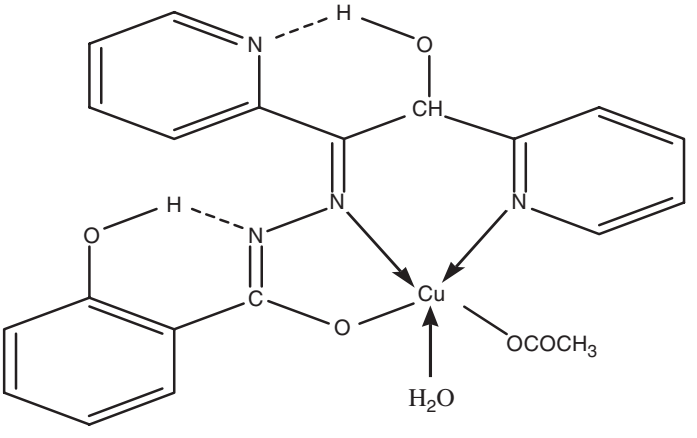

Figure 3. Structure of $[(H_2L^3)Cu(OAc)(H_2O)]$.

attributed to super exchange interaction between copper(II) centers with somewhat long relaxation time; the inhomogeneity of the signal is due to anisotropic exchange interaction.

The Nujol mull electronic spectra of $[(H_2L^1)Cu(H_2O)](ClO_4)_2$, $[(H_2L^2)Cu(H_2O)](ClO_4)_2$, and $[(HL^3)Cu(H_2O)] \cdot 0.5H_2O$ display bands at 525, 793 nm, 531, 667, 829 nm, and 512, 601, 825 nm, respectively. These spectral features are consistent with square-planar copper(II) complexes with band assignments $^2B_{1g} \rightarrow {}^2E_g$ (531–525 nm), $^2B_{1g} \rightarrow {}^2B_{2g}$ (667–601 nm), and $^2B_{1g} \rightarrow {}^2A_{1g}$ (829–793 nm). The spectra of their DMF solutions suggest a solvent–solute interaction while the square-planar structure is maintained.

The Nujol mull electronic spectrum of $[(H_3L^3)Cu(H_2O)](ClO_4)_2$ displays only a band at 501 nm while only one broad band at 519 nm was observed in its DMF solution.

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These data are similar to the data obtained for many copper(II) complexes in a square-planar ligand field.

Room temperature X-band ESR spectra of solid (Supplementary material and table 1) $[(H_2L^1)Cu(H_2O)](ClO_4)_2$, $[(H_2L^2)Cu(H_2O)](ClO_4)_2$, and $[(H_3L^3)Cu(H_2O)](ClO_4)_2$ are axial with $g_\parallel > g_\perp$ suggesting $d_{x^2-y^2}$ ground state. The spectrum of $[(HL^3)Cu(H_2O)]\cdot 0.5H_2O$ gave only one signal with $g = 2.10$. The shape of the spectrum and the deviation of g from 2.0023 support $d_{x^2-y^2}$ ground state. The extent of interaction between the neighboring coppers in the solid state can be measured by using [65]

$$G = \frac{g_\parallel - 2}{g_\perp - 2}$$

where G is the extent of the exchange interaction between copper centers in the solid state. When $G \geq 4$, the exchange interaction between copper centers in the solid state is neglected, while $G < 4$ indicates a considerable exchange interaction. The calculated values are 4.16, 4.16, and 4.67 for $[(H_2L^1)Cu(H_2O)](ClO_4)_2$, $[(H_2L^2)Cu(H_2O)](ClO_4)_2$, and $[(H_3L^3)Cu(H_2O)](ClO_4)_2$, respectively, indicating the absence of exchange interaction between the copper centers in the solid state and that the local tetragonal axes are aligned parallel or slightly misaligned. Based on the previous spectral and magnetic studies, the structures in figure 4 are assumed for these complexes.

The Nujol mull and DMF solution electronic spectra $[L^1Cu(H_2O)_3]$ (table 1) are consistent with either square planar or tetragonally distorted octahedral. The room temperature X-band ESR spectrum for the polycrystalline sample displays axial parameters $g_\parallel = 2.26$ and $g_\perp = 2.06$ with $g_{av.} = 2.13$, characteristics of $d_{x^2-y^2}$ ground state. The G-parameter value of 4.33 suggests a negligible direct copper–copper exchange interaction in the solid state. The spectrum shows a hyperfine structure in the parallel region due to coupling of the unpaired electron with the nuclear spin ($I = 3/2$) of both ^{63}Cu and ^{65}Cu isotopes. However, such splitting in the $g_\perp$ region is not observed due to the unresolved ligand hyperfine interaction at room temperature. The hyperfine line splitting factor of 90 G is obtained from the spectrum. The value is small consistent with strong distortion from planarity. In general, the empirical factor $f = g_\parallel / A_\parallel$ is an index of the tetragonal distortion or the distortion toward tetrahedral, and calculated to be 251 cm^{-1}. The value is higher than or equal to 150 cm^{-1}, the higher limit of planar complexes and indicates a strong distortion (tetrahedral or tetragonal) due to the flexible structure. In general, the distortion from the planarity toward the tetragonally distorted octahedral or tetrahedral structure results in decrease in $A_\parallel$ and increase in $g_\parallel$ as shown in a number of synthetic and biologically active examples involving copper(II) [66]; the value of $A_\parallel$ is small and in line with that of strongly distorted complex, especially tetrahedral. The value of the in-planar π bonding parameter α^2 can be estimated from the expression $\alpha^2 = A_\parallel / 0.036 + (g_\parallel - 2.0023) + 3/7\ (g_\perp - 2.0023) + 0.04$; 0.57 is consistent with mainly covalent copper-in-plane-ligand bonding, in agreement with results obtained for $g_\parallel < 2.30$. Based on the previous spectral and magnetic studies, the structure in figure 5 could be assumed for this complex.

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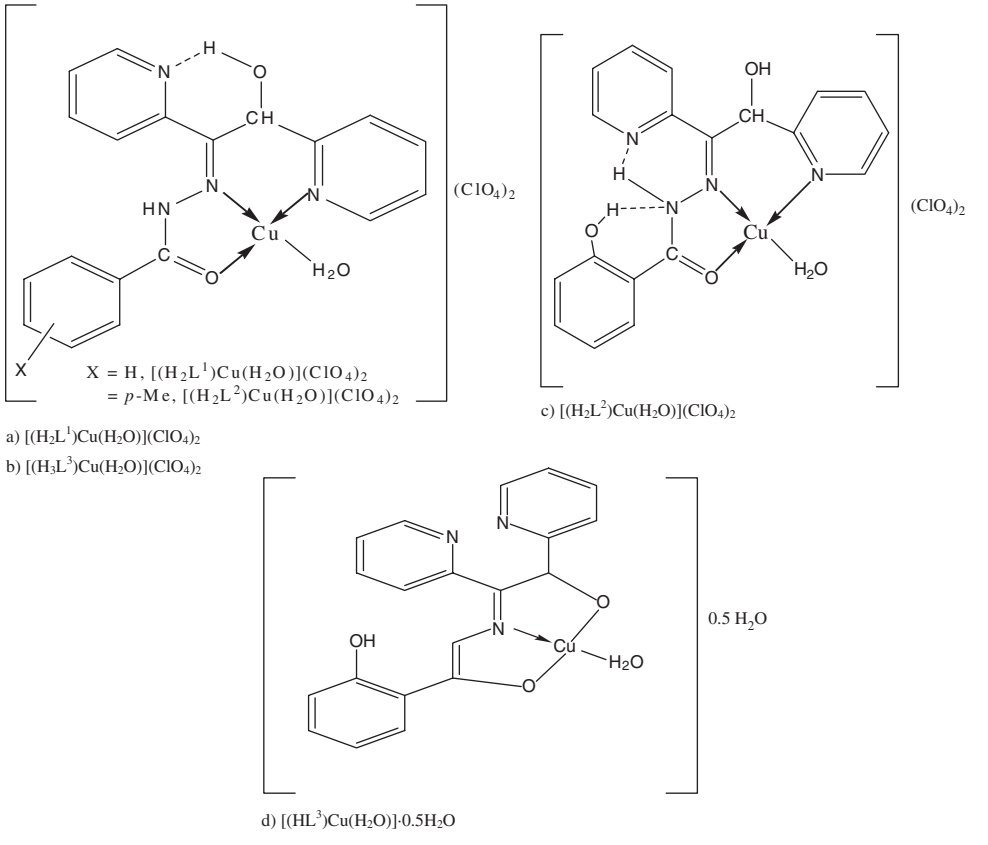

Figure 4. (a) $[(H_2L^1)Cu(H_2O)](ClO_4)_2$; (b) $[(H_3L^3)Cu(H_2O)](ClO_4)_2$; (c) $[(H_2L^2)Cu(H_2O)](ClO_4)_2$; and (d) $[(HL^3)Cu(H_2O)]\cdot 0.5H_2O$.

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3.4. *Thermal analysis*

The thermogravimetric (TG) and differential thermogravimetric analysis (DTG) of the copper(II) complexes were followed from 25°C to 1200°C under dinitrogen. Representative curves and stepwise degradation data are in "Supplementary material". All complexes decompose in two or three steps and the coordinated aroyl hydrazone decomposes in two decomposition steps. The first from 283.2 to 362.2°C corresponds to removal of the aroyl hydrazone moiety, while that at 800–1000°C is due to removal of the pyridoin. In all cases the residual was elemental copper. Accordingly, the following thermal decomposition equations could be assumed.

(1) $[(H_nL)Cu(H_2O)](ClO_4)_2 \rightarrow 2ClO_4 + H_2O + C_7H_8N_2O_x$ at 283.8–296.4°C
$H_nL = H_2L^1$, H_2L^3 or H_3L^3; $n = 2$ or 3; $x = 1$ or 2
Residue $\rightarrow C_{12}H_{10}N_2O + Cu$ at 800–1000° C

(2) $[(L^1)Cu(H_2O)_3] \rightarrow 3H_2O +$ Residue 1 at 264.9°C
Residue 1 $\rightarrow C_7H_8N_2O +$ Residue 2 at 326.3°C
Residue 2 $\rightarrow C_{12}H_{10}N_2O + Cu$ at 880.0°C

(3) $[(H_2L^3)Cu(OAc)]\cdot H_2O \rightarrow H_2O + OAc + C_7H_8N_2O_2$ at 296.5°C
Residue $\rightarrow C_{12}H_{10}N_2O + Cu$
(4) $[(HL^3)Cu(H_2O)]\cdot 0.5H_2O \rightarrow 0.5H_2O +$ Residue 1 at 95.80°C
Residue 1 $\rightarrow H_2O + C_7H_8N_2O_2 +$ Residue 2 at 362.2°C
Residue 2 $\rightarrow C_{12}H_8N_2O + Cu$ at 1000.0°C

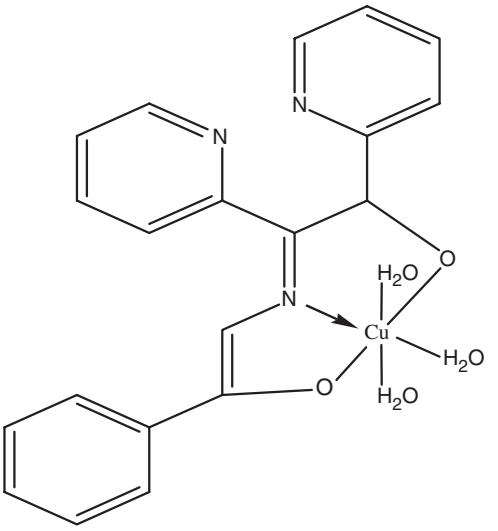

Figure 5. Structure of $[L^1Cu(H_2O)_3]$.

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3.5. *Biological activity*

The antibacterial activities of H_2L^1, H_2L^2, H_2L^3, and H_2L^4 and their copper(II) complexes are given in tables 2–4 and in "Supplementary material". All ligands and their complexes except $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ and $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ are nearly inactive toward most of the studied species. The average of three experimental data for $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ and $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ are given in tables 3 and 4 and in "Supplementary material". Due to the high medical importance of MRSA, we investigated the effects of $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ and $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ on its growth and activity. A 31% of MRSA strains were inhibited by $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ producing zones of inhibition of 0.7–1.3 cm. On the other hand, 86% of MRSA strains were inhibited by $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ producing zones of inhibition of 0.7–1.5 cm, indicating higher inhibitory effects of $[(H_2L^2)Cu(H_2O)](ClO_4)_2$. The inhibitory potentials of the two compounds were further investigated by determining the MIC values. Expectedly, lower MIC values (0.25–0.5 mg mL^{-1}) for $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ were determined compared to MIC values (1.0–2.0 mg mL^{-1}) determined for $[(H_2L^1)Cu(H_2O)](ClO_4)_2$. The results show

Table 2. Antibacterial activity (zone of inhibition) of chemical compounds on five bacterial genera using well diffusion method.

Bacteria compound	MRSA 5	*Bacillus* sp.	*Salmonella* sp. 99	*Escherichia coli DHα*	*Pseudomonas aeruginosa*
H_2L^1	Nil	Nil	Nil	Nil	Nil
$[(L^1)Cu_2(OAc)_2]\cdot 0.5H_2O$	Nil	Nil	Nil	Nil	Nil
$[(L^1)Cu(H_2O)_3]$	0.8 ± 0.030	0.9 ± 0.030	Nil	Nil	Nil
$[(H_2L^1)Cu(H_2O)](ClO_4)_2$	1.3 ± 0.040	1.4 ± 0.050	Nil	Nil	Nil
H_2L^2	Nil	Nil	Nil	Nil	Nil
$[(L^2)Cu_2(OAc)_2]\cdot 0.5H_2O$	1.1 ± 0.030	Nil	Nil	Nil	Nil
$[(H_2L^2)Cu(H_2O)](ClO_4)_2$	1.5 ± 0.045	1.0 ± 0.043	Nil	Nil	Nil
H_3L^3	Nil	Nil	Nil	Nil	Nil
$[(H_2L^3)Cu(OAc)(H_2O)]$	1.0 ± 0.034	Nil	Nil	Nil	Nil
$[(HL^3)Cu(H_2O)]\cdot 0.5H_2O$	1.0 ± 0.050	0.8 ± 0.036	Nil	Nil	Nil
$[(H_3L^3)Cu(H_2O)](ClO_4)_2$	0.9 ± 0.017	0.8 ± 0.030	1.0 ± 0.034	Nil	Nil
H_2L^4	Nil	0.9 ± 0.017	Nil	Nil	Nil
$[(HL^4)Cu(OAc)]$	Nil	0.8 ± 0.043	Nil	1.2 ± 0.050	Nil
$[(HL^4)Cu(OAc)]$	Nil	Nil	Nil	Nil	Nil
$[(L^4)Cu_2(H_2O)_3(C_2H_5OH)](ClO_4)_2$	Nil	Nil	Nil	Nil	Nil

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Table 3. Effect of $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ synthesized chemical compound on the growth rate of bacteria.

Bacteria	Growth rate (OD h^{-1}) (control)	Growth rate (OD h^{-1}) $[(H_2L^2)Cu(H_2O)](ClO_4)_2$	MIC (mg mL^{-1})
MRSA 2	0.0352 ± 0.00058	0.0138 ± 0.00020	0.50
MRSA 3	0.0163 ± 0.00026	0.0136 ± 0.00017	0.50
MRSA 5	0.0024 ± 0.00017	0	0.25
MRSA 8	0.0084 ± 0.00026	0.0031 ± 0.00016	NA
MRSA 11	0.0068 ± 0.00020	0.0001 ± 0.00026	0.50
MRSA 12	0.0087 ± 0.00017	0.0009 ± 0.00017	0.50
MRSA 13	0.0107 ± 0.00020	0.0048 ± 0.00020	0.50
MRSA 14	0.0068 ± 0.00017	0.0001 ± 0.00017	0.50
MRSA 16	0.0107 ± 0.00010	0	0.25
MRSA 17	0.0057 ± 0.00020	0	0.25
MRSA 19	0.0101 ± 0.00010	0.0027 ± 0.00017	NA
MRSA 20	0.0163 ± 0.00030	0.0019 ± 0.00010	NA
MRSA 21	0.0122 ± 0.00034	0.0023 ± 0.00017	NA
MRSA 30	0.0161 ± 0.00026	0.0063 ± 0.00017	0.50
MRSA 31	0.0161 ± 0.00017	0.0063 ± 0.00010	0.50
MRSA 34	0.0107 ± 0.00026	0	0.25
MRSA 38	0.0117 ± 0.00026	0	0.25
MRSA 41	0.0165 ± 0.00020	0.0063 ± 0.00010	0.50
MRSA 43	0.0137 ± 0.00020	0	0.25

MRSA: methicillin resistant *Staphylococcus aureus*; NA: not available because the test compound did not inhibit the bacteria completely; MIC: calculated minimum inhibitory concentration.

Table 4. Effect of $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ synthesized chemical compound on the growth rate of bacteria.

Bacteria	Growth rate (control)	Growth rate $[(H_2L^1)Cu(H_2O)](ClO_4)_2$	MIC (mg mL^{-1})
MRSA 2	0.0352 ± 0.00017	0.0038 ± 0.00017	2.0
MRSA 3	0.0163 ± 0.00020	0.0016 ± 0.00020	2.0
MRSA 5	0.0240 ± 0.00010	0.0083 ± 0.00026	1.0

MIC: calculated minimum inhibitory concentration; MRSA: methicillin resistant *S. aureus*.

that (1) the complexes exhibit inhibitory effects toward the activity of most of the studied bacterial species in contrast to the parent organic ligand, which is biologically inactive under the experimental conditions, and (2) all complexes are inactive toward *P. aeruginosa*, *E. coli DH5α* and *Salmonella* sp. 99 except $[(H_2L^1)Cu(H_2O)](ClO_4)_2$ and $[(H_2L^2)Cu(H_2O)](ClO_4)_2$. As previously reported, the metal salts do not exhibit antimicrobial activity [67–71]. The biological activity of the metal complexes is governed by the following factors [71]: (1) the chelate effect of the ligands; (2) the nature of the donor atoms; (3) the total charge on the complex ion; (4) the nature of the metal ion; (5) the nature of the counter ions that neutralize the complex; and (6) the geometrical structure of the complex [70]. According to the data given in tables 2–4, the antimicrobial activity can be ordered as $[(H_2L^1)Cu(H_2O)](ClO_4)_2 < [(H_2L^2)Cu(H_2O)](ClO_4)_2$. Since the two complexes (1) have the same N_2O_2 with the same coordination number, (2) have the same two five-membered chelating rings, (3) all have the same number and type of counter ions, and (4) all have the same oxidation state in their complexes (Cu^{2+}), the different hydrazone is important. For $[(H_2L^2)Cu(H_2O)](ClO_4)_2$ the increased antimicrobial activity can be attributed to the methyl making the complex less planar, more polar and more lipophilic, leading to additional antimicrobial activity to the complex. These results are comparable to several Schiff-base complexes derived from salicylaldehyde and amino acids [3–36, 72] as well as complexes of different hydrazone Schiff bases [73–80].

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4. Conclusion

New polydentate ligands (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene)aroyl hydrazide (H_2L^1, H_2L^2, H_3L^3) or (*E*)-*N*-(2-hydroxy-1,2-di(pyridin-2-yl)ethylidene) isonicotinohydrazide (H_2L^4) and their copper(II) complexes are prepared. Physical measurements show the ligands are flexidentate forming copper(II) complexes with different structures, magnetic properties, and thermal behavior. The biological activity studies show increased activity for copper(II) bonded to biologically inactive hydrazones and offer the possibility of synthesis of new metalloantibiotics.

Acknowledgments

The support of the Kuwait University received through research grant no. SC01/02 and the facilities of ANALAB and SAF (grant nos GS01/01, GS02/01, and GS03/01) are gratefully acknowledged. Also, the support of college of Graduate Studies, Kuwait University to the MSc student Reem Karbouj is highly appreciated.

References

[1] J.K. Sears, J.R. Darby. *The Technology of Plasticizers*, Wiley, New York (1982).
[2] E. Massarani, D. Nardi, A. Tajana, L. Degan. *J. Med. Chem.*, **14**, 633 (1971).
[3] G.A. Ibanez, G.M. Escandar, A.C. Olivieri. *J. Mol. Struct.*, **605**, 17 (2002).

[4] L. Savini, P. Massarelli, L. Chiasserini, A. Sega, C. Pellerano, A. Barzi, G. Nocentini. *Eur. J. Med. Chem.*, **30**, 547 (1995).
[5] S. Rolls, S.G. Kucukguzel. *Molecules*, **12**, 1910 (2007).
[6] S.M. Sondhi, M. Dinodia, A. Kumar. *Bioorg. Med. Chem.*, **14**, 4657 (2006).
[7] A.C. Cunha, J.L.M. Tributino, A.L.P. Miranda, E.J. Barreiro. *Il Farmaco*, **57**, 999 (2002).
[8] S.K. Sridhar, A. Ramesh. *Biol. Pharm. Bull.*, **24**, 1149 (2001).
[9] M.R. Maurya, S. Agarwal, M. Abid, A. Azam, C. Bader, M. Ebel, D. Rehder. *Dalton Trans.*, 937 (2006).
[10] P. Melnyk, V. Leroux, C. Serghereart, P. Grellier. *Bioorg. Med. Chem. Lett.*, **16**, 31 (2006).
[11] D.R. Dabideen, K.F. Cheng, B. Aljabari, E.J. Miller, V. Pavlov, Y. Al-Abed. *J. Med. Chem.*, **50**, 1993 (2007).
[12] D.S. Kalinowski, P.C. Sharpe, P.V. Bernhardt, D.R. Richardson. *J. Med. Chem.*, **51**, 331 (2008).
[13] M. Kuriakose, M.R.P. Kurup, E. Suresh. *Struct. Chem.*, **18**, 579 (2007).
[14] E.B. Seena, N. Mathew, M. Kuriakose, M.R.P. Kurup. *Polyhedron*, **27**, 1455 (2008).
[15] B.-D. Wang, Z.-Y. Yang. *J. Fluores.*, **18**, 547 (2008).
[16] M.V. Plutenko, Y.S. Moroz, T. Yu. Sliva, M. Haukka, I.O. Fritsky. *Acta Crystallogr., C: Cryst. Struct. Commun.*, **C64**, m137 (2008).
[17] G. Visbal, E. Marchan, A. Maldonado, Z. Simoni, M. Navarro. *J. Inorg. Biochem.*, **102**, 547 (2008).
[18] A. El-Dissouky, N.M. Shuaib, N.A. Al-Aawadi, A.B. Abbas, A. El-Sherif. *J. Coord. Chem.*, **61**, 579 (2008).
[19] H.A. El-Boraey. *J. Therm. Anal. Calorim.*, **81**, 339 (2005).
[20] M. Mancka, W. Plass. *Inorg. Chem. Commun.*, **10**, 677 (2007).
[21] V.K. Yatsimirs'kii, L.P. Oleksenko, V.Ya. Zub, I.V. Shul'gin, I.V. Kuz'mich, K.D. Mel'nikova. *Kiiv Nats. Ukrain. Khimich. Zh.*, **71**, 92 (2005) (Russian Edition).
[22] V.A. Milway, S.M.T. Abedin, L.K. Thompson, D.O. Miller. *Inorg. Chim. Acta*, **359**, 2700 (2006).
[23] A. Bacchi, M. Carcelli, G. Pelizzi, C. Solinas, L. Sorace. *Inorg. Chim. Acta*, **359**, 2275 (2006).
[24] N. Guskos, V. Likodimos, S. Glenis, J. Typek, M. Wabia, D.G. Paschalidis, I.J. Tossidis. *Mag. Mat.*, **272–276**(2), 1067 (2004).
[25] S.K. Dey, T.S.M. Abedin, L.N. Dawe, S.S. Tandon, J.L. Collins, L.K. Thompson, A.V. Postnikov, M.S. Alam, P. Müller. *Inorg. Chem.*, **46**, 7767 (2007).
[26] S.S. Tandon, L.N. Dawe, V.A. Milway, J.L. Collins, L.K. Thompson. *Dalton Trans.*, **19**, 1948 (2007).
[27] L.D. Popov, Yu.P. Tupolova, S.I. Levchenkov, V.V. Lukov, V.A. Kogan. *Russ. J. Coord. Chem.*, **33**, 208 (2007).
[28] S.K. Dey, L.K. Thompson, L.N. Dawe. *Chem. Commun.*, **47**, 4967 (2006).
[29] G. Visbal, E. Marchán, A. Maldonado, Z. Simoni, M. Navarro. *J. Inorg. Biochem.*, **102**, 547 (2008).
[30] N. Chitrapriya, V. Mahalingam, L.C. Channels, M. Zeller, F.R. Fronczek, K. Natarajan. *Inorg. Chim. Acta*, **361**, 2841 (2008).
[31] J. Vinsova, A. Imramovsky, J. Jampilek, J.F. Monreal, M. Dolezal. *Anti-infective Agents Med. Chem.*, **7**, 12 (2008).
[32] Y. Wei, M. Guo. *Angew. Chem.*, **46**, 4722 (2007).
[33] V.P. Singh, P. Gupta. *J. Coord. Chem.*, **59**, 1483 (2006).
[34] P.V. Bernhardt, J. Mattsson, D.R. Richardson. *Inorg. Chem.*, **45**, 752 (2006).
[35] M.C. Rodriguez-Agnelles, M.B. Ferrari, F. Bisceglie, C. Pelizzi, G. Pelosi, M. Sassi. *J. Inorg. Biochem.*, **98**, 313 (2004).
[36] A. Spassky, D.S. Sigman. *Biochemistry*, **24**, 8050 (1985).
[37] E.L. Hegg, J.N. Burstyn. *Coord. Chem. Rev.*, **173**, 133 (1998).
[38] S. Dhar, D. Senapati, P.K. Das, P. Chattopadhyay, M. Nethaji, A.R. Chakravarty. *J. Am. Chem. Soc.*, **125**, 12118 (2003).
[39] A.T. Chaviara, E.E. Kioseoglou, A.A. Pantazaki, A.C. Tsipis, P.A. Karipidis, D.A. Kyriakidis, C.A. Bolos. *J. Inorg. Biochem.*, **102**, 1749 (2008).
[40] A.Th. Chaviara, P.J. Cox, K.H. Repana, R.M. Papi, K.T. Papazisis, D. Zambouli, A.H. Kortsaris, D.A. Kyriakidis, C.A. Bolos. *J. Inorg. Biochem.*, **98**, 1271 (2004).
[41] A. Th. Chaviara, P.J. Cox, K.H. Repana, A.A. Pantazaki, K.T. Papazisis, A.H. Kortsaris, D.A. Kyriakidis, G. St. Nikolov, C.A. Bolos. *J. Inorg. Biochem.*, **99**, 467 (2005).
[42] G.O. Ezeifeka, M.U. Orji, T.I. Mbata, A.O. Patrick. *Biotechnology*, **3**, 41 (2004).
[43] J.V. Bennett, J.L. Brodie, E.J. Benner, W.M.M. Kirby. *Appl. Microbiol.*, **14**, 170 (1966).
[44] R.V.F. Lachica, P.D. Hoeprich, C.E. Frantic. *Appl. Microbiol.*, **24**, 920 (1972).
[45] J.E. Wertz, J.R. Botton. *Electron Spin Resonance*, McGraw-Hill, New York (1972).
[46] M. Moet-Ner. *Chem. Rev.*, **105**, 136 (2005).
[47] D. Braga, L. Maini, M. Polita, E. Tagliavini, F. Grepioni. *Coord. Chem. Rev.*, **246**, 53 (2005).
[48] C.R. Bondy, S.J. Loeb. *Coord. Chem. Rev.*, **240**, 77 (2003).
[49] A. El-Dissouky, S.S. Kandil, G.Y. Ali. *J. Coord. Chem.*, **57**, 105 (2004).
[50] R. Peter, S. Grifith, A. James. *Fourier Transform Infrared Spectroscopy*, 2nd Edn, John Wiley & Sons, NY (2007).
[51] R. Dinda, P. Sengupta, S. Ghash, T.C.M. Mak. *Inorg. Chem.*, **41**, 1648 (2002).

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[52] D. Mishra, S. Nakar, A. Blake. *Inorg. Chim. Acta*, **360**, 2291 (2007).
[53] R.M. Silverstein, F.X. Webster, D. Kiemle. *Spectroscopic Identification of Organic Compounds*, 7th Edn, p. 72, John Wiley & Sons, NY (2005).
[54] T.S. Kassem, A. El-Dissouky, M.A. El-Sayed, H.M. Refaat. *Synth. React. Inorg. Met.-Org. Chem.*, **32**, 1769 (2002).
[55] K. Nakamoto. *Infrared Spectra of Inorganic and Coordination Compounds*, 5th Edn, John Wiley & Sons Inc., NY (1997).
[56] A. El-Dissouky, A.M. Hindawey, A. Abdel-Salam. *Inorg. Chim. Acta*, **18**, 109 (1986).
[57] K. Amourngairusiri, B.J. Hathaway. *Acta Crystallogr.*, **C47**, 1383 (1991).
[58] A. El-Dissouky, G.B. Muhammad. *Inorg. Chim. Acta*, **162**, 263 (1989).
[59] A. El-Dissouky, G.B. Muhammad. *Inorg. Chim. Acta*, **168**, 241 (1990).
[60] P.J . Van Koningsbruggen, D. Gatteschi, R.A.G. Graaf, J. Haasnoot. *Inorg. Chem.*, **34**, 5175 (1998).
[61] E.I. Solomon, A.B.P. Lever (Eds.). *Inorganic Electronic Structure and Spectroscopy, Volume II: Applications and Case Studies*, John Wiley Interscience, NY (2006).
[62] M.K. Awad, A.K. Shehata, A. El-Dissouky. *Transition Met. Chem.*, **20**, 448 (1995).
[63] S. Kandil, A. El-Dissouky. *Transition Met. Chem.*, **27**, 398 (2002).
[64] M.F. El-Shazly, T.M. Salem, A. El-Dissouky. *Inorg. Chim. Acta*, **40**, 1 (1980).
[65] B.J. Hathaway, D.E. Billing. *Coord. Chem. Rev.*, **5**, 143 (1970).
[66] R.D. Bereman, G.D. Shields, J. Bordner, J.R. Dorfman. *Inorg. Chem.*, **20**, 2165 (1981).
[67] J. Liu, L. Li, H. Dai, Z.J. Liu. *Organomet. Chem.*, **69**, 2686 (2006).
[68] L. Tian, Y. Sun, Y. Li, H.X. Zheng, Y. Cheng, X. Liu. *J. Inorg. Biochem.*, **9**, 1646 (2005).
[69] B. Modzelewska, J. Banachiewicz. *Eur. J. Med. Chem.*, **39**, 873 (2004).
[70] D.-K. Kim, J. Kim, H.-J. Park. *Bioorg. Med. Chem. Lett.*, **14**, 2401 (2004).
[71] Z.H. Chohan. *Appl. Organomet. Chem.*, **20**, 112 (2006).
[72] J. Vanco, J. Marek, Z. Travnicek, E. Racanska, J. Muselik, O. Svajlenova. *J. Inorg. Biochem.*, **102**, 595 (2008).
[73] B. Mondal, M.G.B. Drew, T. Ghosh. *Inorg. Chim. Acta*, **362**, 3303 (2009).
[74] V. Mahalingam, N. Chitrapriya, M. Zeller, K. Natarajan. *Polyhedron*, **28**, 1532 (2009).
[75] Q. Wang, Z.-Y. Yang, G.-F. Qi, D.-D. Qin. *Eur. J. Med. Chem.*, **44**, 2425 (2009).
[76] N. Filipović, H. Borrmann, T. Todorović, M. Borna, V. Spasojević, D. Sladić, I. Novaković, K. Andjelković. *Inorg. Chim. Acta*, **362**, 1996 (2009).
[77] R.S. Joseyphus, M.S. Nair. *J. Coord. Chem.*, **62**, 319 (2009).
[78] K.V. Sharma, V. Sharma, U.N. Tripathi. *J. Coord. Chem.*, **62**, 506 (2009).
[79] K.M. Ibrahim, I.M. Gabr, R.R. Zaky. *J. Coord. Chem.*, **62**, 1100 (2009).
[80] V.P. Singh, A. Katiyar, S. Singh. *J. Coord. Chem.*, **62**, 1336 (2009).

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