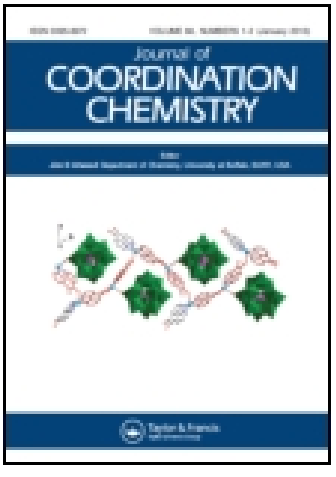


Journal of Coordination Chemistry
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gcoo20

Synthesis, characterization, and antimicrobial properties of two Cu(II) complexes derived from a benzimidazole ligand

Muhammet Kose[a]
[a] Department of Chemistry, K. Maras Sütçü İmam University, Kahramanmaraş, Turkey

Accepted author version posted online: 02 Jul 2014.Published online: 25 Jul 2014.

To cite this article: Muhammet Kose (2014) Synthesis, characterization, and antimicrobial properties of two Cu(II) complexes derived from a benzimidazole ligand, Journal of Coordination Chemistry, 67:14, 2377-2392, DOI: 10.1080/00958972.2014.940924

To link to this article: http://dx.doi.org/10.1080/00958972.2014.940924

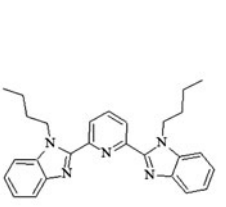
Journal of Coordination Chemistry, 2014
Vol. 67, No. 14, 2377–2392, http://dx.doi.org/10.1080/00958972.2014.940924

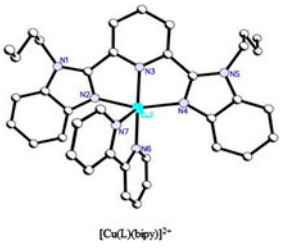
Synthesis, characterization, and antimicrobial properties of two Cu(II) complexes derived from a benzimidazole ligand

MUHAMMET KOSE*

Department of Chemistry, K. Maras Sütçü İmam University, Kahramanmaraş, Turkey

(*Received 21 March 2014; accepted 4 June 2014*)





Two copper(II) complexes, $[Cu(L)_2](ClO_4)_2]$ and $[Cu(L)(bipy)](ClO_4)_2$, were prepared and characterized by the spectroscopic and analytic methods, where L is *N*-butylbenzimidazole and bipy is 2,2′-bipyridine. Single crystals of $[Cu(L)(bipy)](ClO_4)_2$ suitable for X-ray diffraction study were obtained by slow diffusion of diethyl ether into a DMF solution of the complex and the complex was found to crystallize as $[Cu(L)(bipy)](ClO_4)_2 \cdot DMF$. The asymmetric unit contains one $[Cu(L)(bipy)]^{2+}$, two uncoordinated perchlorates, and one DMF solvate. Coordination geometry around Cu (II) is distorted square pyramidal with τ value of 0.31. Thermal properties of the complexes were examined by thermogravimetric analysis, indicating that the complexes are thermally stable to 310 °C. The metal complexes were screened for their *in vitro* antibacterial and antifungal activities *Bacillus subtilis* and *Bacillus cereus* (as Gram(+) bacteria), *Escherichia coli*, *Enterobacter aerogenes*, and *Klebsiella pneumoniae* (as Gram(–) bacteria), and *Saccharomyces cerevisiae*, *Candida utilis*, and *Candida albicans* (as yeasts). The complexes show antibacterial and antifungal activities against bacteria and yeasts.

Keywords: Cu(II) complex; Benzimidazole; 2,2′-Bipyridine; X-ray structure; Antimicrobial

1. Introduction

Benzimidazole is a hetero bicyclic aromatic compound containing a phenyl ring fused to an imidazole ring [1]. Benzimidazole and its derivatives are of wide interest due to their biological activities and clinical applications [2, 3]. Some benzimidazole compounds have been reported to show pharmacological activities such as antiviral, antibacterial, antifungal, and

*Email: muhammetkose@ksu.edu.tr

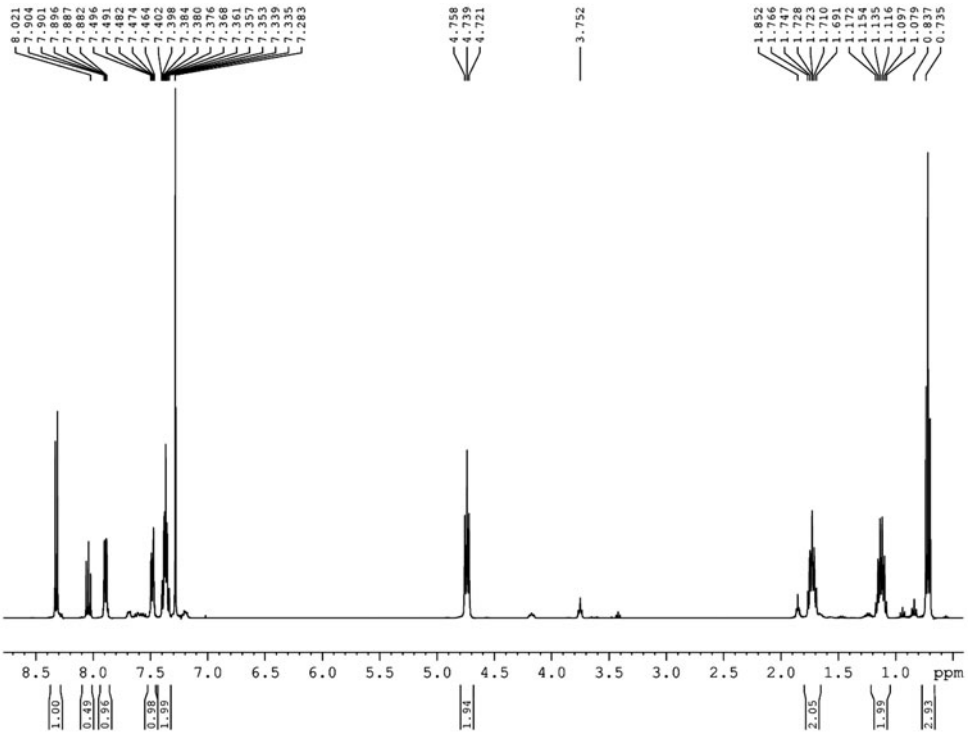


Figure 1. ^{1}H NMR spectrum of L.

antimalarial [4–7]. Benzimidazoles are generally synthesized by the condensation of *o*-phenylenediamine with carboxaldehydes, carboxylic acids, or their derivatives [8, 9]. *N*-substituted benzimidazole derivatives are synthesized by reaction with alky/aryl halide in the presence of base. Several benzimidazole derivatives were synthesized by derivatization at the N–H group [10–12]. Transition metal complexes of 2,6-bis-(benzimidazol-2-yl)-pyridine (bzimpy) (figure 1) were synthesized and their properties were extensively investigated [13–18].

The biological activity and pharmacological properties of benzimidazole derivatives have led us to investigate the coordination behavior of benzimidazole ligands towards transition metal ions. In this study, two Cu(II) complexes of an *N*-butylbenzimidazole ligand (L) were prepared and characterized by analytical and spectroscopic methods.

2. Experimental

2.1. *General methods*

All starting materials and organic solvents were purchased from commercial sources and used as received, unless noted otherwise. IR spectra were performed using KBr pellets on a Perkin Elmer Paragon 1000PC. CHN analysis was performed using a CE-440 elemental

analyzer. ^{1}H and ^{13}C NMR spectra were obtained using a Bruker Avance 400. ESI mass spectra were recorded on a Thermo Fisher Exactive + Triversa Nanomate mass spectrometer. Electronic spectra from 200 to 900 nm were obtained on a Shimadzu UV-1800 UV–vis spectrophotometer. Thermal analyses of the complexes were performed on a Perkin Elmer Pyris Diamond DTA/TG Thermal System under nitrogen at a heating rate of 20 °C min^{-1}.

Data collection and cell refinement for X-ray crystallography were completed using a Bruker APEX2 CCD diffractometer and data reduction was performed using Bruker SAINT. SHELXTL was used to solve and refine the structures [19].

2.2. *X-ray structures solution and refinement for [Cu(L)(bipy)](ClO$_4$)$_2$·DMF*

A single crystal of dimensions 0.39 × 0.13 × 0.09 mm^3 was chosen for the diffraction experiment. X-ray diffraction data were collected at 150(2) K on a Bruker ApexII CCD diffractometer using Mo-Kα radiation ($\gamma = 0.71073$ Å). The structure was solved by direct methods and refined on F^2 using all the reflections [20]. All non-hydrogen atoms were refined using anisotropic atomic displacement parameters and hydrogens were inserted at

Table 1. Crystallographic data.

Complex	[Cu(L)(bipy)](ClO$_4$)$_2$·DMF
Empirical formula	$C_{40}H_{44}Cl_2Cu\ N_8O_9$
Formula weight	915.27
Crystal size/color	0.39 × 0.13 × 0.09/green
Crystal system	*Triclinic*
Space group	*P-1*
Unit cell	
a (Å)	9.4101(6)
b (Å)	11.0932(7)
c (Å)	20.5323(12)
α (°)	93.8370(10)
β (°)	100.1520(10)
γ (°)	95.6090(10)
Volume (Å^3)	2091.9(2)
Z	2
Abs. coeff. (mm^{-1})	0.714
Refl. collected	25,160
Ind. Refl. [R_{int}]	8574 [0.0335]
R_1, wR_2 [$I > 2\sigma(I)$]	0.0375, 0.0933
R_1, wR_2 (all data)	0.0496, 0.1015
CCDC	984,504

Table 2. Selected bond lengths [Å] and angles [°] for [Cu(L)(bipy)](ClO$_4$)$_2$·DMF.

Cu(1)–N(2)	2.0069(18)	Cu(1)–N(6)	1.9885(17)
Cu(1)–N(3)	1.9625(17)	Cu(1)–N(7)	2.2540(19)
Cu(1)–N(4)	2.0075(18)		
N(2)–Cu(1)–N(3)	79.74(7)	N(3)–Cu(1)–N(6)	175.75(7)
N(2)–Cu(1)–N(4)	157.03(7)	N(3)–Cu(1)–N(7)	106.16(7)
N(2)–Cu(1)–N(6)	99.65(7)	N(4)–Cu(1)–N(6)	99.63(7)
N(2)–Cu(1)–N(7)	87.06(7)	N(4)–Cu(1)–N(7)	109.13(7)
N(3)–Cu(1)–N(4)	80.11(7)	N(6)–Cu(1)–N(7)	77.97(7)

calculated positions using a riding model. Details of the crystal data and refinement are tabulated in table 1. Selected bond lengths and angles for the complex are presented in table 2.

2.3. *Synthesis of 2,6-bis-(benzimidazol-2-yl)-pyridine (bzimpy)*

2,6-Bis-(benzimidazol-2-yl)-pyridine (bzimpy) was synthesized by the literature method [21]. Yield: 68%. Colorless; NMR: (DMSO as solvent, ppm, ^{1}H) 7.31 (t, 4H, CH aromatic), 7.76(d 4H CH aromatic), 8.16 (t 1H CH aromatic), 8.34 (d 1H CH aromatic). IR (KBr, ν, cm^{-1}): 3193, 1601, 1573, 1318, 1278, 1230, 819, 738 cm^{-1}. Mass spect. (ESI): *m/z* 312 $[L + H]^+$ (100%), 334 $[L + Na]^+$ (30%).

2.4. *Synthesis of L*

N-butylation of 2,6-bis(benzimidazol-2′-yl)pyridine (bzimpy) was prepared by a slight variation of a reported general *N*-alkylation method [22]. Bzimpy (1.00 g, 3.2 mM) and NaOH (0.50 g, 12.8 mM) were stirred for 4 h at 60 °C. To the stirring solution, 1-bromobutane (1.30 g, 9.6 mM) was added in excess and stirred for two days at 60 °C. The solvent was removed on a rotary evaporator to give white–yellow residue. Chloroform (20 mL) was added to the residue and the precipitated NaBr was removed by filtration. Evaporation of the chloroform yielded a cream-colored product. Yield: 1.05 g, 78% (based on bzimpy). Elemental analysis data: Anal. (%) calculated for $C_{27}H_{29}N_5$ (423.55): C, 76.56; H, 6.90; N, 16.53. Found (%): C, 76.28; H, 6.65; N, 16.37. ^{1}H NMR: ($CDCl_3$ as solvent, ppm,), 0.71 (t 6H CH_3–C), 1.35 (*s* (*sextet*) 4H C–CH_2–C), 4.73 (t 4H C–CH_2–C), 1.72(*q* (*quintet*) 4H C–CH_2–), 7.37–7.47 (t 4H CH aromatic), 7.89(d 4H CH aromatic), 8.06 (t 1H CH aromatic), 8.33 (d 1H CH aromatic). ^{13}C NMR ($CDCl_3$–d_6 as solvent, ppm): 13.48, 19.85, 32.12, 44.64 (aliphatic), 110.39, 120.34, 122.71, 123.47, 125.50, 136.31, 138.11, 142.86, 150.57 (aromatic). IR (KBr, ν, cm^{-1}): 2956, 2929, 2871, 1595, 1434, 1410, 1571, 1328, 1285, 1249, 1178, 1076, 993, 823, 740, 660, 581 cm^{-1}. Mass spect. (ESI): *m/z* 424 $[L + H]^+$ (100%), 446 $[L + Na]^+$ (15%), 847 $[(L)_2 + H]^+$ (15%), 869 $[(L)_2 + Na]^+$ (10%).

2.5. *Preparation of [Cu(L)$_2$](ClO$_4$)$_2$]*

$Cu(ClO_4)_2 \cdot 6H_2O$ (0.37 g, 1 mM) in MeOH (10 mL) was added to a refluxing solution of the ligand (0.84 g, 2 mM) in MeOH (50 mL). The reaction solution was refluxed for 4 h and cooled to room temperature. Green precipitate formed was collected and washed with diethyl ether (20 mL). Single crystals of the complex were obtained via the vapor diffusion method (DMF-diethyl ether); but, due to their small size and very weak diffraction, the data-set was not collected. Yield: 0.86 g, 78% (based on Cu^{2+}) Color: green. m.p. decompose 310–320 °C. Elemental analysis data: Anal (%) calculated for $C_{54}H_{58}CuCl_2O_8$ (1108.55): C, 58.45; H, 5.23; N, 12.63. Found (%): C, 57.97; H, 5.17; N, 12.52. IR (KBr, ν, cm^{-1}): 2960, 2871, 2868, 1601, 1571, 1515, 1481, 1462, 1416, 1333, 1201, 1073, 911, 864, 808, 743, 692, 620, 567, 494, 482, 468, 432, 399 cm^{-1}. Mass spect. (ESI): *m/z* 1008 (65%) $[Cu(L)_2](ClO_4)^+$, 585(20%) $[Cu(L)(ClO_4)]^+$, 486(35%) $[Cu(L)]^+$, 454(100%) $[Cu(L)_2]^{2+}$.

**Caution*: Perchlorate salts of metal complexes are potentially explosive and must be handled with care.

2.6. *Preparation of [Cu(L)(bipy)](ClO$_4$)$_2$*

$Cu(ClO_4)_2 \cdot 6H_2O$ (0.37 g, 1 mM) in MeOH (10 mL) was added to a refluxing solution of L (0.42 g, 1 mM) in MeOH (50 mL). When addition was completed, the green solution was refluxed for 2 h and then 2,2′-bipyridine (bipy) (0.16 g, 1 mM) was added. The reaction mixture was further refluxed for 4 h and cooled to room temperature. Green precipitate was collected and washed with MeOH (20 mL) and diethyl ether (20 mL). Single crystals suitable for X-ray diffraction study were grown by diffusion of diethyl ether into a DMF solution of the complex. Yield: 0.66 g, 77% (based on Cu^{2+}). Color: green. m.p. 310–320 °C (decomp.). Elemental analysis data: Anal (%) calculated for $C_{37}H_{37}CuCl_2N_7O_8$ (842.18): C, 52.77; H, 4.43; N, 11.64. Found (%): C, 52.37; H, 4.21; N, 11.43. IR (KBr, ν, cm^{-1}): 2960, 2930, 2871, 1599, 1572, 1483, 1433, 1332, 1198, 1133, 1088, 1008, 918, 867, 749, 660, 622, 481, 427. Mass spect. (ESI): *m/z* 742.69 (35%), $[Cu(L)(bipy)](ClO_4)^+$, 321(100%) $[Cu(L)]^{2+}$, 486(10%) $[Cu(L)]^+$.

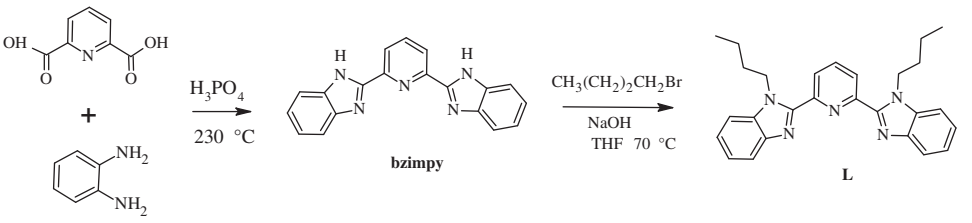
2.7. *Biological properties*

The growth in antimicrobial activities of the complexes were tested against five bacteria (*Bacillus subtilis* IMG22, *Bacillus cereus* EU, *Klebsiella pneumoniaee* FMC *5*, *Escherichia coli* DM, and *Enterobacter aerogenes* (Clinic izolate)) and three yeasts (*Candida albicans* ATCC 1023, *Candida utilis* NRRL-Y-900, and *Saccharomyces cerevisiae* WET 136). These micro-organisms were provided from the Microbiology Laboratory Culture Collection, Department of Biology, Kahramanmaraş Sütçü İmam University, Turkey.

Antimicrobial activities of the complexes were determined using hollow agar, as described below. The bacteria were first incubated at 37 ± 0.1 °C for 24 h in nutrient broth (Difco), and the yeasts were incubated in sabouraud dextrose broth (Difco) at 25 ± 0.1 °C for 24 h. The cultures of the bacteria and yeast were injected into Petri dishes (9 cm) in the amount of 0.1 mL (Mc Farland OD: 0.5, 1.5×10^8 bacteria/mL and 1.5×10^6 yeast/mL). Then, Mueller Hinton agar and sabouraud dextrose agar (sterilized in a flask and cooled to 45–50 °C) were homogeneously distributed onto the sterilized Petri dishes in the amount of 25 mL. Subsequently, the complex 70 microliters (700 µg) in MeOH was pipetted into the hollow agar. In addition, blank paper disks treated with antibacterial ampicillin (10 µg) and antifungal nystatin 100U were used as positive controls. The plates combined with the disks were left at 4 °C for 2 h; the plates injected with yeast were incubated at 25 ± 0.1 °C for 24 h, and those injected with bacteria were incubated at 37 ± 0.1 °C for 24 h. After 24 h, inhibition zones appearing around the disks were measured and recorded in mm [23, 24].

2.8. *Determination of minimal inhibitory concentration*

A micro-dilution broth susceptibility assay was used, as recommended by NCCLS, for determination of the minimal inhibitory concentration (MIC) of the complex. All tests were performed in Mueller Hinton broth (MHB) supplemented with Tween 80 detergent (final concentration of 0.5% (v/v)), with the exception of the yeasts (sabouraud dextrose broth (SDB) + Tween 80). Bacterial strains were cultured overnight at 37 °C in MHB, and the yeasts were cultured overnight at 25 °C in SDB. Geometric dilutions ranging from 100 to 800 µg mL^{-1} of the complexes were prepared including one growth control (MHB + Tween 80) and one sterility control (MHB + Tween 80 + test oil). Test tubes were incubated under



Scheme 1. Synthesis of L.

normal atmospheric conditions at 37 °C for 24 h for bacteria and at 25 °C for 48 h for the yeasts. The microbial growth was determined by turbidimetric methods.

3. Results and discussion

3.1. *Synthesis of L*

2,6-Bis(benzimidazole-2′-yl)pyridine (bzimpy) was prepared by the reaction of 2,6-pyridinedicarboxylic acid with *o*-phenylenediamine in syrupy phosphoric acid at 230 °C [21]. L was synthesized by the reaction of 1-bromobutane and bzimpy in the presence of a

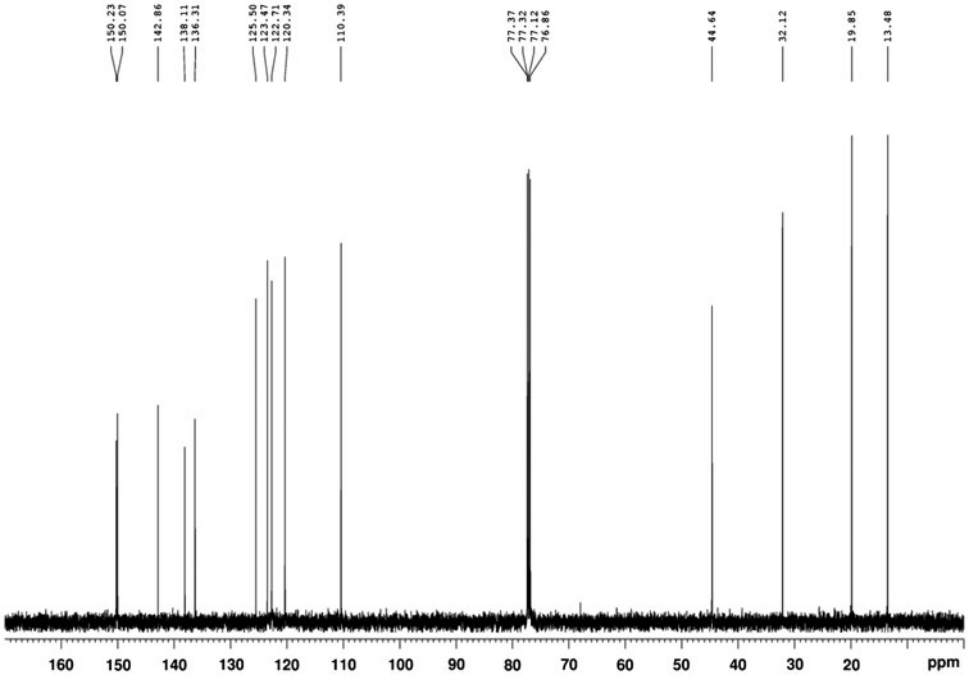


Figure 2. ^{13}C NMR spectrum of L.

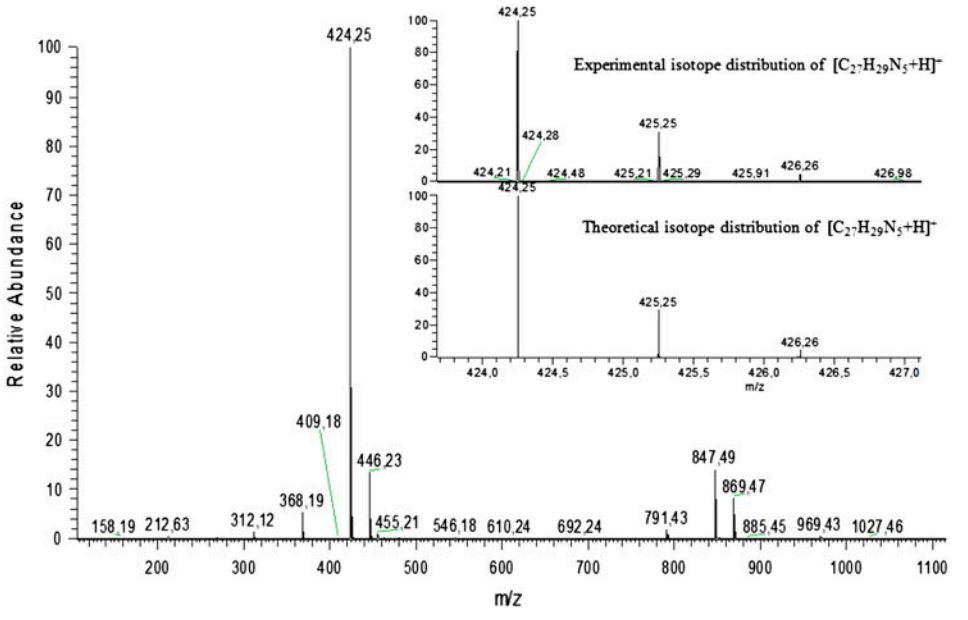


Figure 3. ESI mass spectrum of L.

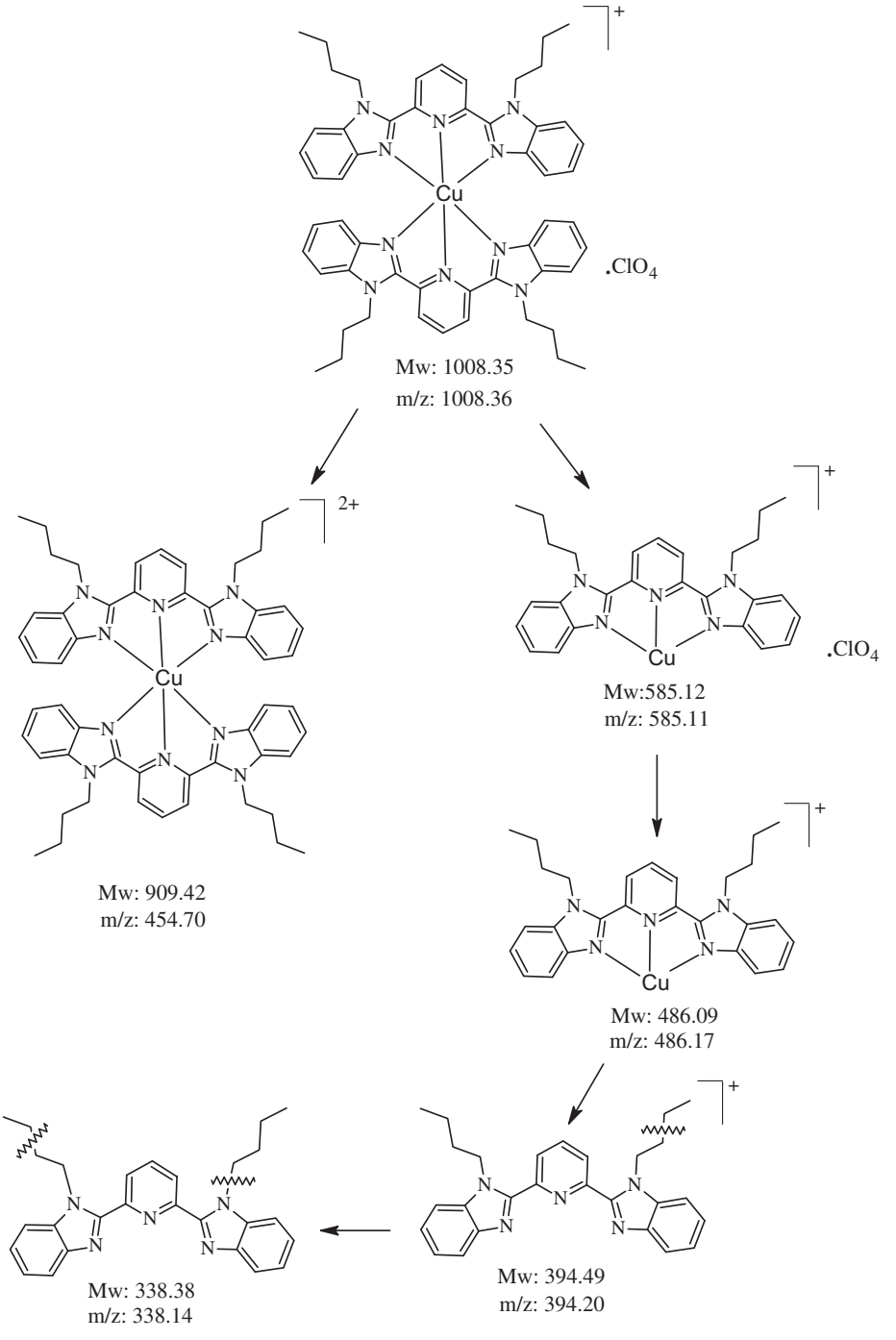
base (NaOH) in THF. Synthesis of L is illustrated in scheme 1. L is stable at room temperature without decomposition and is soluble in most common organic solvents but insoluble in water. ^{1}H and ^{13}C NMR spectra of the ligand are presented in figures 1 and 2, respectively. In the ^{1}H NMR spectrum, aromatic protons are observed at δ 7.28–8.02 ppm as multiplets. A doublet at δ 8.33 ppm and a triplet at δ 8.06 ppm in 2 : 1 ratio were assigned to pyridine protons. Benzene ring protons were observed at δ 7.28–7.89 ppm. Aliphatic protons were observed at δ 0.71–4.73 as multiplets. In ^{13}C NMR spectrum of the ligand, aliphatic C shifts were δ 13.48–44.64 ppm. Aromatic carbon shifts were δ 110–151 ppm. Both ^{1}H and ^{13}C NMR spectra of the ligand showed that there was no significant organic impurity in the sample.

The ESI spectrum of L in MeOH is given in figure 3 and showed signals at *m/z* 424 (100%) and 446(15%) assigned to $[L]H^+$ and $[L]Na^+$, respectively. There are two higher mass peaks at *m/z* 847(15%) and 869(10%) assigned to $[(L)_2 + H]^+$ and $[(L)_2 + Na]^+$, respectively.

N-butylation of benzimidazole ring was further confirmed by IR spectroscopy. In the spectrum of bzimpy, a broad band at 3193 cm^{-1} assigned to ν(N–H) was observed. This band disappeared in the spectrum of L and a new band at 2960–2930 cm^{-1} assigned to ν(C–H)(alkyl) was formed. The ν(C=N) vibration was observed for both bzimpy and L at 1601 and 1595 cm^{-1}, respectively.

3.2. *Synthesis of $[Cu(L)_2](ClO_4)_2$ and $[Cu(L)(bipy)](ClO_4)_2$*

$[Cu(L)_2](ClO_4)_2]$ was obtained by 2 : 1 (L : Cu) reaction of L and $Cu(ClO_4)_2\cdot 6H_2O$ in MeOH. The reaction of one equivalent of L with one equivalent of $Cu(ClO_4)_2\cdot 6H_2O$ in the presence of one equivalent of 2,2′-bipyridine (bipy) results in a mononuclear complex [Cu



Scheme 2. Mass fragmentation pattern of $[Cu(L)_2](ClO_4)_2]$.

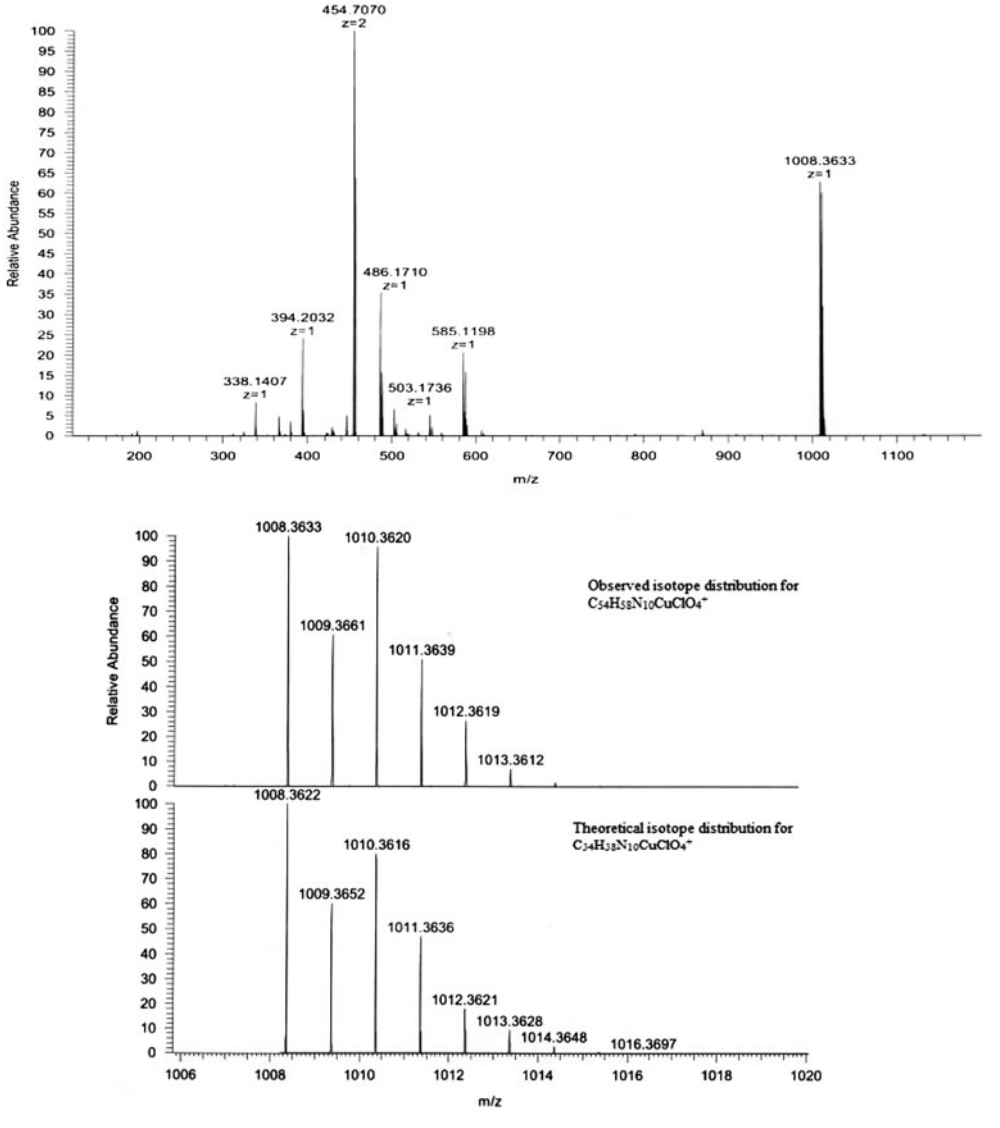


Figure 4. ESI mass spectrum of $[Cu(L)_2](ClO_4)_2]$ (top), observed and theoretical isotope distribution (bottom).

(L)(bipy)]$(ClO_4)_2$. Both complexes are soluble in MeOH, EtOH, acetonitrile, DMF, and DMSO, slightly soluble in chloroform and dichloromethane and not soluble in water and diethyl ether. The elemental analysis data are in agreement with calculated values.

IR spectra of the complexes are similar, and bands at 2960–2871 cm^{-1} can be attributed to aliphatic ν(C–H). The ν(C=N) vibrations for $[Cu(L)_2](ClO_4)_2]$ and [Cu(L)(bipy)]$(ClO_4)_2$ were observed at 1599 and 1601 cm^{-1}, respectively. Two strong stretches at 1073–620 and 1088–622 cm^{-1} were assigned to ν_3 and ν_4 of perchlorate for $[Cu(L)_2](ClO_4)_2]$ and [Cu(L)(bipy)]$(ClO_4)_2$, respectively.

In ESI mass spectra of the complexes, signals due to single and doubly charged ions were observed for both complexes. In the mass spectra of $[Cu(L)_2](ClO_4)_2]$ (figure 4), the signal at *m/z* 1008 (65%) was assigned to the singly charged complex cation $[Cu(L)_2](ClO_4)^+$. Additionally, the signal at *m/z* 454 (100%) was assigned to the doubly charged complex cation $[Cu(L)_2]^{+2}$. Mass spectrum fragmentations of $[Cu(L)_2](ClO_4)_2$ are assigned in scheme 2. Mass spectrum of $[Cu(L)(bipy)](ClO_4)_2$ showed signals at 742.69(35%), 321 (100%), and 486(10%) assigned to $[Cu(L)(bipy)](ClO_4)^+$, $[Cu(L)]^{2+}$, and $[Cu(L)]^+$, respectively.

UV–vis absorption spectra of the complexes were investigated from 200 to 800 nm in MeOH (10^{-5} M). Bands at 400–343 nm can be attributed to n–π^* transitions of the azomethine (C=N) groups. The bands at 344–270 nm may be assigned to π–π^* transitions of aromatic rings. There are also absorption band shoulders for both complexes at 400–413 nm

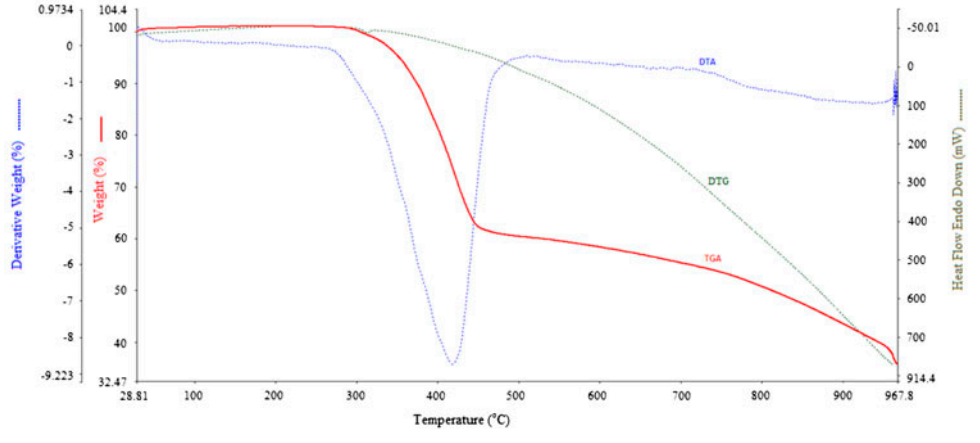


Figure 5. TGA–DTA curves for $[Cu(L)_2](ClO_4)_2]$.

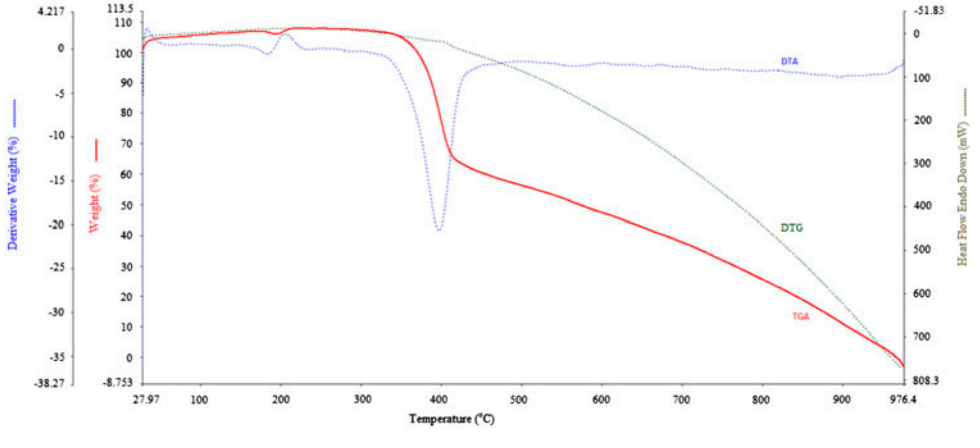


Figure 6. TGA–DTA curves for $[Cu(L)(bipy)](ClO_4)_2$.

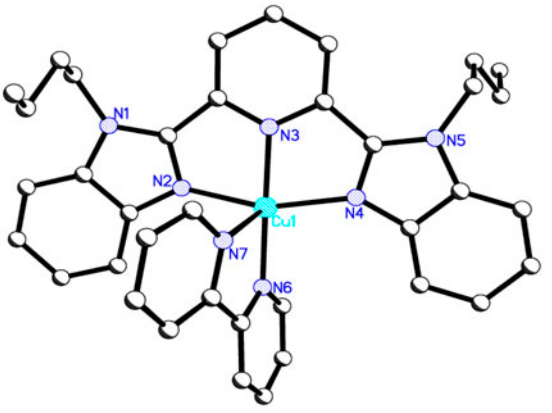


Figure 7. Perspective view of $[Cu(L)(bipy)]^{2+}$; hydrogens, DMF and perchlorate ions are omitted for clarity.

assigned to M → L charge transition. No d–d transitions were observed for the complexes at this concentration.

Thermal studies of the complexes were performed under nitrogen from 20 to 1000 °C. TGA–DTA curves for complexes are shown in figures 5 and 6. Decompositions of the complexes resemble each other, starting at 310 °C. Main weight losses were from 340 to 460 °C. Then, weights of the samples decreased slightly to 1000 °C. For both complexes, all organic moieties decompose at 1000 °C leaving the CuO as the final decomposition product.

3.3. *Molecular structure of [Cu(L)(bipy)](ClO$_4$)$_2$·DMF*

Single crystals suitable for X-ray diffraction were obtained by slow diffusion of diethyl ether into a DMF solution of the complex and the complex was found to crystallize as [Cu(L)(bipy)]$(ClO_4)_2$·DMF. Perspective view of $[Cu(L)(bipy)]^{2+}$ is shown in figure 7. The complex crystallizes in the *triclinic* crystal system, *P-1* space group with unit cell parameters $a = 9.4101(6)$, $b = 11.0932(7)$, $c = 20.5323(12)$ Å, $\alpha = 93.8370(10)$, $\beta = 100.1520(10)$, $\gamma = 95.6090(10)°$, $V = 2091.9(2)$ Å^3, and $Z = 2$ (final refinement value $R = 0.0375$). The asymmetric unit contains one complex cation $[Cu(L)(bipy)]^{2+}$, two uncoordinated perchlorates, and one DMF solvate.

A geometry parameter τ, $\tau = (\beta - \alpha)/60$ where β and α are the two largest angles ($\beta > \alpha$), provides a measure of the degree of square pyramidal (SP) *versus* trigonal bipyramidal geometry. For an ideal SP, τ is zero and for an ideal trigonal bipyramid τ becomes 1.0 [25]. In [Cu(L)(bipy)]$(ClO_4)_2$·DMF, the largest angles within N2, N3, N4, and N6 are $\beta = 175.75(7)°$ for N3–Cu1–N6 and $\alpha = 157.03(7)°$ for N2–Cu1–N4. Thus, τ is (175.75–157.03)/60 = 0.31. This indicates that the geometry around Cu(II) is distorted SP. Four nitrogens (N2, N3, N4 and N6) are located at the equatorial plane and N7 of bipy is located at the axial position. Cu1–N(7) (axial position) distance of 2.2540(19) Å is longer than Cu1–N distances at the equatorial plane (table 2). Moreover, there is a weak interaction between copper and O(6) of a perchlorate at 3.125 Å, respectively; dramatically longer than those of Cu–N bond distances.

There is evidence of π–π stacking interactions in the structure. One imidazole ring (N4–C17–N5–C18–C23) is stacked with C7–C8–C9 edge of a neighboring molecule under sym-

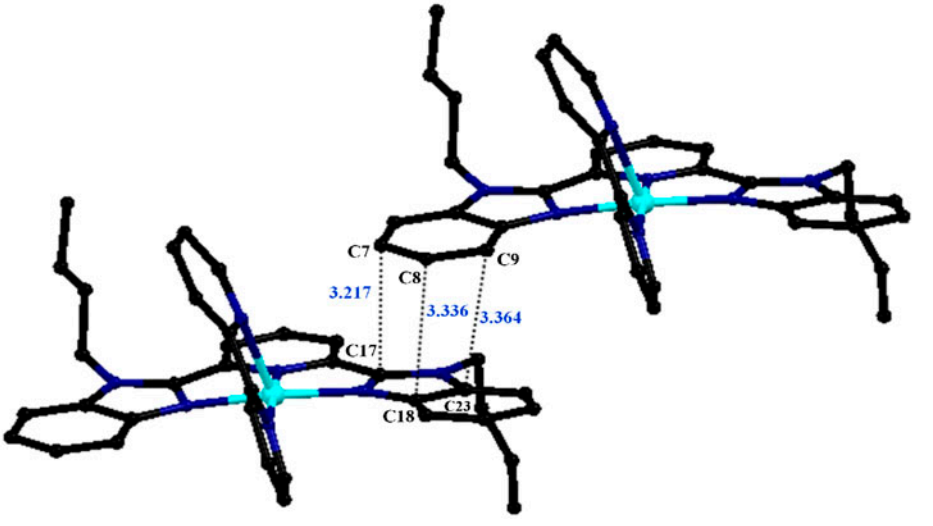


Figure 8. π–π interactions within the structure. Hydrogens, DMF and perchlorate ions are omitted for clarity.

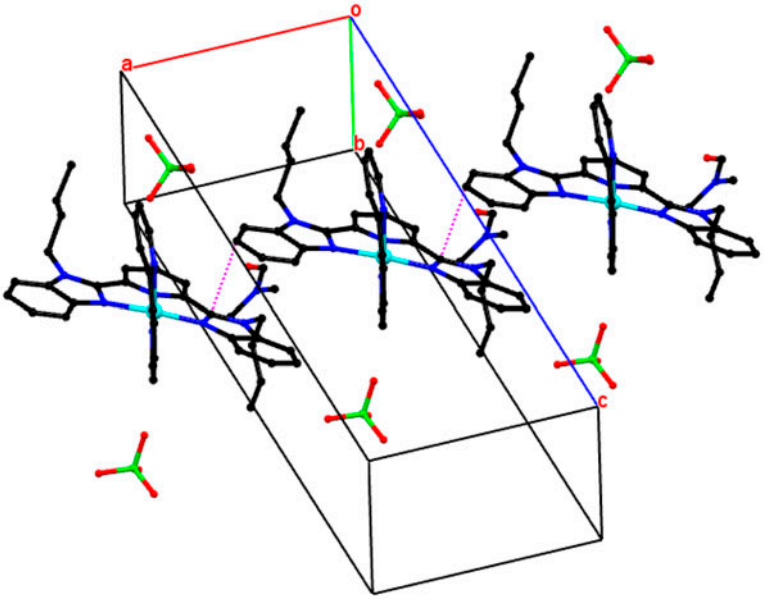


Figure 9. Packing plot for the complex showing π–π interactions within the structure. Hydrogens are omitted for clarity.

metry operation of $-x+1$, y, and z; C7 and C17 is separated by a distance of 3.217 Å (figure 8). Molecular packing of the complex is determined by π–π and CH(aromatic)… $OClO_3$ weak hydrogen bond type interactions as shown in figure 9.

Table 3. Antimicrobial activities of the complexes (700 μg).

Compounds	*K. pneumoniae* Gram(–)	*E. aerogenes* Gram(–)	*E. coli* Gram(–)	*B. cereus* Gram(+)	*B. subtilis* Gram(+)	*S. cerevisiae* (yeast)	*C. utilis* (yeast)	*C. albicans* (yeast)
$[Cu(L)_2](ClO_4)_2$	15[a]	18	19	17	19	21	12	11
$[Cu(L)(bipy)](ClO_4)_2$	13	17	19	16	16	19	8	10
Ampicillin 10 μg (standard antibiotic)	17	16	11	15	12	–	–	–
Nystatin 100U (antifungal)	–	–	–	–	–	17	21	19
MeOH	–	–	–	–	–	–	–	–

[a]Inhibition zone (mm)
Note: No inhibition zone.

Table 4. MIC of the complexes (μg L^{-1}).

Microorganisms	*K. pneumoniae*	*E. aerogenes*	*E. coli*	*B. subtilis*	*B. cereus*	*C. albicans*	*C. utilis*	*S. cerevisiae*	
$[Cu(L)_2](ClO_4)_2$	300	200	200	200	200	200	300	400	This work
$[Cu(L)(bipy)](ClO_4)_2$	400	200	200	200	200	200	400	500	This work
MeOH	>800	>800	>800	>800	>800	>800	>800	>800	This work
Ampicillin	3	3	4	4	4	–	–	–	This work
Nystatin/Unite	–	–	–	–	–	40	30	30	This work
$Cu(ClO_4)_2$	–	–	256	320	–	–	–	–	[27]
$CuCl_2$	–	–	–	256	–	–	–	–	[28]

Note: Not measured.

The mononuclear complexes of L with $CuCl_2{\cdot}2H_2O$ and $Cu(NO_3)_2{\cdot}3H_2O$ were previously prepared in our group [26]. It is informative to compare crystal structures of reported $[Cu(L)Cl_2]{\cdot}2MeOH$ and $[Cu(L)(NO_3)_2]$ with $[Cu(L)(bipy)](ClO_4)_2{\cdot}DMF$. In the structures of both published complexes ($[Cu(L)Cl_2].2MeOH$ and $[Cu(L)(NO_3)_2]$) and $[Cu(L)(bipy)](ClO_4)_2{\cdot}DMF$, the Cu(II) ions are five-coordinate with distorted square-pyramidal geometry and they have similar Cu-donor distances. Trigonality indices (τ) are 0.105 and 0.0023 for $[Cu(L)Cl_2]{\cdot}2MeOH$ and $[Cu(L)(NO_3)_2]$, respectively [26]. In the structures of $[Cu(L)Cl_2]{\cdot}2MeOH$ and $[Cu(L)(NO_3)_2]$, chloride and nitrate coordinate.

3.4. *Antimicrobial activity studies*

Antimicrobial properties of the complexes were investigated against the bacteria and yeasts (*B. subtilis* and *B. cereus* (as Gram(+) bacteria); *E. coli*, *E. aerogenes*, and *K. pneumoniae* (as Gram(–) bacteria); and *S. cerevisiae*, *C. utilis*, and *C. albicans* (as yeasts). The diffusion agar technique was used to determine the antimicrobial activity of the complexes. The results of the microbial screening of the complexes are given in table 3.

The complexes show activity against all tested bacteria compared with Ampicillin 10 μg under identical experimental conditions. Both complexes exhibit similar antimicrobial activity against bacteria and yeasts studied. The effect of the complexes on *K. Pneumonia* is less than the other bacteria studied. The complexes are also active against yeasts used in this study (*S. cerevisiae*, *C. utilis*, and *C. albicans*). The complexes show considerable antifungal activity against *S. cerevisiae*, *C. utilis*, and *C. albicans* compared with Nystatin 100U (antifungal). The complexes are more effective on *S. cerevisiae* than *C. utilis* and *C. albicans* under identical experimental conditions.

MIC values indicated that both complexes are active at low concentration against bacteria and yeasts studied (table 4). However, antibacterial and antifungal activities of the complexes are much less than Ampicillin (standard antibiotic) and Nystatin (antifungal) (table 4). Both complexes showed the lowest MIC value of 200 μg mL^{-1} against *B. subtilis*, *B. cereus*, *E. coli*, *E. aerogenes*, and *S. cerevisiae*. $[Cu(L)_2](ClO_4)_2$ exhibits higher activity against *K. pneumonia*, *C. utilis*, and *S. cerevisiae* than $[Cu(L)(bipy)](ClO_4)_2{\cdot}DMF$ under identical experimental conditions. Both complexes were more effective on *E. coli* and *B. subtilis* than simple $CuCl_2$ and $Cu(ClO_4)_2$ salts (table 4).

4. Conclusion

Two copper(II) complexes of a benzimidazole ligand (L) were synthesized and characterized by spectroscopic and analytic methods. Molecular structure of $[Cu(L)(bipy)](ClO_4)_2$ was determined by single-crystal X-ray diffraction. The complexes were screened for *in vitro* antibacterial and antifungal activity of *B. subtilis* and *B. cereus* (as Gram(+) bacteria); *E. coli*, *E. aerogenes*, and *K. pneumoniae* (as Gram(–) bacteria); and *S. cerevisiae*, *C. utilis*, and *C. albicans* (as yeasts). The complexes show moderate antibacterial and antifungal activities against bacteria and yeasts used.

Supplementary material

Crystallographic data have been deposited with the Cambridge Crystallographic Data Center, CSD reference for [Cu(L)(bipy)]$(ClO_4)_2$•DMF is 984504. Copies of this information can be obtained from The Director, CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK (Fax: +44 1223 335033; Email deposit@ccdc.cam.ac.uk or http://www.ccdc.cam.ac.uk).

Acknowledgements

The author is grateful to the Department of Chemistry, Loughborough University for providing laboratory and analytical facilities. The author wishes to thank Prof. Vickie McKee for allowing the use of the X-ray diffractometer and Prof. Metin Dığrak for antimicrobial studies.

References

[1] T.M. Kalyankar, S.S. Pekamwar, S.J. Wadher, P.S. Tiprale, G.H. Shinde. *Int. J. Chem. Pharm. Sci.*, **3**, 1 (2012).
[2] K.K. Mothilal, C. Karunakaran, A. Rajendran, R. Murugesan. *J. Inorg. Biochem.*, **98**, 322 (2004).
[3] V. Klimešová, J. Kočí, M. Pour, J. Stachel, K. Waisser, J. Kaustová. *Eur. J. Med. Chem.*, **37**, 409 (2002).
[4] K.F. Ansari, C. Lal. *Eur. J. Med. Chem.*, **44**, 4028 (2009).
[5] E. Lukevics, P. Arsenyan, I. Shestakova, I. Domracheva, A. Nesterova, O. Pudova. *Eur. J. Med. Chem.*, **36**, 507 (2001).
[6] S. Özden, D. Atabey, S. Yildiz, H. Göker. *Bioorg. Med. Chem.*, **13**, 1587 (2005).
[7] Y. He, B. Wu, J. Yang, D. Robinson, L. Risen, R. Ranken, L. Blyn, S. Sheng, E.E. Swayze. *Bioorg. Med. Chem. Lett.*, **13**, 3253 (2003).
[8] M.A. Phillips. *J. Chem. Soc.*, 2395 (1928).
[9] M.R. Grimmet, A.R. Katritzky, C.W. Rees. *Heterocycl. Chem.*, **5**, 457 (1984).
[10] X. Xu, Z. Xi, W. Chen, D. Wang. *J. Coord. Chem.*, **60**, 2297 (2007).
[11] G. Muller, J.C.G. Bunzli, K.J. Schenk, C. Piguet, G. Hopfgartner. *Inorg. Chem.*, **40**, 2642 (2001).
[12] A.Y.Y. Tam, W.H. Lam, K.M.C. Wong, N. Zhu, V.W.W. Yam. *Chem. Eur. J.*, **14**, 4562 (2008).
[13] R. Boča, L. Dlháň, W. Linert, H. Ehrenberg, H. Fuess, W. Haase. *Chem. Phys. Lett.*, **307**, 359 (1999).
[14] R. Boča, P. Baran, M. Boča, L. Dlháň, H. Fuess, W. Haase, W. Linert, B. Papánková, R. Werner. *Inorg. Chim. Acta*, **278**, 190 (1998).
[15] B. Machura, A. Świtlicka, M. Penkala. *Polyhedron*, **45**, 221 (2012).
[16] W. Shuangxi, Z. Ying, Z. Fangjie, W. Qiuying, W. Liufang. *Polyhedron*, **11**, 1909 (1992).
[17] X.Q. Bai, S.H. Zhang. *Acta Cryst.*, **E65**, 397 (2009).
[18] M. Boča, R.F. Jameson, W. Linert. *Coord. Chem. Rev.*, **255**, 290 (2011).
[19] Bruker. *APEX2 and SAINT*, Bruker AXS Inc, Madison, WI (1998).
[20] G.M. Sheldrick. *Acta Cryst.*, **A64**, 112 (2008).
[21] A.W. Addison, P.J. Burke. *J. Heterocycl. Chem.*, **18**, 803 (1981).
[22] V. McKee, M. Zvagulis, J.V. Dagdigian, M.G. Patch, C.A. Reed. *J. Am. Chem. Soc.*, **106**, 4765 (1984).
[23] C.H. Collins, P.M. Lyne, J.M. Grange. *Microbiological Methods*, Butterworths, London (1989).
[24] L.J. Bradshaw. *Laboratory Microbiology*, 4th Edn, Saundes College Publishing, Ft. Worth, TX (1992).
[25] A.W. Addison, T.N. Rao, J. Reedijk, J. van Rijn, G.C. Verschoor. *J. Chem. Soc., Dalton Trans.*, 1349 (1984).
[26] M. Kose, M. Digrak, I. Gonul, V. Mckee. *J. Coord. Chem.*, **67**, 1746 (2014). doi: 10.1080/00958972.2014.920502.
[27] Z.B. Ou, Y.H. Lu, Y.M. Lu, S. Chen, Y.H. Xiong, X.H. Zhou, Z.W. Mao, X.Y. Le. *J. Coord. Chem.*, **66**, 2152 (2013).
[28] J.Y. Chen, X.X. Ren, Z.W. Mao, X.Y. Le. *J. Coord. Chem.*, **65**, 2182 (2012).