

Spectroscopic, thermal and kinetic studies of coordination compounds of Zn(II), Cd(II) and Hg(II) with norfloxacin

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Abstract Some metal complexes of norfloxacin (NOR) with the formula $[M(\text{NOR})_2]X_{2-n}H_2O$ [$M = \text{Zn(II)}$, ($X = \text{Cl}^-$, AcO^- , Br^- and I^-), Cd(II) , ($X = \text{Cl}^-$, NO_3^- and SO_4^{2-}) and Hg(II) ($X = \text{Cl}^-$, NO_3^- and AcO^-)] have been synthesised and studied using elemental analysis (CHN), electronic (UV–vis, mid infrared, mass, and $^1\text{H-NMR}$ spectra), TG and DTA. The thermal decomposition processes of these complexes were discussed. The Correlation coefficient, the activation energies, E^* , the pre-exponential factor, A , the entropies, S^* , enthalpies, H^* and Gibbs free energies, G^* , of the thermal decomposition reactions have been derived from thermogravimetric (TG) and differential thermogravimetric (DTG) curves. The characterization of

the final products of the decomposition was achieved by IR spectra and X-ray powder diffraction (XRD). Using the Coats–Redfern and Horowitz–Metzger methods, kinetic analysis of the thermogravimetric data is performed.

Keywords Norfloxacin · Thermal analysis · Infrared spectra · Kinetic data · Complexes

Introduction

Norfloxacin (NOR; Fig. 1), 1-ethyl-6-fluoro-1,4-dihydro-4-oxo-7-(1-piperazinyl)-3-quinolinecarboxylic acid, belongs to the family of molecules known as the fluoroquinolones and is a wide-ranging drug used in treating bacterial infections of the urinary tract, the respiratory tract, and the skin, amongst others. It is also known that NOR can be effective in treating diarrhoea, and could in addition treat conjunctivitis when it was administered in the form of eye drops. Norfloxacin was not, however, effective against infections involving anaerobic bacteria (e.g. yeast, athlete's foot) [1–6].

When dealing with the interaction between drugs and metal ions in living systems, a particular attention has been paid to the interaction of metal ions with antibiotics. Antibiotics that interact with metal ions constituted a class of drugs which has been widely used in medicine both for human beings and animals [1, 2]. In particular, the interaction between transition metals and β -lactamic antibiotics such as cephalexin had been recently investigated by several physicochemical and spectroscopic methods, and with detailed biological data [3–6].

Many drugs possess modified pharmacological and toxicological properties when administered in the form of metallic complexes. Probably the most widely studied cation in this respect is Cu(II), for which a host of

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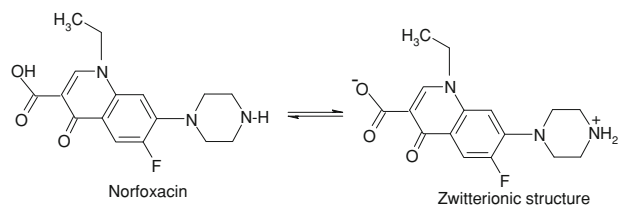


Fig. 1 Structure of norfloxacin (Nor) and its zwitterionic structure

low-molecular-weight Cu(II) complexes have been proved beneficial against several diseases such as tuberculosis, rheumatoid arthritis, gastric ulcers, and cancers [7–10]. There has been a tremendous growth in the study of drugs from quinolone family, which began with the discovery of nalidixic acid some over 40 years ago. Since then, the exponential growth of this family had produced more than ten thousand analogues [11].

The coordination chemistry of these drugs with metal ions of biological and pharmaceutical importance is of considerable interest. Norfloxacin is considered the best of the third generation quinolone family. There are several reports regarding the synthesis and crystal structure of metal complexes with quinolone derivatives [12–15].

Quinolone antibiotics could participate in the formation of complexes in a number of ways [16–20]. When in acidic media, quinolones are usually singly and/or doubly protonated making them unable to coordinate to the metal cations and, in such cases, only electrostatic interaction are observed between the drug and the metal ions [16–18]. On the other hand it was found that neutral quinolones in the zwitterionic state were capable of forming simple complexes (bidentate chelating) [19–21]. The quinolones could also act as bridging ligands and are, consequently, capable of forming polynuclear complexes [20, 21].

The synthesis and characterization of new metal complexes with quinolone antibacterial agents are of great importance for understanding the drug-metal ion interaction and taking into account their potential pharmacological use. The objective of this study is the isolation and characterization of the Zn(II), Cd(II) and Hg(II) complexes, as well as their characterization using spectroscopic and thermal analysis techniques. The thermal behaviour of these complexes was also studied. The antibacterial activity of the investigated complexes was tested against *Escherichia coli* (Gram –ve), *Bacillus subtilis* (Gram +ve) and antifungal activity was also investigated (trichoderma and penicillium activities).

Experimental

Chemicals

Norfloxacin used in the present study was obtained from the Egyptian International Pharmaceutical Industrial

Company (EIPICO). All chemicals used for the preparation of the complexes were of analytical reagent grade, commercially available, used without further purification and received from different sources (Fluka and Aldrich).

Synthesis

Complexes with the general formula $[M(NOR)_2]X_2 \cdot nH_2O$ [$M = Zn(II)$, ($X = Cl^-$, CH_3COO^- , Br^- and I^-), $Cd(II)$, ($X = Cl^-$, NO_3^- and SO_4^{2-}) and $Hg(II)$ ($X = Cl^-$, NO_3^- and CH_3COO^-)] were synthesized.

All the complexes were prepared as follows, employing a 1:2 (metal ions: NOR) ratio. A solution of 1.0 mmol of a salt of each Zn(II), Cd(II) or Hg(II) previously dissolved in 10 cm³ of distilled water was added to a solution of 1.0 mmol of norfloxacin in 50 cm³ of acetone. The resulting mixtures were heated at ~60 °C under reflux on a water bath for about 10 h and then cooled. The obtained complexes were separated from the reaction mixture by filtration, washed with boiling water and acetone and dried under *vacuum* over CaCl₂.

Instruments

Elemental analysis was carried out by standard micro chemical methods using a Perkin-Elmer CHN 2400 and the metal contents were determined gravimetrically by ignition weighed samples in air atmosphere at 1,073 K to constant weight as the metal oxide forms. IR spectra were recorded on a Bruker II FT-IR spectrophotometer (KBr discs) in the range from 4,000 to 400 cm⁻¹. ¹H-NMR spectra were recorded on a Varian Gemini 200 MHz spectrometer using DMSO-d₆ as solvent. Mass spectra were performed on an AEI MS 30 mass spectrometer at 70 eV. TG–DTG measurements were carried out under N₂ atmosphere within the temperature range from room temperature to 1,073 K using a Shimadzu TGA-50H thermal analyzer. Electronic spectra were obtained using a Jenway 6405 Spectrophotometer with a 1 cm quartz cell. Molar conductivities in DMSO at 10⁻³ mol dm⁻³ concentration were measured on a Jenway 4010 conductivity meter. The X-ray powder diffraction patterns of the decomposition products of NOR complexes were recorded with a Rigaku diffractometer using Cu/K α radiation.

The anion analysis was performed as follows: the complexes were dissolved in concentrated HNO₃, and the obtained samples diluted with water to 25 cm³. The qualitative analysis of Cl⁻ and SO₄²⁻ ions were performed by reactions with AgNO₃ and BaCl₂ solutions, respectively.

Antibacterial investigation

The procedure described by Gupta et al. [22] as employed. The investigated isolates of bacteria were seeded in tubes with nutrient broth (NB). The seeded NB (1 cm³) was

homogenized in the tubes with 9 cm³ of melted (318 K) nutrient agar (NA). The homogeneous suspensions were poured into Petri dishes. The holes (diameter 4 mm) were done in the cool medium. After cooling, 2 × 10⁻³ dm³ of the investigated compounds were applied using a micropipette. After incubation for 24 h in a thermostat at 298–300 K, the inhibition (sterile) zone diameters (including disc) were measured and expressed in mm. An inhibition zone diameter over 7 mm indicates that the tested compound is active against the bacteria under investigation.

The antibacterial activities of the investigated compounds were tested against *Escherichia coli* (Gram -ve), *Bacillus subtilis* (Gram +ve), as well as the antifungal activity (trichoderma and penicillium).

Results and discussion

The elemental analysis results are summarized in Table 1. These results, as well as the obtained mass spectra are in good agreement with the proposed formula.

The melting points of the complexes are higher than that of the free ligand, revealing that the complexes are much more stable than ligand. The molar conductance values of the complexes were found to be in the range from 30-to-60 Ω⁻¹ cm² mol⁻¹ at 298 K, which indicates that the complexes are of a non-electrolytic nature [23]. The low conductivity values are in agreement with the low solubility of NOR complexes in water, ethanol, chloroform, acetone and most organic solvents. On the other hand, they are soluble in DMSO, DMF and concentrated acids.

IR data and bonding

The IR data to NOR and its complexes are listed in Table 2. The IR spectra of the complexes are compared with those of

the free ligand in order to determine the coordination sites that may involved in chelation. There are some guide peaks, in the spectra of the ligand, which are useful in achieving this goal. The position and/or the intensities of these peaks are expected to be changed upon chelation. These guide peaks are listed in Table 2. The ν(OH), ν(C=O), ν_{asym}(COO) and ν_{sym}(COO) stretching vibrations are observed at 3,448, 1,727, 1,590 and 1,396 cm⁻¹ for free NOR ligand. The participation of the carboxylate O atom in the complexes formation is evidenced from the shift in position of these bands to 3,276–3,427, 1,709–1,720 or the disappearance of the bands between 1,549–1,591 and 1,381–1,394 cm⁻¹ for NOR–metal complexes. For comparison the carbonyl–O; ν(C=O), stretching vibration is found in the free ligand at 1,716 cm⁻¹. This band is shifted to lower wavenumbers (1,621–1,632 cm⁻¹) in the complexes indicating the participation of the carbonyl–O in coordination. New bands are found in the spectra of the complexes in the regions 524–555, 497–523 and 464–498, which are assigned to ν(M–O) stretching vibrations of coordinated water, carboxylate–O and carbonyl–O, respectively. Therefore, from the IR spectra, it is concluded that NOR behaves as neutral bidentate ligand and binds to the metal ions through protonated carboxylate O and carbonyl groups.

UV–vis spectra

The formation of the M(II) complexes was also confirmed by UV–vis spectra. The electronic absorption spectra of the ligand and its M(II) complexes in DMSO in the 200–600 nm range. It can be seen that free NOR has two distinct absorption bands. The first one at 285 nm may be attributed to π → π* transition of the heterocyclic moiety and benzene ring. The second band observed at 335 nm is attributed to n → π* electronic transition. In the spectra of the M(II) complexes, the two bands are hypochromically

Table 1 Analytical and physical data of NOR and its metal complexes

Complex Mwt	Formula	%C		%H		%N		%M	
		Calc.	Found	Calc.	Found	Calc.	Found	Calc.	Found
[Cd(NOR) ₂] ₂ Cl ₂ ·2H ₂ O 857.99	[Cd(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ Cl ₂ ·2H ₂ O	44.76	44.53	7.67	4.67	9.79	9.68	13.10	12.96
[Cd(NOR) ₂](NO ₃) ₂ 875.10	[Cd(C ₁₆ H ₁₈ FN ₃ O ₃) ₂](NO ₃) ₂	43.88	44.13	4.12	4.13	9.60	9.49	12.84	12.77
[Cd(NOR) ₂] ₂ SO ₄ 847.15	[Cd(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ SO ₄	45.33	45.12	4.25	4.20	9.92	9.85	13.27	13.06
[Cd(NOR) ₂] ₂ I ₂ 957.87	[Cd(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ I ₂	40.09	39.65	3.76	3.49	8.77	8.70	11.73	11.56
[Hg(NOR) ₂] ₂ Cl ₂ 910.17	[Hg(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ Cl ₂	42.19	41.54	3.96	4.12	9.23	9.13	22.04	21.89
[Hg(NOR) ₂] ₂ (NO ₃) ₂ 963.27	[Hg(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ (NO ₃) ₂	39.87	40.69	3.74	4.32	8.72	8.69	20.82	20.64
[Hg(NOR) ₂] ₂ (OA) ₂ 957.35	[Hg(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ (OA) ₂	40.11	39.89	3.76	3.49	8.78	8.77	20.95	20.79
[Zn(NOR) ₂] ₂ Cl ₂ ·2H ₂ O 810.97	[Zn(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ Cl ₂	47.35	47.26	4.94	4.79	10.36	10.12	8.06	8.05
[Zn(NOR) ₂] ₂ (OA) ₂ 822.15	[Zn(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ (OA) ₂	46.71	46.55	4.38	4.21	10.22	9.98	7.96	7.95
[Zn(NOR) ₂] ₂ Br ₂ 863.87	[Zn(C ₁₆ H ₁₈ FN ₃ O ₃) ₂] ₂ Br ₂	44.46	45.38	4.17	4.53	9.73	9.68	7.57	7.49

Table 2 IR spectra (4,000–400 cm^{-1}) of NOR and its metal complexes

Compound	$\nu(\text{C}=\text{O})$	$\nu(\text{COO})$ (asym)	$\nu(\text{COO})$ (sym.)	$\nu(\text{C}=\text{O})$ (carbonyl)	$\nu(\text{M}-\text{O})$	$\nu(\text{M}-\text{O})$	$\nu(\text{M}-\text{O})$ (H_2O)
NOR	1727sh	1590sh	1396sh	1716sh	–	–	–
$[\text{Hg}(\text{NOR})_2]\text{Cl}_2$	1720sh	1556s	1394m	1627sh	499s	474s	536s
$[\text{Hg}(\text{NOR})_2](\text{NO}_3)_2$	1716sh	1549m	1384s	1632sh	497w	478w	527s
$[\text{Hg}(\text{NOR})_2](\text{OA})_2$	1709m	1580m	1383sh	1628sh	499s	470w	528s
$[\text{Cd}(\text{NOR})_2](\text{NO}_3)_2$	1716sh	1574m	1385m	1632sh	500w	470w	530s
$[\text{Cd}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$	Dis.	1579m	1381sh	1627sh	505s	475s	529s
$[\text{Cd}(\text{NOR})_2]\text{SO}_4$	Dis.	1566sh	1384sh	1630sh	500s	474w	524s
$[\text{Cd}(\text{NOR})_2]\text{I}_2$	1713m	1579m	1385m	1621sh	523s	498s	545w
$[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$	Dis.	1580sh	1381sh	1623sh	498s	475w	530s
$[\text{Zn}(\text{NOR})_2]\text{Br}_2$	Dis.	1559sh	1384sh	1627sh	500s	470w	525w
$[\text{Zn}(\text{NOR})_2](\text{OA})_2$	Dis.	1591m	1384sh	1628sh	509s	464w	555s

sh Sharp, m medium, s small, w weak

affected obviously, suggesting the ligand has changed to the zwitterionic form. The results clearly indicate that the ligand coordinate to metal(II) ions via carboxylic and ketone groups, which is in accordance with the results of the FT-IR spectra.

Mass spectra

In the mass spectra of $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$, $[\text{Cd}(\text{NOR})_2]\text{NO}_3$ and $[\text{Hg}(\text{NOR})_2]\text{NO}_3$, intense mass peaks at m/z 319, 275, 233, 161, 107, and 56 are detected. The first mass peak corresponds to the $[\text{H-NOR}]^+$ ion and the second one proceeds by loss of CO_2 from the molecular ion at m/z 275 with intensity 72%, then the elimination of $\text{C}_2\text{H}_4\text{N}$ leads to the formation of an ion at $m/z = 233$. In comparison between the NOR (ligand) and the three NOR complexes, the peak assigned to molecular ion $m/z = 319$ of NOR ligand is present in all three complexes, and new peaks appear at $m/z = 65$, 112 and 201 can be assigned to zinc(II), cadmium(II) and mercury(II) metal, respectively. These results are again consistent with the presence of direct metal-ligand bonding in the three NOR complexes.

$^1\text{H-NMR}$ spectra

The ^1H NMR spectra further support the assignment of the coordination modes. Figure 2 shows the $^1\text{H-NMR}$ spectrum

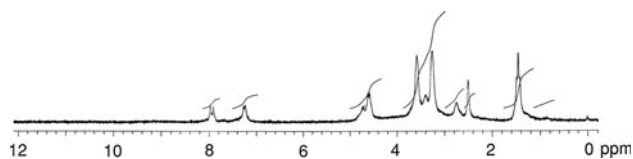


Fig. 2 $^1\text{H-NMR}$ spectrum of $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ complex

of Zn(II) complex which was carried out in DMSO- d_6 as a solvent. Upon comparison with the free ligand, the signal observed at 11 ppm can be assigned to the carboxylate OH. This signal disappears in the spectrum of the $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ complex, which confirms the coordination of NOR ligand to the M(II) ions through the deprotonated carboxylic O group. Due to the different chemical environments, two signals are recorded for the quaternized nitrogen ($-\text{NH}_2^+$) at δ 2.50 and 2.77 ppm. The peak at δ 3.55 ppm can be assigned as coming from the water molecules of hydration, which were not detected in the spectrum of the free NOR ligand. The protons of the $-\text{CH}_2-$ group quartet have a total integral of two units with the values δ 4.50–4.80 ppm, while the $-\text{CH}_3$ group (triplet) have an integral of three units with the values δ 1.40, 1.42 and 1.45 ppm.

Thermogravimetric analysis (TG)

In the present investigation, the heating rates were controlled at 283 K min^{-1} under nitrogen atmosphere and the weight loss was measured from ambient temperature up to $\cong 1,273 \text{ K}$. The data are listed in Table 3 and shown in Fig. 3. The weight losses for each chelate were calculated within the corresponding temperature ranges. The different thermodynamic parameters are listed in Table 4.

The thermogravimetric curve of $[\text{Cd}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ chelate shows three decomposition steps within the temperature range 303–1,273 K. The first steps of decomposition within the temperature range 303–413 K correspond to the loss of water molecules of hydration and Cl_2 gas with a mass loss of 12.58% (calcd. 12.47%). The energy of activation was $37.98 \text{ kJ mol}^{-1}$. The subsequent steps (413–1,273 K) correspond to the removal of the organic part of the ligand leaving metal oxide as a residue. The overall weight loss amounts to 86.34% (calcd. 85.03%).

Table 3 Thermogravimetric data of NOR metal complexes

Complex	TG range/ K	DTG _{max} / K	# <i>n</i>	Mass loss	Total mass loss/% found (calcd.)	Assignment	Final solid state residue
[Cd(NOR) ₂]Cl ₂ ·2H ₂ O	303–413	333	1	12.58 (12.47)		Loss of 2H ₂ O and Cl ₂	CdO
	413–843	593	1	38.04 (37.24)		Loss of C ₁₆ H ₁₈ FN ₃ O ₃	
	843–1,273	993	1	35.72 (35.32)	86.34 (85.03)	Loss of C ₁₆ H ₁₈ FN ₃ O ₂	
[Cd(NOR) ₂](NO ₃) ₂	373–693	633	1	44.63(43.60)		Loss of C ₁₆ H ₁₈ FN ₃ O ₃ and NO ₃	CdO
	693–1,173	953	1	42.03 (41.77)	86.66 (85.37)	Loss of C ₁₆ H ₁₈ FN ₃ O ₂ and NO ₃	
[Cd(NOR) ₂]SO ₄	303–1,073	338, 593, 933	3		74.84 (75.44)	Loss of 2C ₁₆ H ₁₈ FN ₃ O ₃	CdSO ₄
[Hg(NOR) ₂]Cl ₂	323–423	343	1	7.81 (7.80)		Loss of Cl ₂	HgO
	423–923	543, 763	2	68.86 (68.46)	76.67 (76.26)	Loss of C ₁₆ H ₁₈ FN ₃ O ₃ and C ₁₆ H ₁₈ FN ₃ O ₂	
[Hg(NOR) ₂](NO ₃) ₂	323–873	643	1		77.12 (77.56)	Loss of 2NO ₃ , C ₁₆ H ₁₈ FN ₃ O ₃ and C ₁₆ H ₁₈ FN ₃ O ₂	HgO
[Hg(NOR) ₂](OA) ₂	303–373	333	1	11.86 (12.32)		Loss of C ₂ H ₆ and 2CO ₂	HgO
	373–773	453, 603	2	65.73 (65.06)	77.59 (77.38)	Loss of C ₁₆ H ₁₈ FN ₃ O ₃ and C ₁₆ H ₁₈ FN ₃ O ₂	
[Zn(NOR) ₂]Cl ₂ ·2H ₂ O	313–403	338	1	4.71 (4.44)		Loss of 2H ₂ O	ZnO
	403–1,173	593, 923	2	85.86 (85.58)	90.57 (90.02)	Loss of Cl ₂ , C ₁₆ H ₁₈ FN ₃ O ₃ and C ₁₆ H ₁₈ FN ₃ O ₂	
[Zn(NOR) ₂](OA) ₂	303–423	373	1	7.02 (7.18)		Loss of C ₂ H ₃ O ₂	ZnO
	423–823	653	1	22.75 (22.51)		Loss of C ₂ H ₃ O ₂ and C ₇ H ₉ FN	
	823–1,273	993	1	59.70 (60.40)	89.47 (90.09)	Loss of C ₁₆ H ₁₈ FN ₃ O ₃ and C ₉ H ₉ N ₂ O ₂	
[Zn(NOR) ₂]Br ₂	423–1,273	773	1		89.91 (90.65)	Loss of Br ₂ , C ₁₆ H ₁₈ FN ₃ O ₃ and C ₁₆ H ₁₈ FN ₃ O ₂	ZnO

n Number of decomposition steps

Meanwhile, the TG curve of the [Cd(NOR)₂](NO₃)₂ chelate shows two stages of decomposition within the temperature range of 373–1,173 K. The first stage at 373–693 K corresponds to the loss of C₁₆H₁₈FN₃O₃ and NO₃ molecules with mass loss of 44.63% (calcd. 43.60%). The energy of activation for this step was 71.66 kJ mol⁻¹. The second step involves the loss of C₁₆H₁₈FN₃O₂ and NO₃ molecules with a mass loss of 42.03% (calcd. 41.77%). The energy of activation for this step was 56.79 kJ mol⁻¹. In addition, the [Cd(NOR)₂]-SO₄ complex decomposes in three successive steps within the temperature range 303–1,073 K with mass loss of 74.84% (calcd. 75.44%) leaving CdSO₄ as residue. The activation energies were 96.38, 241.0 and 92.93 kJ mol⁻¹ for the 1st, 2nd and 3rd steps, respectively (Table 4).

On the other hand, [Hg(NOR)₂]Cl₂ and [Hg(NOR)₂](AcO)₂ chelates exhibit three decomposition steps. The first step in the temperature range 323–423 and 303–373 K [mass loss = 7.81% (calcd. 7.80%) and 11.86% (calcd. 12.32%)] may accounted for the loss of Cl₂ gas and C₂H₆ and 2CO₂ gases for [Hg(NOR)₂]Cl₂ and [Hg(NOR)₂](AcO)₂ complexes, respectively. As shown in Table 3, the mass losses of the remaining decomposition steps amount

to 68.86% (calcd. 68.46%) and 65.73% (calcd. 65.06%). They correspond to the removal of NOR molecules leaving HgO as a residue. The energy of activation for these steps was 59.40 and 49.82 and 61.89 and 67.83 kJ mol⁻¹ for the 2nd and 3rd steps of [Hg(NOR)₂]Cl₂ and [Hg(NOR)₂](AcO)₂ complexes, respectively. The [Hg(NOR)₂](NO₃)₂ complex was thermally decomposed in one decomposition step within the temperature range of 323–873 K. The estimated mass loss of 77.12% (calcd. mass loss = 77.56%) may be attributed to the liberation of the 2NO₃ and 2 NOR molecules leaving HgO as a residue. The activation energy was 17.24 kJ mol⁻¹.

The TG curves of the [Zn(NOR)₂]Cl₂·2H₂O and [Zn(NOR)₂](OA)₂ chelates represent three decomposition steps as shown in Table 3. The first step of decomposition within the temperature range 313–403 and 303–423 K corresponds to the loss of hydrated water molecules and C₂H₃O₂ with a mass loss of 4.71% (calcd. for 2H₂O; 4.44%) and 7.02% (calcd. for C₂H₃O₂; 7.18%) for [Zn(NOR)₂]Cl₂·2H₂O and [Zn(NOR)₂](OA)₂ chelates, respectively. The energy of activation for this step was 46.75 and 112.7 kJ mol⁻¹ for [Zn(NOR)₂]Cl₂·2H₂O and [Zn(NOR)₂](OA)₂ chelates, respectively. The remaining steps of decomposition within

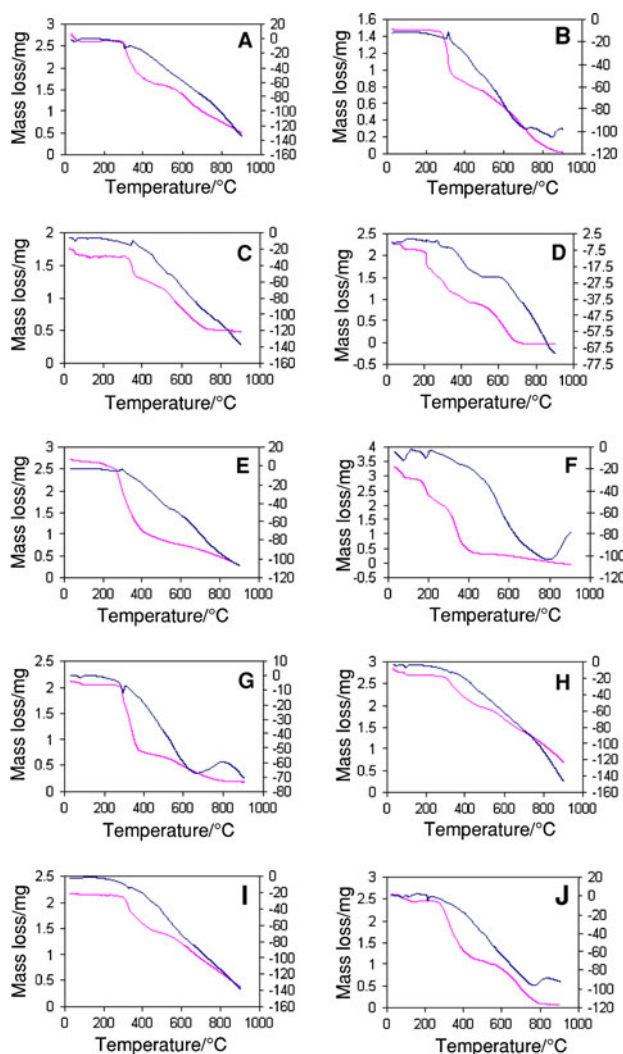


Fig. 3 TG/DTG curves of **a** $[\text{Cd}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$, **b** $[\text{Cd}(\text{NOR})_2](\text{NO}_3)_2$, **c** $[\text{Cd}(\text{NOR})_2]\text{SO}_4$, **d** $[\text{Hg}(\text{NOR})_2]\text{Cl}_2$, **e** $[\text{Hg}(\text{NOR})_2](\text{NO}_3)_2$, **f** $[\text{Hg}(\text{NOR})_2](\text{OA})_2$, **g** $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$, **h** $[\text{Zn}(\text{NOR})_2](\text{OA})_2$, **i** $[\text{Zn}(\text{NOR})_2]\text{Br}_2$ and **j** $[\text{Cd}(\text{NOR})_2]_2$ complexes

the temperature range 403–1,173 and 423–1,273 K correspond to the removal of NOR ligands in the form of gases with an energy of activation for these steps of 113.6 and 65.91, and 47.81 and 70.13 kJ mol^{-1} for the 2nd and 3rd steps of $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ and $[\text{Zn}(\text{NOR})_2](\text{OA})_2$ chelates, respectively. The overall weight losses amount to 90.57% (calcd. 90.02%) and 89.47% (calcd. 90.09%) for $[\text{Zn}(\text{NOR})_2]\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ and $[\text{Zn}(\text{NOR})_2](\text{OA})_2$ chelates, respectively. The $[\text{Zn}(\text{NOR})_2]\text{Br}_2$ complex was thermally decomposed in one decomposition step within the temperature range of 423–1,273 K. The estimated mass loss of 89.91% (calcd. mass loss = 90.65%) may be attributed to the liberation of the Br_2 and 2(NOR) molecules leaving ZnO as a residue. The activation energy was 205.0 kJ mol^{-1} . The

starting and final products were confirmed using IR spectrometry and X-ray powder diffraction. As an example, the X-ray powder pattern of the final products of ZnO for the Zn(II) complexes is shown in Fig. 4.

Kinetic data

The thermodynamic activation parameters of decomposition processes of dehydrated complexes namely activation energy (E^*), enthalpy (ΔH^*), entropy (ΔS^*) and Gibbs free energy change of the decomposition (ΔG^*) were evaluated graphically by employing the Coats–Redfern relation [24]. The entropy of activation (ΔS^*), enthalpy of activation (ΔH^*) and the free energy change of activation (ΔG^*) were calculated using the following equations

$$\Delta S^* = 2.303[\log(Ah/kT)]R \quad (1)$$

$$\Delta H^* = E^* - RT \quad (2)$$

$$\Delta G^* = \Delta H^* - T\Delta S^* \quad (3)$$

The data are summarized in Table 4. The activation energies of decomposition were found to be in the range 17.24–241.0 kJ mol^{-1} . The high values of the activation energies reflect the thermal stability of the complexes [25–27]. The entropy of activation was found to have negative values in all the complexes which indicate that the decomposition reactions proceed with a lower rate than the normal ones.

Antimicrobial activity

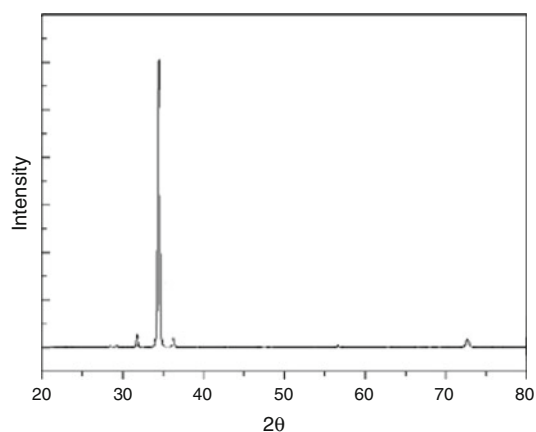
Antibacterial and antifungal activities of the NOR ligand and its complexes are carried out against the *Escherichia coli* (Gram –ve), *Bacillus subtilis* (Gram +ve) and antifungal (trichoderma and penicillium activities). The results of the antimicrobial test are given in Table 5 and shown in Fig. 5. The antimicrobial activity is estimated based on the size of inhibition zone around dishes. The complexes are found to have high activity against *Bacillus subtilis* and penicillium, whereas the Hg(II) complex is more active than the Zn(II) and Cd(II) complexes against trichoderma.

Structural interpretation

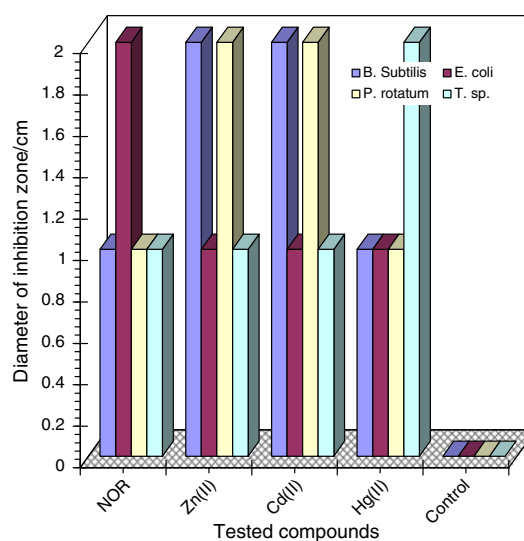
The structures of the complexes of NOR with Cd(II), Hg(II) and Zn(II) ions have been confirmed from the elemental analyses, IR, molar conductance, UV–vis, mass and thermal analysis data. Thus, from the IR spectra, it is concluded that NOR behaves as a monobasic bidentate

Table 4 Thermodynamic data of the thermal decomposition of NOR metal complexes

Complex	Decomp. temp./K	$E^*/$ kJ mol ⁻¹	A/s^{-1}	$\Delta S^*/$ JK ⁻¹ mol ⁻¹	$\Delta H^*/$ kJ mol ⁻¹	$\Delta G^*/$ kJ mol ⁻¹	Correlation coefficient/ r^2
[Cd(NOR) ₂]Cl ₂ ·2H ₂ O	303–413	37.98	2.24×10^5	-129.2	37.48	45.23	0.92
	413–843	27.96	1.81×10^8	-87.45	25.31	53.30	0.91
	843–1,273	71.28	5.28×10^7	-104.4	65.29	140.5	0.90
[Cd(NOR) ₂](NO ₃) ₂	373–693	71.66	8.42×10^5	-133.0	68.67	116.6	0.94
	693–1,173	56.79	1.33×10^8	-96.26	51.14	116.6	0.96
[Cd(NOR) ₂]SO ₄	303–433	96.38	5.06×10^{14}	-49.25	95.84	92.64	0.91
	433–793	241.0	1.96×10^{19}	-123.8	238.4	198.8	0.90
	793–1,073	92.93	1.41×10^6	-133.8	87.44	176.0	0.92
[Hg(NOR) ₂]Cl ₂	323–423	116.2	3.35×10^{16}	-83.50	115.6	109.7	0.99
	423–693	59.40	1.21×10^5	-146.8	57.15	96.79	0.90
	693–923	49.82	8.96×10^7	-96.82	45.74	93.18	0.90
[Hg(NOR) ₂](NO ₃) ₂	323–773	17.24	2.33×10^9	-67.41	14.17	39.11	0.90
[Hg(NOR) ₂](OA) ₂	303–373	56.33	1.05×10^8	-78.05	55.83	60.52	0.94
	373–553	61.89	7.97×10^5	-127.8	60.39	83.39	0.98
	553–773	67.83	2.58×10^5	-142.2	66.08	112.0	0.91
[Zn(NOR) ₂]Cl ₂ ·2H ₂ O	303–413	46.75	1.12×10^6	-116.5	46.21	53.78	0.91
	473–583	113.6	4.22×10^8	-80.39	111.0	136.7	0.92
	723–893	65.91	4.46×10^7	-105.0	60.51	10.9228.7	
[Zn(NOR) ₂](OA) ₂	303–423	112.7	5.39×10^{17}	-103.6	111.8	101.5	0.94
	423–823	47.81	1.20×10^7	-111.4	44.64	86.99	0.95
	823–1,273	70.13	6.25×10^7	-103.0	64.14	138.3	0.91
[Zn(NOR) ₂]Br ₂	423–1,273	205.0	3.10×10^9	-67.52	16.34	50.10	0.90

**Fig. 4** X-ray pattern of the final products of Zn(II)/NOR complexes**Table 5** Antimicrobial activity of NOR and its complexes

Tested compounds	Diameter of inhibition zone/cm			
	<i>B. subtilis</i>	<i>E. coli</i>	<i>P. rotatum</i>	<i>T. sp.</i>
NOR	1	2	1	1
Zn(II)	2	1	2	1
Cd(II)	2	1	2	1
Hg(II)	1	1	1	2

**Fig. 5** Biological activity for NOR and its complexes

ligand coordinated to the metal ions via the deprotonated carboxylate O and carbonyl groups. From the molar conductance data, it is found that the complexes are non-electrolytes. On the basis of the above observations,

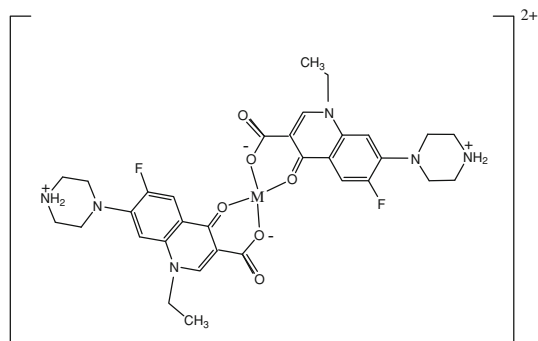


Fig. 6 The proposal of M-ligand coordination, where M = Zn(II), Cd(II) and Hg(II)

tetrahedral geometries are suggested for the investigated complexes. As a general conclusion, the investigated complexes structures can be given as shown below (Fig. 6).

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