

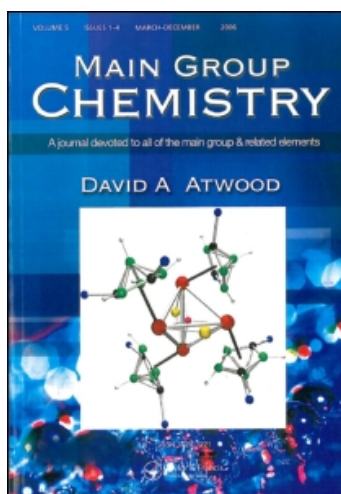
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### $^1\text{H}$ NMR, spectroscopic and molecular modeling studies on paramagnetic lanthanide(III)-quercetin complexes

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# <sup>1</sup>H NMR, spectroscopic and molecular modeling studies on paramagnetic lanthanide(III)-quercetin complexes

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Nine coordinated [Ln(quercetin)<sub>3</sub>]*n*H<sub>2</sub>O complexes were synthesized in non-aqueous solution (where, *n*=0 for Pr, Sm, Gd, Tb, Dy and Ho; *n*=3, for La and Nd). The complexes were characterized by elemental analysis, molar conductance, UV–vis spectra, IR spectra, thermal analysis and NMR spectra. The optimized structures of the complexes were obtained by molecular modeling. The complexes behave as non-electrolytes in DMSO. TGA study showed anhydrous nature of the complexes (except La and Nd). The <sup>1</sup>H NMR spectra of lanthanum, praseodymium, neodymium and samarium complexes have been studied in DMSO-*d*<sub>6</sub>. The complexes do not dissociate in DMSO and retain their coordination number. The NMR spectra of paramagnetic and diamagnetic complexes of quercetin exhibit lower as well as higher field shifts that show change in geometry during the metal ligand coordination.

*Keywords:* Quercetin; Lanthanides; Molecular modeling; Density functional theory; <sup>1</sup>H NMR

## 1. Introduction

Polyphenolic compounds are widely distributed in plants [1,2]. They have potential beneficial effects on human health in the prevention of chronic and degenerative diseases where free radicals are involved [3–5]. Flavonoids have long been recognized to possess anti-hepatotoxic, anti-inflammatory, anti-atherogenic, anti-allergic, anti-osteoporotic and anti-tumor (anti-cancer) activities due to their free radical scavenging abilities [6–10]. Although free radicals may have useful physiological functions [11,12], they can damage bio-molecules when generated in excess, being therefore implicated in the aetiology of several diseases and ageing [13]. The chelating ability of flavonoids with metal ions has a role in the diagnosis and treatment of diseases [13–18]. It has been reported that Ln(III) complexes have been used as contrast agents in magnetic resonance imaging and for expanding employment in nuclear medicine [19–26]. The paramagnetic nature of lanthanide (III) ions (except La) shows induced substantial chemical shifts in the <sup>1</sup>H NMR of ligands, the signals of the protons located in the vicinity of the metal center are due to the vibronic coupling of

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the central ion with its ligands [21,26]. Such frequency shifts have been the subject of NMR studies [21–26], and have led to the widespread use of paramagnetic lanthanide complexes as NMR shift reagents [20,22–28]. The effect of lanthanide (III) ions on both chemical shifts and relaxation time of the different nuclei of organic ligands give information on the chelation of the ligand, type, stoichiometry and geometry of the complexes in solution.

Recently, it has been reported that the interaction of quercetin with trivalent lanthanides in methanol solution yields complex species of the type  $[\text{Ln}(\text{quercetin})_3 \cdot 6\text{H}_2\text{O}]$  in which both the coordinated and non-coordinated lattice water molecules are present, making the lanthanides eight-coordinated [15]. In the present work, we investigate in detail the spectroscopic and molecular modeling studies of Ln-tris(quercetin) complexes.

## 2. Experimental

### 2.1 Materials

Lanthanide oxides (99.9%, Lieco Chemicals, USA) are converted to their corresponding chlorides. Quercetin dihydrate methanol (99.9%, Sigma-Aldrich, USA), xylene orange (SD Fine Chemicals) and EDTA (BDH) were used as such in this study.

### 2.2 Synthesis

**2.2.1 Preparation of  $\text{Ln}(\text{quercetin})_3 \cdot n\text{H}_2\text{O}$  complexes.** The complexes were synthesized by the method reported earlier with a little modification [13,15]. A hot solution of 3 mmol of the quercetin dihydrate in methanol ( $50 \text{ cm}^3$ ) was added dropwise to the stirred solution of 1 mmol of hydrated lanthanum chloride (for example) in methanol ( $50 \text{ cm}^3$ ). The reaction mixture was stirred constantly for 6 h at  $100^\circ\text{C}$  temperature on a hot plate, and the volume of the solution was reduced, then filtered and washed with chloroform. The solution was kept at room temperature for slow evaporation. Pale yellow color crystals were obtained and dried *in vacuo* over  $\text{P}_4\text{O}_{10}$ .

## 3. Methods or physical measurements

Microanalysis (carbon and hydrogen) was carried out with a FI-SONS EA-1108 elemental analyzer. The metal content of the complexes was estimated by complexometric titration. Molar conductances of  $10^{-3} \text{ M}$  DMSO solution of the complexes were measured with an orion conductivity meter. The thermograms were recorded on a du Pont TA 2000 TGA machine under nitrogen atmosphere at a heating rate of  $10^\circ\text{C min}^{-1}$ . Melting points (MP) were measured with a Gallenkamp MBF-595 apparatus. A shimadzu UV-2501PC spectrophotometer was used to obtain the electronic spectra in the region of 250–700 nm in DMSO solvent. FTIR spectra in the 4000–400  $\text{cm}^{-1}$  regions were recorded from KBr pellets on a PerkinElmer Lambda-40B spectrophotometer.  $^1\text{H}$  NMR chemical shift was measured in DMSO- $d_6$  solvent on a Bruker 300 MHz spectrophotometer. Molecular modeling studies on quercetin and its complex were carried out by using the software Hyperchem 7.51 professional version.

#### 4. Results and discussion

Elemental analysis, molar conductance, UV–vis, IR, TGA and  $^1\text{H}$  NMR indicated the formation of a mononuclear lanthanide complex where one metal ion is bound with three quercetin molecules (figure 1). These results suggested that the complexes have the empirical formula  $[\text{Ln}(\text{quercetin})_3 \cdot x\text{H}_2\text{O}]$  (where  $\text{Ln} = \text{La}, \text{Nd}, \text{Sm}, \text{Tb}, \text{Gd}, \text{Dy}$  and  $\text{Ho}$ ) (figure 2). These complexes are air stable and cannot be affected by air or moisture. The synthesis was carried out at room temperature and no precaution was taken to exclude moisture. Quercetin complexes are crystalline solids that have sharp melting points between the range of 290 and 310°C. These complexes do not show any trace of moisture (except La and Nd complexes). The complexes are soluble in polar organic solvents, but insoluble in non-polar solvents. All the metal complexes that exhibit low molar conductances behave as non-electrolytes in DMSO [29] ( $10^{-3}$  M solution).

#### 5. Optical absorption spectral studies

The study of the fundamental absorption edge in the UV–visible region is a useful method for the investigation of optical absorption transitions in solution medium. The absorption spectra of the ligand and their eight complexes were recorded in methanol, DMF and DMSO solvents. The characteristic absorption peaks are given in table 1. The optical absorption spectrums of Pr(III), Nd(III), Dy(III) and Ho(III) complexes were also measured in the visible region in the range 250–900 nm. But principal characteristic absorption transitions of Pr ( $^3\text{P}_0, ^3\text{P}_1$  and  $^3\text{P}_2 \leftarrow ^3\text{H}_4$ ), Nd ( $^2\text{K}_{13/2}, ^4\text{G}_{7/2}, ^4\text{G}_{9/2}$  and  $^2\text{G}_{7/2}, ^4\text{G}_{5/2} \leftarrow ^4\text{I}_{9/2}$ ) and Ho ( $^5\text{G}_6, ^5\text{G}_5, ^3\text{G}_5, ^3\text{H}_6, ^3\text{H}_5 \leftarrow ^5\text{I}_8$ ) could not be observed [26,30] owing to the strong absorption of quercetin ligand in the visible region. The quercetin ligand shows two absorption bands in methanol, DMF and DMSO solution spectrums [14,16], band I is due to the  $n\text{-}\sigma^*$ ,  $n\text{-}\pi^*$  and  $\pi\text{-}\pi^*$  transitions, whereas band II represents ring B, due to  $n\text{-}\sigma^*$  and  $\pi\text{-}\pi^*$  transitions [31,32]. The explanation of the above two bands would be similar as that discussed for the analogous complexes [32]. The spectrum of the complexes exhibit an extra band of slight intensity in the middle of the two bands of ligand. The intensity of this extra band was different from that of these two bands (table 1). The presence

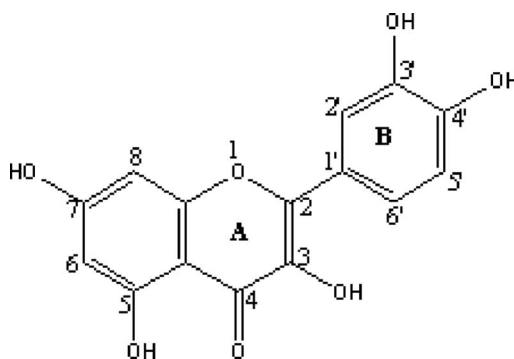


Figure 1. Structure of quercetin.

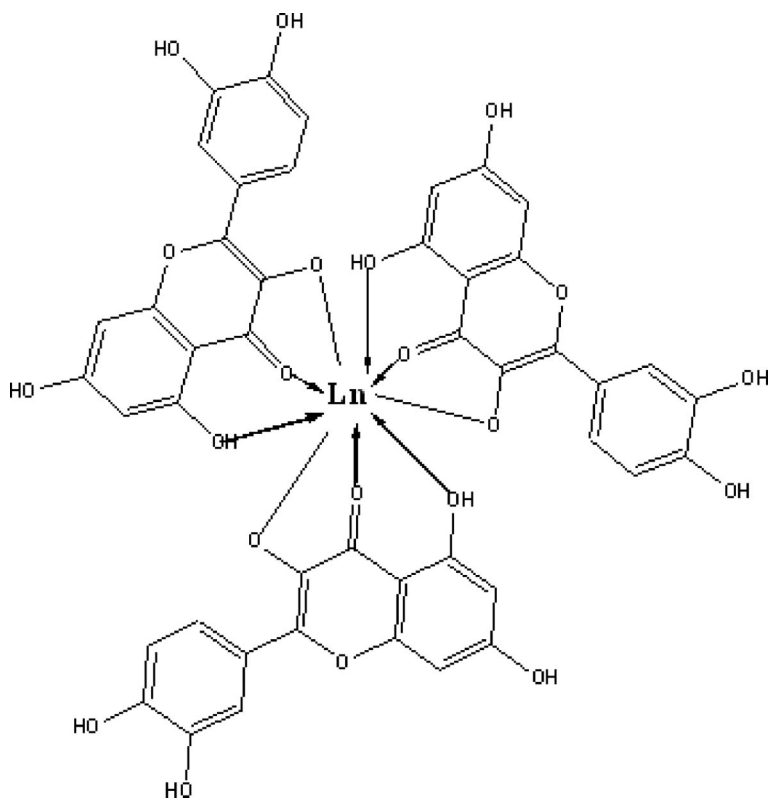


Figure 2. Tentative proposed structure of lanthanide complexes.

Table 1. UV–visible spectral data of quercetin complexes.

Ligand/Complex	Quercetin	La	Pr	Nd	Sm	Gd	Tb	Dy	Ho
Band I									
MeOH	412	–	–	–	–	–	–	–	–
DMF	375	–	–	–	–	–	–	–	–
DMSO <sup>a</sup>	370	371	379	372	373	374	375	379	370
Band II									
MeOH	238	–	–	–	–	–	–	–	–
DMF	262	–	–	–	–	–	–	–	–
DMSO	260	305	306	305	306	306	306	302	305
Band III									
DMSO	–	269	263	267	268	269	267	265	277

<sup>a</sup>Reference 16.

of this extra band in the middle of the spectrum suggested that the solvent (DMSO) coordinates in the inner coordination sphere of the metal ion of the complexes. It is believed that DMSO enters the coordination sphere in the complex by replacing the hydroxyl group [OH(5)] without affecting the carbonyl group and phenolic OH(3) group to the metal ion in the complex(s). It is certain that DMSO could not displace any of the quercetin molecules from the complex, low molar

conductance shows that the complexes are non-electrolytes in this solvent [15,30]. But it is uncertain as to whether the number of DMSO molecules is associated to the metal ion in the complex. Gutmann has reported that DMSO has high electron pair donating ability to the metal ion in the complexes [33]. The results agreed with the reported literature [34,35], which suggested that the solvent coordinates to the metal ion in the complexes.

## 6. Infrared spectral studies

Infrared absorption spectra are found to be the most useful physical method for investigating and identifying functional groups. The characteristic IR absorption frequencies in the spectral range of  $4000\text{--}400\text{ cm}^{-1}$  were measured for free quercetin and their metal complexes. The IR absorption data are given in table 2. Comparison of quercetin absorption frequencies and their lanthanide (III) complexes provides positive indication that quercetin is involved in bonding to the metal ion. The IR absorption at  $502\text{--}478\text{ cm}^{-1}$  in the complexes is assignable to  $\nu(\text{M}\text{--}\text{O})$  [37,38]. Two intense and broad bands around  $3409$  and  $3292\text{ cm}^{-1}$  corresponding to  $\nu(\text{OH})_{\text{as}}$  and  $\nu(\text{OH})_{\text{s}}$ , respectively, and a medium intensity band around  $1430\text{ cm}^{-1}$  corresponding to  $\delta(\text{OH})$  are consistent with the presence of a high degree of hydration for almost all the complexes [36–39]. This OH stretching has shifted to lower frequency ( $\sim 100\text{ cm}^{-1}$ ) in the complexes spectrum compared with its free quercetin spectrum. The OH in-plane and out-of-plane having strong deformation vibrational bending modes in the free ligand appeared at  $1014$  and  $822\text{ cm}^{-1}$  which were shifted after complex formation to medium sharp intensity at  $1012$  and  $820\text{ cm}^{-1}$  in the case of La and Nd complexes [37,38]. Moreover, the rest of the complexes exhibited these peaks at  $1006$  and  $819\text{ cm}^{-1}$  with medium intensity. The small shift of IR absorption bending modes to lower frequency may be due to the presence of water molecules, and the high shift indicates coordination of hydroxyl group to the metal ion in the complexes (La and Nd complexes). The appearance of these bending vibrational modes in the spectrum of the complexes suggests that some hydroxyl groups remain uncoordinated. It means that the OH(3) group is losing H ion during the coordination and the OH(5) group participates in the coordination to the metal ion without losing H ion in the complexes. This was confirmed by the presence of bending modes in the spectrum of the complexes. In the IR spectrum of lanthanum complexes, the C=O stretching band was more shifted to a lower frequency in comparison with the C–O–C stretching bands; this indicates that the  $\nu\text{C}=\text{O}$  group takes part in the coordination of the metal ion in the complex. Of the skeletal vibrations, the  $\nu\text{C}=\text{C}$  and  $\nu\text{C}\text{--}\text{C}$  stretching absorptions lie in the region of  $1611\text{--}1000\text{ cm}^{-1}$ , and the deformation bands occur below  $1000\text{ cm}^{-1}$ . The skeletal ring vibrational modes in the in-plane and out-of-plane deformations with medium IR absorption intensities in the region of  $1000\text{--}500\text{ cm}^{-1}$  characteristic frequencies were observed in the spectrum of complexes [40].

## 7. Thermal analysis

The thermal stability of lanthanide complexes was determined by thermo-gravimetric analysis between the temperature ranges of  $30$  and  $600^\circ\text{C}$  under a nitrogen atmosphere

Table 2. IR absorption frequencies of quercetin complexes.

Functional Groups	Quercetin	La	Pr	Nd	Sm	Gd	Tb	Dy	Ho
$\nu(\text{O-H})$	3409–3100	3291	3292	3293	3294	3292	3293	3298	3293
$\nu(\text{C-H})$	2965	2996	merg	2992	2999	merg	2996	2890	2996
$\nu(\text{C=O})$	1666	1672	1673	1611	1669	1663	1670	1617	1613
$\nu(\text{C}\equiv\text{C})$	1611, 1562, 1522	1617, 1517	1617, 1513, 1457	1513	1614, 1516	1615, 1554, 1513	1615, 1514	1513	1516
$\delta(\text{O-H}), \text{C-O-H}$	1452	1430	1430	1427	1429	1458	1430	1430	1429
$\nu(\text{C-O}), \text{C-O-C}, \text{C-C-O}$	1382, 1320	1383, 1318	1360, 1316	1359	1360, 1319	1360, 1319	1358, 1317	1362, 1319	1360, 1320
$\nu(\text{C-C}), \parallel$	1262	1244, 1213	1244, 1211	1240, 1213	1245, 1213	1246, 1211	1245, 1212	1246, 1212	1246, 1213
$\nu(\text{C-C}), \parallel$									
$\nu(\text{O-H})$ in plane deformation	1014	1166	1165	1166	1167	1168	1166	1167	1168
$(\text{C-H}),$ in plane deformation	1199, 1169	1096	1094	1096, 975	1097	1094	1095	1095	1069
$(\text{C-C})$ in plane deformation	864	1012, 933	1000, 932	1004	1006, 934	1000, 933	1001, 933	1001	1000
$(\text{O-H})$ out of plane deformation	822	880	878, 819	933, 882	882	884	882	933, 879	931, 881
$(\text{C-H})$ out of plane deformation	722	821, 789	636	791, 701	820, 705	790, 704	790, 704	819, 790	820
$(\text{C-C})$ out of plane deformation	679, 602	707, 636	597	597	598	639, 598	598	598	602
M-O	—	498	486	Not obs	478	499	502	497	Not obs

Merg, Merged; Obs, Observed.

with a heating rate of  $10^{\circ}\text{C min}^{-1}$ . These complexes were devoid of lattice water (except La and Nd complexes) as well as coordinated water, since the thermograms did not show any weight loss below  $200^{\circ}\text{C}$ . No degradation was observed below this temperature (figure 3). The thermograms of La and Nd complexes were similar in shape and showed degradation of their constituents into three successive decomposition steps. The first inflexion point in the thermograms of La and Nd complexes appeared at  $85^{\circ}\text{C}$  and  $100^{\circ}\text{C}$  with a weight loss of 5.6% and 5.2%, respectively, which corresponds to removal of three water molecules (calculated weight loss for three water molecules is 4.9% and 5.15%, respectively). A corresponding endothermic peak in the DTG curve was observed at this temperature. The elimination of water molecules at this temperature indicates that these water molecules are present outside the coordination sphere. This is supported by the peaks appearing at  $1012$  and  $820\text{ cm}^{-1}$  in the IR spectra of the complexes. Other derivative curves were observed at  $398$  and  $397^{\circ}\text{C}$  with the weight loss of 44.9% and 44.0%, respectively, which is equivalent to two molecules of quercetin (calculated weight loss for two quercetin molecules is 55.08% and 57.44%, respectively). The thermograms revealed a third inflexion point at  $449$  and  $457^{\circ}\text{C}$  with the weight loss of 36.50 and 36.15%, respectively, which corresponds to that of the one molecule of quercetin (calculated weight loss for one molecule is 27.54 and 28.72%, respectively). The observed weight loss in the second DTA curve was less than the calculated weight loss due to the decomposition of the constituents. The decomposition of the third molecule of quercetin began without the complete removal of the second molecule of quercetin, which is also confirmed from the II inflexion point of the complexes that is more than one molecule of quercetin.

The thermograms of Pr, Sm, Tb, Dy and Ho complexes were analogous in shape to one another (figure 4). Only two major weight losses in the thermograms of these complexes occurred. The first inflexion point in the thermograms of the complexes appears in the temperature range of  $339$ – $392^{\circ}\text{C}$  with a corresponding peak in the DTG curve. The observed weight losses are in the range between 27.8–38.8%, that is

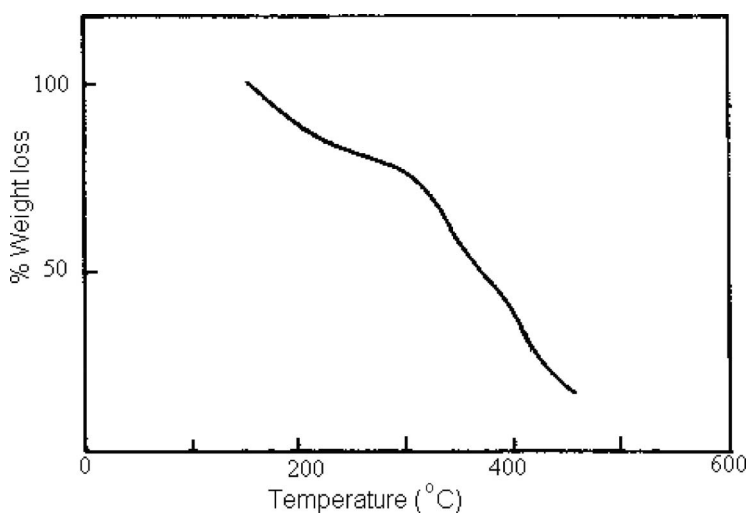


Figure 3. Thermogram spectra of  $[\text{Pr}(\text{quercetin})_3]$  complex.



equivalent to removal of 1 molecule of quercetin (calc. weight loss for 1 molecule of quercetin is in the range 28.76–28.3%). The observed weight loss in the first inflexion point is more than the calculated weight loss due to the second molecule beginning to come out before the complete removal of the first molecule, which is reflected by a TGA break and a DTG peak at this temperature. The second inflexion point in the thermograms appears between the range 424–471°C and the observed weight loss represents the elimination of two quercetin molecules (observed weight loss in the range 47.2–56.8%; calc. weight loss is in the range 56.52–57.44%) (table 3).

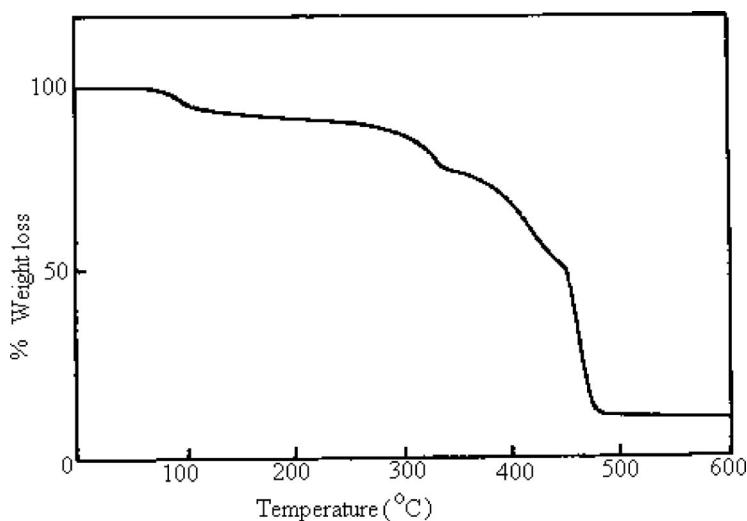


Figure 4. Thermogram spectra of  $[\text{Nd}(\text{quercetin})_3] 3\text{H}_2\text{O}$  complex.

Table 3. Thermal analysis data of quercetin complexes.

Complexes	Temperature (°C)	% Weight loss		Constituents eliminated
		Calc.	Obs.	
La	85	4.9	5.65	3 H <sub>2</sub> O
	397	55.08	44.96	2 molecules of quercetin
	449	27.54	36.50	1 molecule of quercetin
Pr	372	28.78	27.78	1 molecule of quercetin
	471	57.56	56.8	2 molecules of quercetin
Nd	100	5.15	5.60	3 H <sub>2</sub> O
	397	57.44	44.59	2 molecules of quercetin
	457	28.72	36.15	1 molecule of quercetin
Sm	339	28.65	38.8	1 molecule of quercetin
	462	57.2	47.25	2 molecules of quercetin
Tb	378	28.32	28.00	1 molecule of quercetin
	456	56.65	55.68	2 molecules of quercetin
	392	28.32	29.9	1 molecule of quercetin
Dy	424	56.64	56.5	2 molecules of quercetin
	383	28.32	32.85	1 molecule of quercetin
	436	56.52	51.9	2 molecules of quercetin

## 8. NMR spectral studies

<sup>1</sup>H NMR spectra of lanthanum, praseodymium, neodymium and samarium complexes have been recorded in DMSO-d<sub>6</sub>. Assignments of proton signals are based on the reports available in the literature [14]. The chemical shifts and the paramagnetic shifts are summarized in table 4. The chemical shift data of the free ligand [14] and lanthanum complex [16] have been reported earlier and are shown here for comparison purposes, but our observed spectral results does not coincide with the reported results. <sup>1</sup>H NMR spectrum of the complexes are shown in figures 5–7. The proton resonances of quercetin molecule shifted remarkably to downfield as well as up field on coordination with metal ion relative to the free quercetin molecule. The lower field as well as up field shifts of quercetin resonances are the strong evidence that the aromatic ring remains coordinated to the lanthanum ion even in DMSO solution. The larger downfield shift was detected for biphenolic aromatic ring protons, which confirmed stronger bonding of the ligand to the metal ion. The quinonolic aromatic ring protons of quercetin in La complex shift to lower fields as compared with those of free ligand [except to H(8)]. However, the hydroxyl group proton-resonance shift of quercetin in La complex is opposite to higher field in comparison to the free ligand. The up field shifts of hydroxyl proton resonances probably due to the intermolecular hydrogen bonding between the hydroxyl groups. Proton H(8) is up field shifted due to the shielding effect (positive inductive effect) of the hetero-aromatic ring, indicating that the quinonolic carbonyl group is associated preferentially with the  $\pi$ -ring of the quercetin. In addition, the H(8) proton is reported to shift to high field in the case of transition metals because there is no interaction between hydrogen and metal ions [14], but in the complex this interaction is not possible as the M–H distance is large. This is in agreement with our observed results. These protons, which are shifted to lower fields, are subjected to no perturbing influence other than the deshielding as expected from the electron withdrawing inductive effect of coordination. The shifts of hydroxyl group proton increase in diamagnetic lanthanum complex with increase in the distance of protons from the metal ion and it is larger for OH(7) proton and smaller for OH(4') in comparison to the free ligand.

The spectra of paramagnetic complexes are more interesting as compared with the diamagnetic complex as the quercetin proton resonances have been shifted to lower as well as up fields. In all the paramagnetic complexes, changes in chemical shifts of quercetin resonance are approximately equal. The magnitude and direction of such changes are a function of the central atom. The paramagnetic shifts are also given in table 4. From the literature reports [41], electron delocalization in lanthanide complexes may be obtained from NMR studies of paramagnetic species, provided nuclear relaxation times are short enough to allow well-resolved spectra to be obtained. A large number of reports are available in literature [20–26,41] about the paramagnetic shift (dipolar or pseudo-contact) in paramagnetic trivalent lanthanide complexes. The dipolar shift may arise from two sources, contact or pseudo-contact interactions when the paramagnetic centre is a rare earth ion; the pseudo-contact shift (dipolar) is expected to be substantial contributions, particularly in the absence of extensive conjugation. The quercetin proton resonances displayed larger dipolar shifts in paramagnetic complexes spectrum relative to their corresponding diamagnetic analogue. The pseudo-contact shifts and paramagnetic relaxation times are powerful sources for investigation of the geometrical information and region around a metal

Table 4. <sup>1</sup>H NMR spectral data of quercetin complexes in DMSO-d<sub>6</sub>.

Compound	Chemical shifts (paramagnetic shifts)										
	5-OH	7-OH	3-OH	4'-OH	3'-OH	H-2'	H-6'	H-5'	H-8	H-6	H <sub>2</sub> O
Quercetin	12.52 <sup>a</sup> 11.72 <sup>b</sup>	10.8 10.83	9.58	9.32 9.27	9.29 9.21	7.65 7.85	6.92 7.14	6.51 6.56	6.83 6.42	6.16 6.18	3.3-4.0
La	12.30	10.32	-	9.13	8.91	7.74s	7.89d	7.59d	6.36s	6.18s	-
Pr	12.49	10.82	-	9.61	9.37	7.67s	7.55d	6.90d	6.41s	6.19s	-
Nd	(0.19) 11.8	(0.50) 10.4	-	(0.48) 7.08	(0.46) *	(-0.07) 7.70s	(-0.34) 9.10d	(-0.69) 8.00d	(0.05) 6.58s	(0.01) 6.23s	-
Sm	(-0.50) 12.18	(0.08) 10.41	-	(-2.05) 9.01	(-1.83) 8.75	(-0.04) 8.25s	(1.21) 7.77d	(0.41) 6.92d	(0.22) 6.42s	(0.05) 6.23s	-
	(-0.12)	(0.09)	-	(-0.12)	(-0.16)	(0.51)	(-0.12)	(-0.67)	(0.06)	(0.05)	

Chemical shift and paramagnetic shifts are expressed in ppm ( $\delta$ ); s: singlet; d: doublet.

The negative sign indicates an up field shift and positive shifts are downfield to TMS.

<sup>a</sup> and <sup>b</sup>References 14 and 16.

\*Signal is merged with 4'-OH proton.

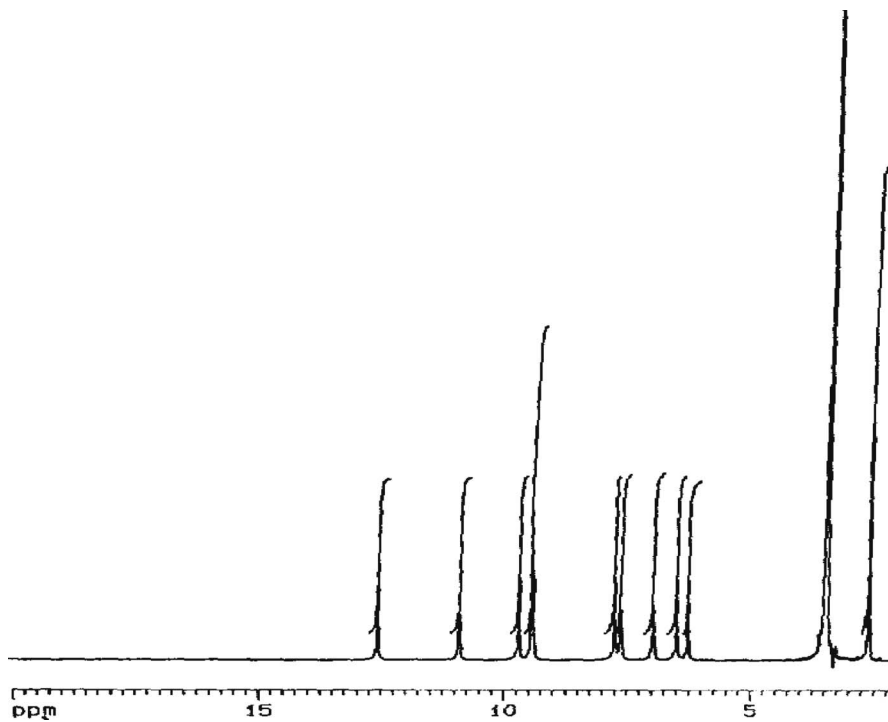


Figure 5. <sup>1</sup>H NMR spectra of Pr(quercetin)<sub>3</sub> complex in DMSO-d<sub>6</sub>.

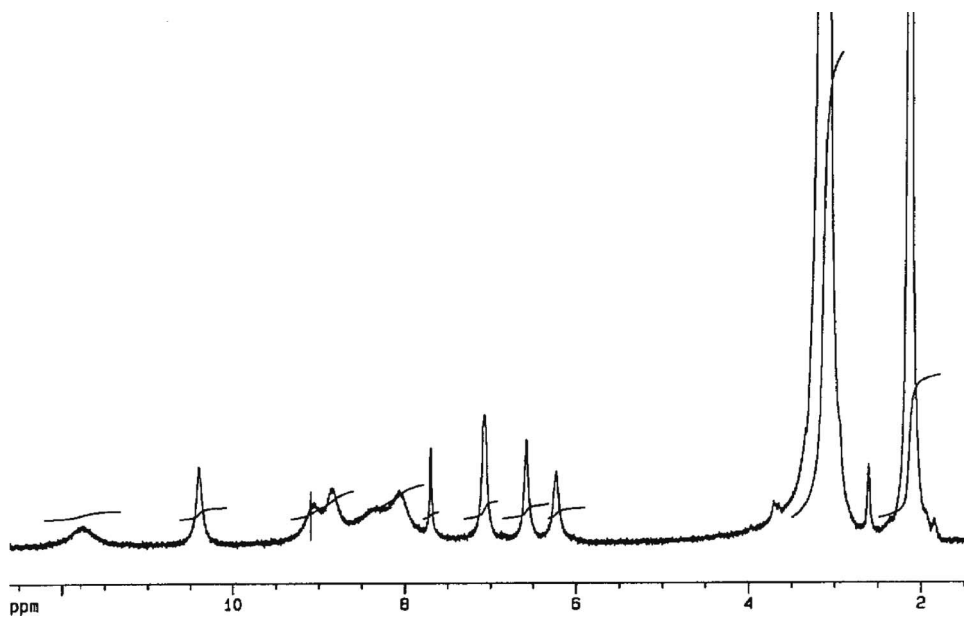


Figure 6. <sup>1</sup>H NMR spectra of Nd(quercetin)<sub>3</sub>·3H<sub>2</sub>O complex in DMSO-d<sub>6</sub>.

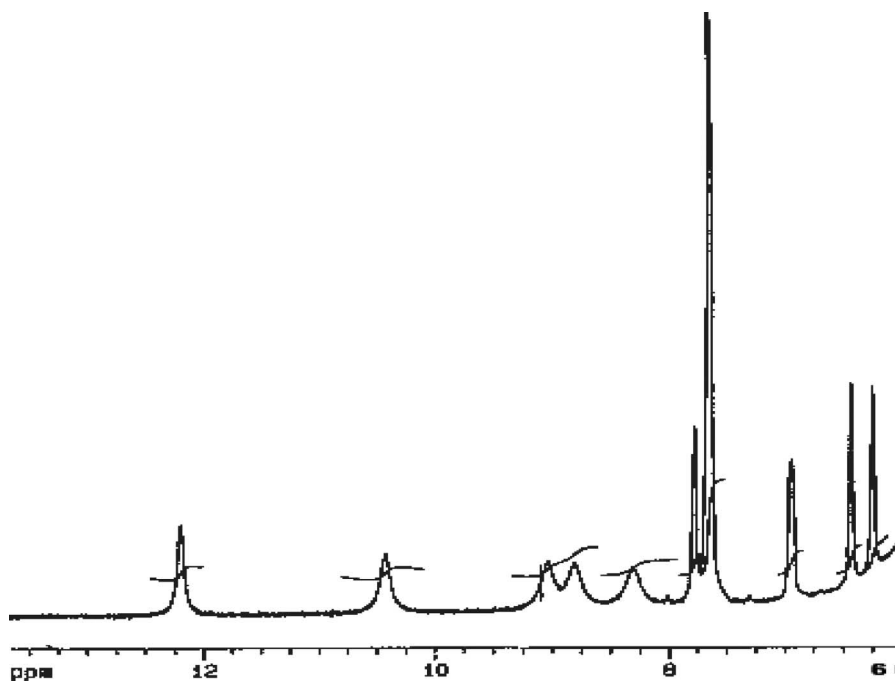


Figure 7.  $^1\text{H}$  NMR spectra of  $\text{Sm}(\text{quercetin})_3$  complex in  $\text{DMSO-d}_6$ .

center, because both are strongly dependent on the distance between the nucleus and unpaired electrons spin, whereas pseudo-contact shifts have an additional angular dependence. However, in lanthanides, the radial extension of the 4f orbital is exceedingly small and the electrons in these orbitals are shielded from the ligand by s and p electrons. Consequently, contact interactions are greatly diminished and the induced chemical shifts arise predominantly from the dipolar mechanism [22,26,42], which can provide information related to the geometrical configuration of the ligands of a metal ion in solution. Appearances of the broad resonance signals of quercetin protons in paramagnetic ions may be due to short electron spin relaxation time. In the praseodymium complex spectrum, aromatic ring protons of biphenolic ring are shifted to up field, whereas hetero-aromatic quinonolic ring protons and hydroxyl protons are oppositely shifted to lower field as compared with the diamagnetic lanthanum complex. Praseodymium generally induces up field shifts and, therefore, the resonances of complex have small isotropic shift in the proton spectrum [20,21,40,41]. The proton resonances of quinonolic aromatic ring displayed least downfield shift. The shifts of hydroxyl proton resonance increases with increase in the distance of hydroxyl group from the metal ion and it is larger for OH(7) proton and OH(5') proton resonance is least shifted. In the case of neodymium and samarium complexes very contrasting results were obtained. The sign of resonance shift of the hydroxyl groups and aromatic ring protons are inverted relative to that observed for the praseodymium complex.  $^1\text{H}$  NMR spectrum of the Nd(III) complex shows a strong up field shift of the OH(5), OH(4' and 3') and H(2') protons relative to the diamagnetic analogue, while these protons in samarium complex also show up field shift, but in comparison to Nd(III) the shift is smaller. The shifts of aromatic ring proton resonances in Nd(III) complex appear downfield in both rings. H(2') proton resonance in Nd(III) complex detected up field

whereas in Sm(III) complex it is oppositely shift to downfield. Moreover, the H(6'), H(5'), H(8) and H(6) aromatic ring proton resonances in neodymium complex are shifted to downfield but in the case of Sm(III) complex H(6') and H(5') proton

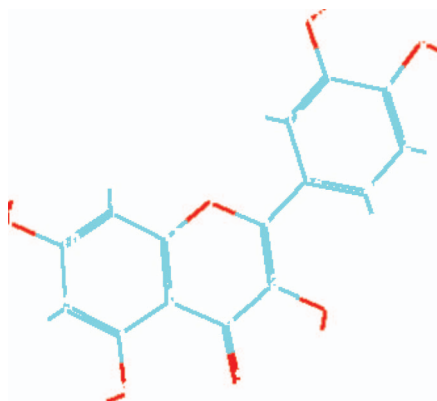


Figure 8. Energy minimized structure of quercetin molecule.

Table 5. Optimized geometrical parameters of quercetin obtained by density functional theory with STO-3G functional set.

Bond length	Value (Å)	Bond angle	Value (Å)
C(1)–C(2)	1.4176	C(4)–C(2)–O(3)	117.666
C(2)–O(3)	1.3940	C(2)–C(4)–O(5)	117.593
O(3)–H(23)	0.9909	C(6)–C(4)–O(5)	124.915
C(2)–C(4)	1.4529	C(6)–C(7)–O(8)	116.826
C(4)–O(5)	1.3363	C(9)–C(7)–O(8)	122.603
C(4)–C(6)	1.4595	O(11)–C(10)–C(12)	122.846
C(6)–C(13)	1.4247	O(11)–C(10)–C(9)	117.123
C(6)–C(7)	1.4359	C(16)–C(17)–O(18)	119.046
C(7)–O(8)	1.3952	O(18)–C(17)–C(19)	120.999
O(8)–H(24)	0.9889	C(17)–C(19)–O(20)	115.499
C(7)–C(9)	1.4104	O(20)–C(19)–C(21)	124.794
C(9)–H(25)	1.0821	O(14)–C(1)–C(15)	111.411
C(9)–C(10)	1.4186	O(14)–C(13)–C(12)	114.421
C(10)–O(11)	1.3967	O(14)–C(1)–C(2)	120.702
C(11)–H(26)	0.9891	C(1)–C(2)–O(3)	120.887
C(10)–C(12)	1.4115		
C(12)–H(27)	1.0816		
C(12)–C(13)	1.4139		
C(13)–O(14)	1.3976		
O(14)–C(1)	1.4102		
C(1)–C(15)	1.4631		
C(15)–C(16)	1.4342		
C(16)–H(28)	1.0809		
C(16)–C(17)	1.4076		
C(17)–O(18)	1.3975		
O(18)–H(29)	0.9892		
C(17)–C(19)	1.4280		
C(19)–O(20)	1.4001		
O(20)–H(30)	0.9872		
C(19)–C(21)	1.4128		
C(21)–H(31)	1.0830		
C(21)–C(22)	1.4106		
C(22)–H(32)	1.0805		
C(22)–C(15)	1.4316		

resonances are shifted to up field, however, H(9) and H(6) proton resonances shifted downfield. These up field as well as downfield shifts of the aromatic protons can be due to conversion of geometry during coordination of ligand to the metal ion. This kind of up field shift has been reported in the literature [42], which has been calculated through ring current effect on the ligand protons of coordinated ligand.

In the spectrum of Nd(III)-quercetin complex an additional signal of quercetin proton resonance was observed, which shifted to up field. This signal has an area corresponding to two protons, i.e. it must be due to meta and para hydroxyl protons of complexes coupled together.

## 9. Computational details

To study the coordination behaviour of quercetin molecule, molecular modeling studies were carried out by using Hyperchem 7.51 professional version [43]. Geometry optimization of quercetin was carried out via density functional theory with STO-3G

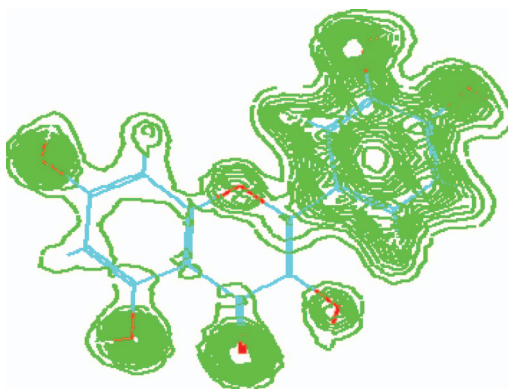


Figure 9. Charge density contour diagram of quercetin molecule.

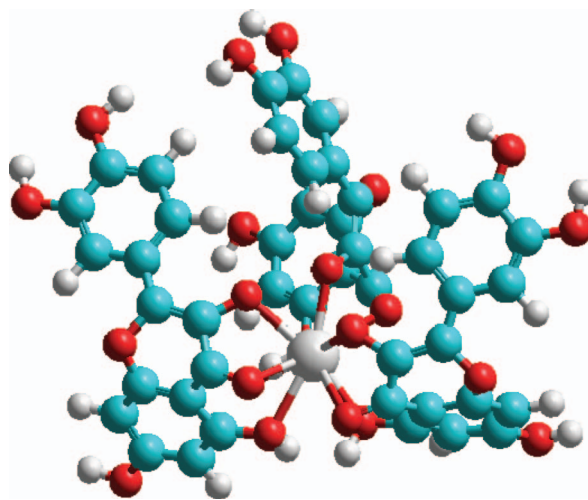


Figure 10. Energy minimized structure of Ln(quercetin)<sub>3</sub> complex.

functional set. Charge density around quercetin indicates OH(5), CO(4) and OH(3), and are the possible chelating sites (figure 8).

The main geometrical parameters of quercetin are presented in table 5. The bond length of OH(3)[O(3)-H(23)] is shorter than bond length of OH(5) [O(8)-H(24)], and suggests that OH(3) is coordinated strongly where as OH(5) interacts weakly with lanthanide ion, which supports spectroscopic results (figure 9). A three dimensional energy minimized structure of Ln-tris(quercetin) was obtained with the aid of molecular mechanics (MM<sup>+</sup>) (figure 10).

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