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Synthesis, spectroscopic studies and electrochemistry of palladium (II) macrocyclic complexes derived from a new tetraazahalogen substituted ligands by template method and their antimicrobial and pesticidal activities

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ABSTRACT

A new series of Pd(II) macrocyclic complexes have been synthesized by template condensation of bis(benzil)4-chloro 1,2-phenylenediamine (ML^1) and bis(benzil)4-fluro 1,2-phenylenediamine (ML^2) respectively, with appropriate diamine i.e. 1,2-phenylenediamine, 4-chloro 1,2-phenylenediamine and 4-fluro 1,2-phenylenediamine in the presence of $PdCl_2$ to form complexes of the type $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$, $[Pd(C_{40}H_{27}N_4X)]Cl_2$ and $[Pd(C_{40}H_{26}N_4X_2)]Cl_2$, where X = Cl, F. The complexes have been characterized with the help of elemental analysis, IR, ^1H NMR, electronic spectra, conductance measurement, magnetic susceptibility, cyclic voltammetry and X-ray powder diffraction studies. On the basis of these studies a square planar geometry has been proposed around the metal ion. The newly synthesized ligands and their complexes have been screened for antimicrobial and pesticidal activities. The results obtained from bioassays indicate that this class of compounds can be utilized for the design of new substance with pesticidal activity and promising antimicrobial activity.

1. Introduction

The design and study of well arranged metal containing macrocycles is an interesting field of chemistry and has attracted the interest of both inorganic and bioinorganic chemists in recent years [1]. The field of macrocyclic chemistry of metals is developing very rapidly because of its importance in the area of coordination chemistry [2]. The transition metal coordination chemistry of macrocyclic ligands has been developed extensively in the past decades [3–5]. This enormous growth is due to the synthesis of great number and variety of synthetic macrocycles which behave as coordinating agents for metal ions. For various applications tetraazamacrocyclic ligands are of special interest, and coordinating side chains may increase the stability of the metal complexes and tune the selectivity between various metal ions [6]. An intriguing feature of these systems is that the size of the ligands can be changed with relative ease by synthetic means [7–9]. Template condensation lies at the heart of macrocyclic chemistry and is one of the most highlighted methods. Metal template condensation often provides selective route towards the products that are not obtainable in absence of metal ion [10]. Finally design of the macrocyclic compounds depends upon the stereochemical requirements and coordinating features of metal ion [11]. The coordination chemistry of square planar metal complexes involving nitrogen donor ligands has excited great interest among chemists in recent years due to the applications of these in catalysis and their relevance to bioinorganic systems [12]. Biologically potent square planar macrocyclic complexes of Pd(II) and Pt (II) have been reported [13]. Singh et al. [14] have reported the antifertility and antimicrobial activities of tetraazamacrocyclic complexes of lead, palladium and platinum. Electrochemical behaviour of these complexes has also been studied [7]. Macrocyclic complexes have been used as drugs and are reported to possess a wide variety of biological activity against bacteria, fungi and certain type of tumors and they are also useful models for biological process [15,16]. Complexes of Pd(II) are new reagents for selective hydrolytic cleavage of peptide and proteins [17]. The cytotoxic and antiproliferative studies show that the complexes of Pd(II) exhibit good cytotoxic activity against different cell lines [18]. In view of the above applications, in the present paper template synthesis of tetraaza macrocyclic complexes of Pd(II) is reported. These complexes have been characterized with the help of various physicochemical techniques. The electron transfer mechanism of the metal is investigated by the aid of cyclic voltammetry. Further antibacterial and antifungal activities of the ligands and their metal complexes have been determined by screening of the compounds against various bacterial and fungal strains. The results obtained, were compared with antibacterial and antifungal activities shown by standard bactericide Streptomycin and fungicide

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Table 1
The physico-chemical properties and analytical data of the ligands and their complexes.

S.N.	Compound	M.W.	Colour	M.P. (0 °C)	Yield	Elemental analysis found (calculated)%				
						Pd	C	H	N	Cl
1	$C_{34}H_{23}N_2O_2Cl$	524.13 (527.02)	Black	85 °C	70%		77.15 (77.48)	4.24 (4.39)	5.19 (5.31)	6.02 (6.73)
2	$C_{34}H_{23}N_2O_2F$	508.17 (510.56)	Light brown	74 °C	75%		79.03 (79.98)	4.49 (4.54)	5.32 (5.48)	–
3	$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	784.04 (794.44)	Dark gray	280 °C	75%	13.12 (13.39)	60.11 (60.47)	3.21 (3.29)	6.99 (7.05)	13.10 (13.38)
4	$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	772.32 (776.45)	Dark gray	290 °C	65%	13.48 (13.70)	61.44 (61.87)	3.44 (3.50)	7.11 (7.21)	13.21 (13.69)
5	$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	801.19 (810.90)	Black	292 °C	65%	13.01 (13.12)	59.10 (59.24)	3.11 (3.23)	6.37 (6.90)	17.05 (17.48)
6	$[Pd(C_{40}H_{27}N_4F)]Cl_2$	751.26 (760.00)	Light green	275 °C	67%	13.99 (14.00)	63.10 (63.21)	3.39 (3.58)	7.20 (7.37)	9.25 (9.32)
7	$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	769.25 (777.99)	Brown	285 °C	73%	13.46 (13.67)	61.75 (61.75)	3.19 (3.36)	7.01 (7.20)	8.99 (9.11)

Bavistin. These complexes were also evaluated for their pesticidal activity and the results are quite encouraging.

2. Experimental

2.1. Materials

All the chemical used were of AnalaR grade. Palladium chloride ($PdCl_2$) and various diamines were purchased from Sigma–Aldrich. Solvents of analytical grade were distilled from appropriate drying agents immediately prior to use.

2.2. Analytical and physical measurements

Elemental analysis of C and H were performed at CDRI Lucknow. The nitrogen and chlorine contents of the complexes were estimated by the Kjeldahl's and Volhard's method, respectively [19]. Palladium was estimated gravimetrically [20]. Molecular weights were determined by Rast Camphor method. Melting point was determined by using capillaries in electrical melting point apparatus. The electronic spectra were recorded on an Ultraviolet visible spectrophotometer 752/752N, infrared spectra of the ligands and their complexes were recorded with the help of Nicolet Megna FTIR-550 spectrophotometer on KBr pellets. ^1H NMR spectra were recorded on a JEOL-AL-300 FT NMR spectrometer in DMSO-d_6 using TMS as the internal standard, XRD were measured on Panalytical make Xpert Pro 3040 and magnetic susceptibility were measured on a model 155 vibrating sample magnetometer at RSIC, IIT Chennai. The conductivity values measured on 10^{-3} mol dm^{-3} solution in DMF at room temperature on century digital conductivity meter model CC601.

The cyclic voltammetric experiments were carried out with a three electrode apparatus using a CH instrument 1200A electrochemical analyzer. Cyclic voltammetric data were recorded using a glassy carbon working electrode, a platinum counter electrode, and an Ag/Ag^+ reference electrode. Glassy carbon electrode surfaces were polished with alumina, rinsed in water, and air-dried immediately before use. The DMSO solution (containing tetra n-butylammonium iodide, as supporting electrolyte, 10^{-3} molar concentration of the complexes) was placed in a single-compartment electrochemical cell and degassed by bubbling with $N_2(g)$ saturated with DMSO. A N_2 atmosphere was continuously maintained above the solution while the experiments were in progress.

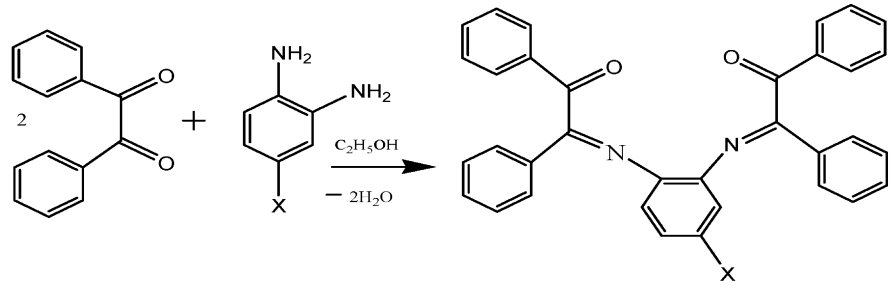
2.3. Synthesis of ligands (ML^1 and ML^2)

The ligands (ML^1 and ML^2) were prepared by dissolving benzil (20 mmol, 4.20 g) in 40 mL of ethanol then calculated amount of diamine i.e. 4-chloro 1,2-phenylenediamine (10 mmol, 1.42 g) or 4-fluro 1,2-phenylenediamine (10 mmol, 1.26 g) was added in 2:1 molar ratio. The reaction mixture was heated under reflux for 4–6 h on a ratio head. It was then concentrated to half of the volume. The solution was cooled and the excess solvent was removed by slow evaporation by keeping it in a desiccator overnight. The coloured crystalline products so obtained were purified by recrystallization in the same solvent and dried *in vacuo*. The analysis and physical properties of these ligands are given in Table 1.

The synthetic route of the ligands has been shown in Fig. 1 and the structure of bis(benzil)4-chloro 1,2-phenylenediamine (ML^1) is given in Fig. 2.

2.4. Synthesis of the Pd(II) macrocyclic complexes

The complexes were synthesized by the template condensation of ligands bis(benzil)4-chloro 1,2-phenylenediamine (ML^1) or bis(benzil)4-fluro 1,2-phenylenediamine (ML^2) with various diamine such as 1,2-phenylenediamine, 4-chloro 1,2-phenylenediamine and 4-fluro 1,2-phenylenediamine in the



Benzil 4-halo 1,2- phenylenediamine bis(benzil)4- halo 1,2- phenylenediamine

Where X= Cl, F

Fig. 1. Synthetic route of the ligands.

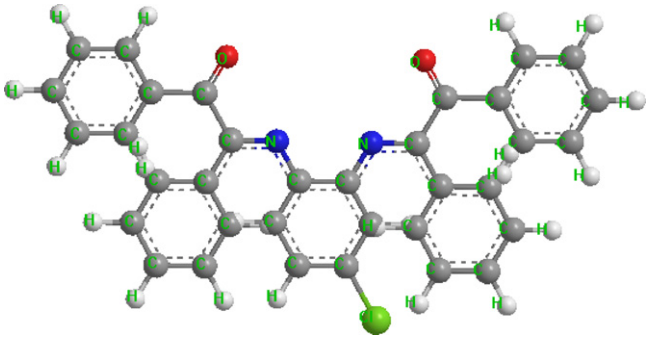


Fig. 2. Structure of bis(benzil)4-chloro 1,2-phenylenediamine (ML^1).

presence of $PdCl_2$.

2.4.1. Synthesis of $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$ complex

A weighed amount of methanolic solution of ligand ML^1 (10 mmol, 5.27 g) was taken into a 100 mL round bottom flask. The solution of ligand was mixed with the methanolic solution of 4-fluro 1,2-phenylenediamine (10 mmol, 1.26 g) and $PdCl_2$ (10 mmol, 1.77 g). After addition of all the reagents, the contents were boiled under reflux for about 7–8 h on a ratio head; the reaction mixture was concentrated to half of its volume and kept in a desiccator at room temperature. The complexes obtained as solids, were washed with methanol and dried under vacuo.

2.4.2. Synthesis of $[Pd(C_{40}H_{27}N_4X)]Cl_2$ complexes (X = Cl, F)

To obtain this type of complexes the methanolic solution of ligand ML^1 ((10 mmol, 5.27 g) or ML^2 (10 mmol, 5.10 g) was mixed with the methanolic solution of 1,2-phenylenediamine (10 mmol, 1.08 g) in the presence of $PdCl_2$ (10 mmol, 1.77 g). After addition was completed, the contents were refluxed for 7–8 h on a ratio head. It was then concentrated to half of the volume by removing the solvent and kept in a desiccator at room temperature. The complexes obtained as solids, were washed with methanol and dried under vacuo.

2.4.3. Synthesis of $[Pd(C_{40}H_{26}N_4X_2)]Cl_2$ complex (X = Cl)

This type of complex was prepared by mixing a methanolic solution of ML^1 (10 mmol, 5.27 g) with methanolic solution of 4-chloro 1,2-phenylenediamine (10 mmol, 1.42 g) and $PdCl_2$ (10 mmol, 1.77 g). The reaction mixture was heated under reflux for 7–8 h. The reaction mixture was concentrated to half of its volume. After cooling, the solution was kept overnight in a desiccator at room temperature. The complexes obtained as solids, were washed with methanol and dried under vacuo.

2.4.4. Synthesis of $[Pd(C_{40}H_{26}N_4X_2)]Cl_2$ complex (X = F)

This complex was prepared by following the above procedure, using the ligand ML^2 and 4-fluro 1,2-phenylenediamine in the presence of $PdCl_2$ in 1:1:1 molar ratio.

All the complexes were recrystallized from 1:1 molar solution of methanol and benzene. The purity of the complexes was checked by thin layer chromatography (TLC). The analysis and physical properties of these complexes are given in Table 1.

The template synthesis of the complexes may be represented by the following scheme in Fig. 3

3. Result and discussion

3.1. Chemistry

The elemental analysis and spectral data suggested the formation of the ligands ($ML^1$and ML^2) and their macrocyclic complexes $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$, $[Pd(C_{40}H_{27}N_4X)]Cl_2$ and $[Pd(C_{40}H_{26}N_4X_2)]Cl_2$ of the type where X = Cl, F. The resulting macrocyclic complexes are coloured, solids, stable at room temperature and non hygroscopic. They are soluble in DMF and DMSO. Molecular weight determination showed that they are monomeric in nature. The molar conductance measurements of 10^{-3} M solution in DMF indicate that the complexes are 1:2 electrolytes. The molar conductance of the Pd(II) macrocyclic complexes are given in Table 2.

3.2. Magnetic susceptibility measurement and electronic spectra

The magnetic susceptibility measurements show that all the palladium (II) macrocyclic complexes are diamagnetic, as expected of square planar d^8 complexes. The values lie in the range $(0.3–0.8 \times 10^{-6})$ c.g.s. units.

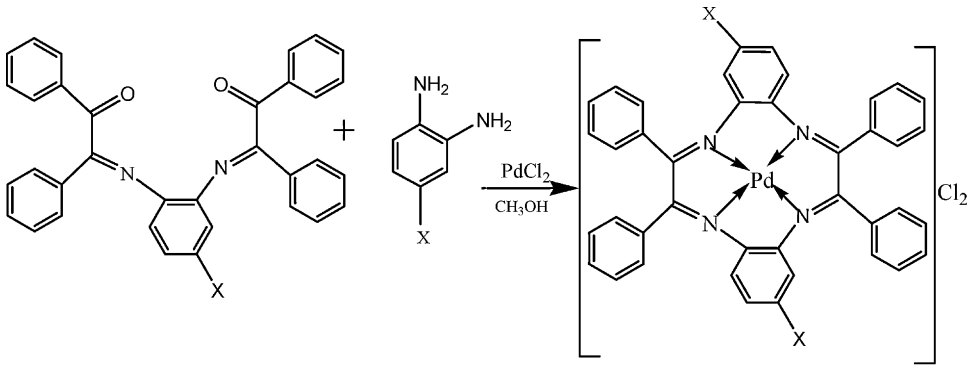
The electronic spectra of the ligands and their complexes were recorded in distilled DMSO. The spectra of both the ligands ML^1 and ML^2 show a broad band at 400 nm which can be assigned to the $n–\pi^*$ transitions of the azomethine group which undergoes a blue shift in the complexes due to the polarization within the ⟩C═N chromophore caused by the metal–ligand electron interaction during the chelation. The shift of this band in the spectra of the complexes suggests the coordination of nitrogen to metal atom. The spectra of the complexes show three bands due to three d–d spin allowed transitions. These are corresponding to the transitions from the three lower lying d orbitals to the empty $d_{x^2-y^2}$ orbital. The ground state is $^1A_{1g}$ and the excited states corresponding to the above transitions are $^1A_{2g}$, $^1B_{1g}$ and $^1E_{1g}$ in the order of increasing energy. The three orbital parameters (Δ_1, Δ_2, and Δ_3) were calculated using a value of $F_2 = 10F_4 = 600\ cm^{-1}$ for Slater Condon interelectronic repulsion [21] which are given in Table 2. The ν_2/ν_1 was also calculated and is in close agreement with the data reported by others for square planar complexes [21,22].

3.3. IR-spectra

The tentative absorption frequencies of the ligands and their Pd(II) complexes along with their assignment are listed in Table 3. The bands due to $\nu_{as}(NH_2)$ at 3380 cm^{-1}, $\nu_s(NH_2)$ at 3250 cm^{-1} and ν(C═O) in the region 1670–1680 cm^{-1} were present in the spectra of diamines and ligands respectively but were absent in the infrared spectra of all the complexes. The disappearance of the $\nu_{as}(NH_2)$, $\nu_s(NH_2)$ and ν(C═O) bands and appearance of absorption band near at 1610–1615 cm^{-1} indicates the formation of macrocyclic framework, as these bands may be assigned to ν(C═N) [23] The value of absorption band due to ν(C═N) is lower than that usually occur for azomethine group which supports the coordination of this group to the metal atom [12] and formation of macrocyclic complexes. This lower value of ν(C═N) stretching may be explained on the basis of a drift of lone pair density of azomethine nitrogen towards the metal atom. The phenyl ring absorption appears in the 1465–1495 and 1355–1390 cm^{-1} region are assigned to $\nu_{asym}C_6H_5$ and $\nu_{sym}C_6H_5$, respectively. The mode of coordination is further supported by the presence of the new bands at 360–390 cm^{-1} due to ν(Pd ← N).

3.4. ^1H NMR spectra

Further evidence for the coordinating mode of the ligands was obtained from ^{1}H NMR spectra which were recorded in DMSO-d^6. The spectra of the ligands and their complexes do not show any signal assignable to primary amino protons. This is strong evidence that proposed macrocyclic complexes are formed by template reaction. These complexes exhibit multiplet in the region δ 7.26–8.18 ppm, which is assigned to aromatic protons.



Where X= Cl, F

Fig. 3. Synthetic route of the Pd(II) macrocyclic complexes.

Table 2
Molar conductance and electronic spectral data (cm^{-1}) of palladium (II) complexes.

Complexes	Spectral bands (cm^{-1})	Transitions	Δ_1	Δ_2	Δ_3	ν_2/ν_1	Molar conductance
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	17391	$^1A_{1g} \rightarrow {}^1A_{2g}(\nu_1)$	19490	5643	3183	1.19	159
	20833	$^1A_{1g} \rightarrow {}^1B_{1g}(\nu_2)$					
	25316	$^1A_{1g} \rightarrow {}^1E_{1g}(\nu_3)$					
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	17241	$^1A_{1g} \rightarrow {}^1A_{2g}(\nu_1)$	19341	5012	3647	1.22	161
	21053	$^1A_{1g} \rightarrow {}^1B_{1g}(\nu_2)$					
	25000	$^1A_{1g} \rightarrow {}^1E_{1g}(\nu_3)$					
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	17153	$^1A_{1g} \rightarrow {}^1A_{2g}(\nu_1)$	19253	4455	3682	1.18	169
	20408	$^1A_{1g} \rightarrow {}^1B_{1g}(\nu_2)$					
	24390	$^1A_{1g} \rightarrow {}^1E_{1g}(\nu_3)$					
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	16949	$^1A_{1g} \rightarrow {}^1A_{2g}(\nu_1)$	19049	4955	3506	1.22	167
	20704	$^1A_{1g} \rightarrow {}^1B_{1g}(\nu_2)$					
	24510	$^1A_{1g} \rightarrow {}^1E_{1g}(\nu_3)$					
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	17094	$^1A_{1g} \rightarrow {}^1A_{2g}(\nu_1)$	19194	4308	3888	1.18	170
	20202	$^1A_{1g} \rightarrow {}^1B_{1g}(\nu_2)$					
	24390	$^1A_{1g} \rightarrow {}^1E_{1g}(\nu_3)$					

Table 3
IR (cm^{-1}) and ^1H NMR (δ, ppm) spectral data of the ligands and their corresponding complexes.

S.N.	Compound	IR spectral data (cm^{-1})			^1H NMR spectral data (δ ppm)
		ν(C=O)	ν(C=N)	ν(Pd ← N)	Aromatic protons (m)
1	$C_{34}H_{23}N_2O_2Cl$	1680	1610	–	7.69–8.18
2	$C_{34}H_{23}N_2O_2F$	1670	1620	–	7.79–8.13
3	$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	–	1600	360	7.36–8.10
4	$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	–	1598	362	7.26–8.18
5	$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	–	1595	390	7.31–8.18
6	$[Pd(C_{40}H_{27}N_4F)]Cl_2$	–	1600	370	7.32–8.16
7	$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	–	1590	382	7.38–8.16

m = multiplet.

On the basis of analytical and spectral data the structures of the complexes have been proposed. Fig. 4 represents 3D structure of $[Pd(C_{40}H_{27}N_4Cl)]Cl_2$ macrocyclic complex.

3.5. X-ray powder diffraction studies

The possible lattice dynamics of the finely powdered product, $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$ has been deduced on the basis of X-ray powder diffraction studies and Fig. 5 shows the XRD pattern of $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$ compound. The observed interplanar spacing values ('*d*' in Å) have been measured from the diffractogram of the compound and the Miller indices *h*, *k* and *l* have been assigned to each *d* value and 2-Theta angles are reported. The results show that the compound belongs to 'orthorhombic' crystal system having unit cell parameters as *a* = 25.75, *b* = 17.5, *c* = 10.20, maximum deviation of 2-Theta = 0.10 and Alpha = 90, Beta = 90, Gamma = 90 at the wavelength = 1.540598. Table 4 shows XRD measurement data of $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$.

3.6. Electrochemical studies

The electrochemical behaviour of Pd compound was studied by cyclic voltammetric techniques on glassy carbon electrode (GCE). Pd compound gave one well defined reduction peaks at −0.76 V peak potential (Fig. 6) in the non-aqueous solution DMSO which is attributed to the reduction of Pd(II) at glassy carbon electrode and tetrabutylammonium iodide (TBI) react as a supporting electrolyte. The reduction peak can be explained with the help of two electron transfer during reduction of Pd(II) to Pd(0) [24]. No peak could be observed in anodic direction of the reverse scans suggesting the

Table 4
XRD measurement data of $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$.

h	*k*	*l*	2Theta (Exp.)	2Theta (Calc.)	2Theta (Diff.)	*d* (Exp.)	*d* (Calc.)	Intensity (Exp.)
3	4	1	24.380	24.427	−0.047	3.648	3.641	53.43
3	5	0	27.512	27.499	0.013	3.239	3.240	24.28
9	0	1	32.481	32.475	0.006	2.754	2.754	24.25
8	3	2	36.404	36.394	0.010	2.465	2.466	9.35
3	3	4	39.945	39.958	−0.013	2.255	2.254	11.27
7	6	2	43.334	43.350	−0.016	2.086	2.54	27.58

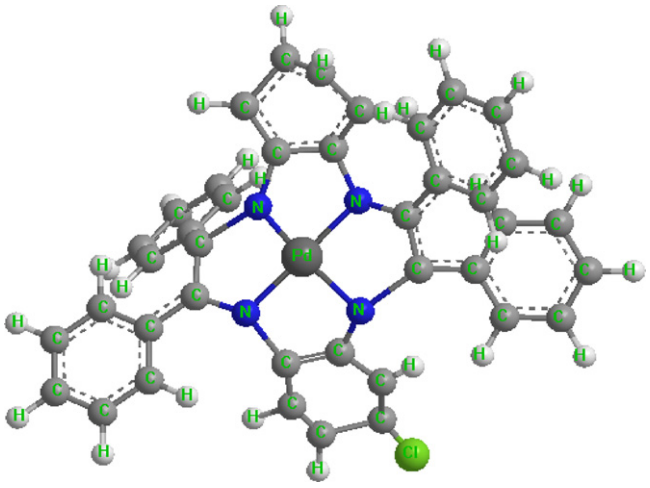


Fig. 4. 3D Structure of $[Pd(C_{40}H_{27}N_4Cl)]Cl_2$ macrocyclic complex.

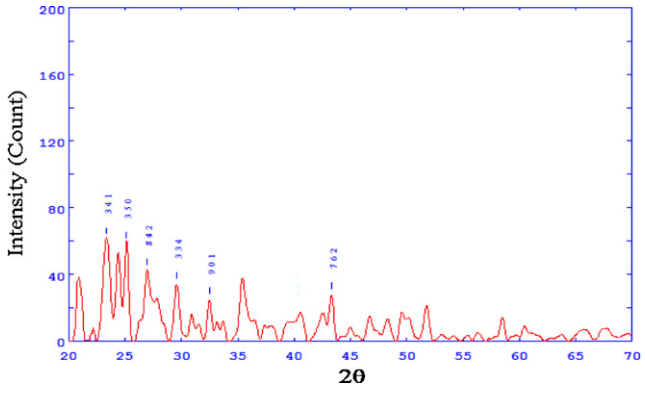


Fig. 5. XRD graph of $[Pd(C_{40}H_{26}N_4ClF)]Cl_2$.

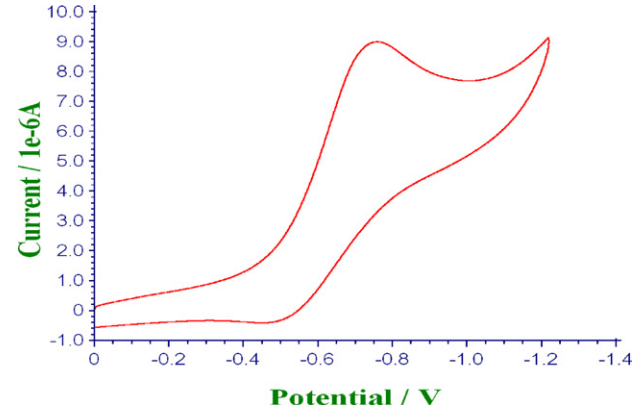


Fig. 6. Cyclic voltammogram of complex at scan rate 100 mV s^{-1}.

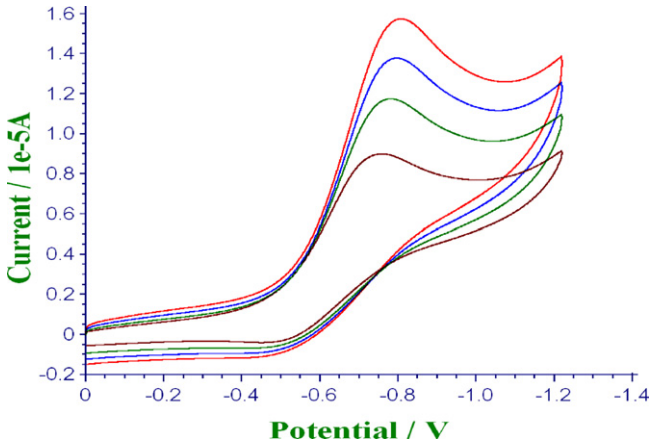


Fig. 7. Cyclic voltammogram of complex at different scan rates 50,100, 150 and 200 mV s^{-1}.

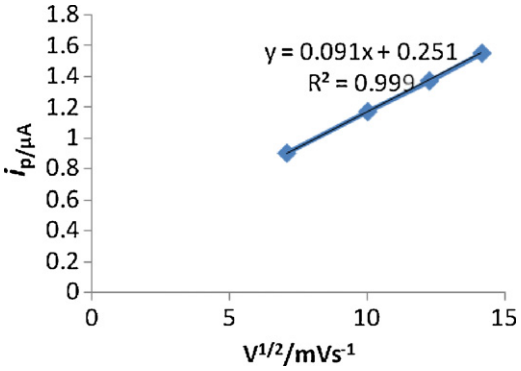


Fig. 8. Plot of peak current vs scan rate for reduction peak of complex.

irreversible nature of the electrode process. The peak potential shifted towards more negative values with increase in scan rate, (Fig. 7) confirming the irreversible nature of the reduction process.

The effect of scan rate ($\upsilon^{1/2}$) on stripping peak current (i_p) was examined under the above experimental conditions (Fig. 8). As the sweep rate is increased from 50 to 200 mV/s at a fixed concentration 10^{-3} M of the compound.

(i) The peak potential shifted cathodically.
(ii) The peak current increased steadily.

A straight line is obtained when i_p is plotted against $\upsilon^{1/2}$, which may be expressed by the equation.

For reduction peak:

$$Y(i_p) = 0.091\upsilon^{1/2}\,(\text{mV/s}) + 0.251\,(\mu\text{A}), \quad r^2 = 0.9994$$

All these facts pointed towards the diffusion-controlled nature of the electrode process.

Table 5
Comparison of properties of the synthesized Pd(II) macrocyclic complexes with related complexes.

Complex	Electronic transition (cm^{-1})	IR bands ν(C=N)	Molar conductance ($cm^2\ \Omega^{-1}\ mol^{-1}$)	Geometry	Refs.
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	17391 (ν_1) 20833 (ν_2) 25316 (ν_3)	1600	159	Square planar	This work
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	17241 (ν_1) 21053 (ν_2) 25000 (ν_3)	1598	161	Square planar	This work
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	17153 (ν_1) 20408 (ν_2) 24390 (ν_3)	1595	169	Square planar	This work
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	16949 (ν_1) 20704 (ν_2) 24510 (ν_3)	1600	167	Square planar	This work
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	17094 (ν_1) 20202 (ν_2) 24390 (ν_3)	1590	170	Square planar	This work
$[Pd(C_{39}H_{27}N_5)]Cl_2$	18348–18018 (ν_1) 21141–20618 (ν_2) 24509–24096 (ν_3)	1625–1595	205–225	Square planar	a
$[Pd(C_{35}H_{27}N_5)]Cl_2$	18939–18656 (ν_1) 21505–20833 (ν_2) 28011–27027 (ν_3)	1615–1598	206–218	Square planar	b
$Pd[(TAAP)]I_2$	21276 (ν_1) 23809 (ν_2)	1602–1610	145.3	Square planar	c
$[Pd(C_{40}H_{28}N_4)]Cl_2$	20747 (ν_1) 27933 (ν_2) 36764 (ν_3)	1610–1620	206	Square planar	d

a, b, c, d taken from Refs. [14,7,8,9], respectively. (TAAP) tetrapyrazolo [1,5,9,13] tetraazacyclohexadecine.
$\nu_1 = {}^1A_{1g} \rightarrow {}^1A_{2g}$, $\nu_2 = {}^1A_{1g} \rightarrow {}^1B_{1g}$, $\nu_3 = {}^1A_{1g} \rightarrow {}^1E_{1g}$.

The structural data of Pd(II) macrocyclic complexes have been compared with related derivatives described in the literature and the data have been included in Table 5.

4. Biological assay

4.1. Test microorganism

All the compounds were evaluated for their antimicrobial properties. MIC was recorded as minimum concentration which inhibits the growth of microorganism. The results obtained were compared with those of the standard drug Streptomycin for bacteria and Bavistin for fungi. The microorganisms used were *E. coli* (ATCC25922), *B. subtilis* (ATCC6633), *F. oxysporum* (ATCC7808) and *R. nigricans* (ATCC6227b). The synthesized macrocyclic complexes were also tested for the pesticidal activity against fifth instar larva of *Corcyra cephalonica*.

4.2. In vitro antibacterial activity

The newly prepared compounds were screened for their antibacterial activity against *Escherichia coli* (ATCC25922) and *Bacillus subtilis* (ATCC6633) by paper disc plate method [25]. Each compound was dissolved in DMSO and solutions of the concentrations (500 and 1000 ppm) were prepared separately. Paper discs of Whatman filter paper (No. 42) of uniform diameter (5 mm) were cut and sterilized in an autoclave. The paper discs soaked in the desired concentration of the complex solutions were placed aseptically in the petri dishes containing nutrient agar media (agar 20 g + beef extract 3 g + peptone 5 g) seeded with *E. coli* (ATCC25922) and *B. subtilis* (ATCC6633) bacteria strains separately. The petri dishes were incubated at 37 °C and the inhibition zones were recorded after 24 h of incubation. The antibacterial activity of common standard antibiotic Streptomycin was also recorded using the same procedure as above at the same concentrations and solvent. The medium with DMSO as solvent was used as a negative control whereas media with Streptomycin were used as positive control. The experiments were performed in triplicates.

4.3. In vitro antifungal activity

The newly prepared complexes were also screened for their antifungal activity against *Fusarium oxysporum* (ATCC7808) and *Rhizopus nigricans* (ATCC6227b) in DMSO by agar diffusion method [26,27]. Sabourand's agar media was prepared by dissolving peptone (10 g), D-glucose (40 g) and agar (20 g) in distilled water (1000 mL) and adjusting pH to 5.7. Normal saline water was used to make suspension spore of fungal strain lawning. A loopful of particular fungal strain was transferred to 3 mL saline to get suspension of corresponding species. Twenty milliliters of agar media were poured into each petri dish. Excess of suspension was decanted and plates were dried by placing in an incubator at 37 °C for 1 h using an agar punch, wells were made and each well was labelled. A control was also prepared in triplicate and maintained at 37 °C for 96 h. The fungal activity of each compound was compared with Bavistin as standard drug. The medium with DMSO as solvent was used as a negative control whereas media with Bavistin were used as positive control. The experiments were performed in triplicates. The cultures were incubated for 96 h at 35 °C and the growth was monitored and the percentage of inhibition was calculated by equation:

$$\%\ \text{of inhibition} = \frac{C - T}{C} \times 100$$

where C and T are the diameters of the fungal colony in the control and the test plates, respectively.

4.4. Determination of minimum inhibitory concentration (MIC)

Minimum inhibitory concentration, MIC, is the lowest concentration of test agent that inhibited visible growth of bacteria after 18 h incubation at 37 °C. The determination of the MIC involves a semi quantitative test procedure, which gives an approximation to the least concentration of an antimicrobial needed to pre-

Table 6
Antibacterial screening data for the ligands and their complexes.

Compound	Diameter (mm) of inhibition zone after 24 h (conc. in ppm)			
	Bacillus subtilis		*Escherichia coli*	
	500	1000	500	1000
$C_{34}H_{23}N_2O_2Cl$	7 ± 0.06	7.2 ± 0.05	6.8 ± 0.05	9 ± 0.08
$C_{34}H_{23}N_2O_2F$	6 ± 0.05	7 ± 0.08	6.0 ± 0.05	6 ± 0.08
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	8 ± 0.08	8.2 ± 0.11	7.2 ± 0.08	8 ± 0.14
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	8.5 ± 0.03	9 ± 0.08	8.0 ± 0.15	9 ± 0.12
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	11 ± 0.08	11.2 ± 0.08	11 ± 0.15	12 ± 0.34
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	9 ± 0.05	10 ± 0.08	10 ± 0.11	11 ± 0.11
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	8 ± 0.05	9 ± 0.03	9 ± 0.08	10 ± 0.20
Streptomycin	16 ± 0.01	18 ± 0.11	17 ± 0.18	20 ± 0.18

Table 7
Antifungal screening data for the ligands and their complexes.

Compound	(%) Inhibition after 96 h (conc. in ppm)					
	Fusarium oxysporum			*Rhizopus nigricans*		
	50	100	200	50	100	200
$C_{34}H_{23}N_2O_2Cl$	42 ± 0.75	53 ± 0.60	65 ± 0.34	28 ± 0.53	47 ± 0.39	61 ± 0.77
$C_{34}H_{23}N_2O_2F$	35 ± 0.69	39 ± 0.55	50 ± 0.52	29 ± 0.54	35 ± 0.40	53 ± 0.89
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	48 ± 0.70	58 ± 0.51	67 ± 0.55	35 ± 0.22	50 ± 0.50	66 ± 0.36
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	46 ± 0.55	55 ± 0.55	64 ± 0.71	33 ± 0.55	48 ± 0.62	63 ± 0.53
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	49 ± 0.50	57 ± 0.55	67 ± 0.49	37 ± 0.59	52 ± 0.66	68 ± 0.42
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	37 ± 0.45	43 ± 0.69	52 ± 0.55	31 ± 0.52	49 ± 0.50	57 ± 0.50
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	39 ± 0.57	45 ± 0.32	54 ± 0.57	35 ± 0.39	52 ± 0.55	59 ± 0.60
Bavistin	61 ± 0.10	90 ± 0.80	100 ± 0.10	55 ± 0.10	88 ± 0.10	99 ± 0.30

Table 8
Minimum inhibitory concentration (μg/mL) of the ligands and their complexes.

Compound	*Bacillus subtilis*	*Escherichia coli*	*Fusarium oxysporum*	*Rhizopus nigricans*
$C_{34}H_{23}N_2O_2Cl$	50	50	6.25	12.5
$C_{34}H_{23}N_2O_2F$	50	50	12.5	12.5
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	50	50	3.125	6.25
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	25	25	3.125	6.25
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	25	25	3.125	6.25
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	50	50	6.25	6.25
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	50	50	6.25	6.25

vent microbial growth. The minimum inhibitory concentration was determined by microbroth dilution method [28]. Stock solution (100 μg/mL) of Pd(II) complexes were prepared in DMSO. Further concentrations were prepared by serial dilution. Inoculum of the overnight culture was prepared. In a series of tubes, 1 mL each of Pd(II) complex solution with different concentrations was taken and 0.4 mL of the inoculum was added to each tube. Further 3.5 mL of the sterile water was added to each of the test tubes. These test tubes were incubated for 18 h and observed for the presence of turbidity. The absorbance of the suspension of the inoculum was observed with spectrophotometer at 555 nm. The end result of the test was the minimum concentration of antimicrobial agent (test materials) which gave a clear solution, i.e., no visual growth [29,30].

4.5. Pesticidal activity

Fifth instar larva of *Corcyra cephalonica* were obtained from stock culture maintained at the storage section of Division of Entomology, Durgapura Agricultural Research Institute, Jaipur. Insects were reared on wheat grain at 27 ± 1 °C and 70% relative humidity. Glass jars containing 500 g of wheat cereals were labelled to indicate the date of introduction of adults and new emergence. At alternate day larva were shifted to fresh jars so that successive rearing jars can be maintained and insects of known age can be obtained regularly. Pesticidal activity of the synthesized compounds was tested by Immersion method. All the synthetic compounds were weighed and dissolved in methanol to prepare 1000 mg L^{-1} stock solution. Further concentrations *viz*., 900, 800, 700, 600, 500, 400, 300, 200, 100 mg L^{-1} were prepared by serial dilution. 20 larvas were released in each petri plate then 1 mL of each concentration of various compounds was directly poured in each petri plate with the help of a brush. Petri plates with test solution were rotated vigorously and were kept at 27 ± 1 °C and 70% relative humidity. Mortality was observed after 96 h larva was considered dead if they failed to respond to stimulus by touch. Control mortality was corrected by using Abbott's formula [31] and data was subjected for probit analysis according to Finney [32].

$$\text{Corrected \% mortality} = \frac{\text{\% mortality observed} - \text{\% mortality in control} \times 100}{100 - \text{\% mortality in control}}$$

5. Biological results and discussion

In the present study, the ligands and their palladium (II) macrocyclic complexes were evaluated for their antimicrobial activity against two bacteria, *Escherichia coli* (ATCC25922) and *Bacillus subtilis* (ATCC6633) and two fungi, *Fusarium oxysporum* (ATCC7808) and *Rhizopus nigricans* (ATCC6227b). The results are summarized in Tables 6 and 7. The results were compared with those of the standard drug Streptomycin for bacteria and Bavistin for fungi. All

Table 9
Pesticidal activity of the ligands and their complexes.

Compound	LC_{50}	χ^2	Corrected mortality (%)
$C_{34}H_{23}N_2O_2Cl$	410	0.274	55.55
$C_{34}H_{23}N_2O_2F$	840	0.431	50
$[Pd(C_{40}H_{26}N_4ClF)]Cl_2$	200	0.537	61.11
$[Pd(C_{40}H_{27}N_4Cl)]Cl_2$	190	0.694	66.66
$[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$	160	0.160	77.77
$[Pd(C_{40}H_{27}N_4F)]Cl_2$	405	0.48	66.66
$[Pd(C_{40}H_{26}N_4F_2)]Cl_2$	170	0.282	72.22
Control	–	1.142	–

lc = lethal concentration.
χ^2 = chi square.

the ligands and their respective Pd(II) complexes were found to be sensitive against all the fungal and bacterial strains. The antimicrobial screening data indicate that the metal complexes are more potent antimicrobial agents than the free ligands.

MIC values for the ligands and their palladium (II) complexes are shown in Table 8. Minimum inhibitory concentration of the ligands and their metal complexes was determined against four tested strains. Compound $[Pd(C_{40}H_{27}N_4Cl)]Cl_2$ and $[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$ show low MIC value at 25 μg/mL for bacterial strain *Escherichia coli* (ATCC25922), *Bacillus subtilis* (ATCC6633) and at 3.125 μg/mL for fungal strain *Fusarium oxysporum* (ATCC7808), respectively. Metal complexes are more active against fungal strains in comparison to bacterial strains.

The biological activity of the ligands exhibited a marked enhancement on coordination with the metal ions against all the test bacterial/fungal strains which shows that metal chelates are more active than the ligands. This may be explained by Tweedy's Chelation theory [33] according to which chelation reduces the polarity of the central metal atom because of partial sharing of its positive charge with the ligand [34], which favours permeation of the complexes through the lipid layer of cell membrane [35]. Other factors such as solubility, conductivity and dipole moment which are affected by the presence of metal ions may also be possible reasons for increasing biological activity of metal complexes as compared to the corresponding ligands. It was further noted that an increase in the concentration of the compounds increases the activity.

Both the ligands and their palladium complexes were also evaluated for pesticidal activity and they have a potent inhibitory effect on growth and development of *Corcyra cephalonica* larva. The LC_{50} values in mg L^{-1} are shown in Table 9. The data indicate that all Pd(II) complexes exhibit greater pesticidal activity than the respective ligands but compound $[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2]$ was highly effective as a pesticide with LC_{50} 160 mg L^{-1} against *Corcyra cephalonica*. A possible explanation is that, the compound inhibit molting hormone of pest larva [36] i.e. ecdysis disruption.

6. Conclusion

We describe the synthesis, characterization and biological activity of Pd(II) macrocyclic complexes. The structural properties of Pd(II) macrocyclic complexes have been compared with several related complexes in Table 5. On the basis of magnetic, analytical and spectral data a square planar geometry has been proposed for the Pd(II) macrocyclic complexes. The electrochemical properties of metal complexes revealed the irreversible two electron transfer redox process. The antimicrobial activity results indicated that the complexes showed promising antibacterial and antifungal activities but compound $[Pd(C_{40}H_{27}N_4Cl)]Cl_2$ and $[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2$ showed highest activity against bacterial strain *E. coli* ATCC25922, *B. subtilis* ATCC6633 (MIC = 25 μg/mL) and fungal strain *F. oxysporum* ATCC7808 (MIC = 3.125 μg/mL). The enhanced activity of the macrocyclic complexes than the parent ligands has been explained on the basis of chelation theory. The newly synthesized complexes exhibited considerable pesticidal activity however, compound $[Pd(C_{40}H_{26}N_4Cl_2)]Cl_2]$ was found to be highly effective as a pesticide with LC_{50} 160 mg L^{-1} against *Corcyra cephalonica*.

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References

[1] D.P. Singh, R. Kumar, J. Singh, Eur. J. Med. Chem. 44 (2009) 1731–1736.
[2] S. Ilhan, H. Temel, Transit. Met. Chem. 32 (2007) 1012–1017.
[3] G.A.E. Melson, Coordination Chemistry of Macrocyclic Complexes, Plenum Press, New York, 1982.
[4] L.F. Lindoy, The Chemistry of Macrocyclic Ligand Complexes, Cambridge University Press, Cambridge, New York, 1989.
[5] B. Dietrich, P. Viout, J.M. Lehn, Macrocyclic Chemistry. Aspects of Organic, Inorganic and Supramolecular Chemistry, VCH, New York, Weinheim, 1991.
[6] P. Comba, S.M. Luther, O. Maas, H. Pritzkow, A. Vielfort, Inorg. Chem. 40 (2001) 2335–2345.
[7] A. Bansal, R. Singh, R.V. Singh, Met. Based Drugs 7 (2000) 211–218.
[8] Abd El-M. Ramadan, T.I. El-Emary, Transit. Met. Chem. 23 (1998) 491–495.
[9] S. Chandra, S. Raizada, S. Rani, Spectrochim. Acta Part A 71 (2008) 720–724.
[10] S.G. Kang, J. Song, J.H. Jeong, Inorg. Chim. Acta 357 (2004) 605–610.
[11] F. Athar, F. Arjmand, S. Tabassum, Transit. Met. Chem. 26 (2001) 426–429.
[12] A. Bansal, N. Fahmi, R.V. Singh, Main Group Met. Chem. 26 (2003) 335–347.
[13] K. Sharma, N. Fahmi, R.V. Singh, Appl. Organometal. Chem. 15 (2001) 221–226.
[14] R.V. Singh, S.C. Joshi, S. Kulshrestha, P. Nagpal, A. Bansal, Met. Based Drugs 8 (2001) 149–158.
[15] N.K. Singh, S.B. Singh, A. Shrivastav, S.M. Singh, Proc. Indian Acad. Sci.: Chem. Sci. 113 (2001) 257–273.
[16] O.E. Offiong, S. Martelli, Transit. Met. Chem. 22 (1997) 263–269.
[17] N.M. Milovic, L.M. Dutca, N.M. Kostic, Inorg. Chem. 42 (2003) 4036–4045.
[18] E.J. Gao, L. Wang, M.C. Zhu, W.Z. Zahang, Eur. J. Med. Chem. 45 (2010) 311–316.
[19] A.I. Vogel, A Text Book of Inorganic Analysis, Longmans Green and Co, London, 1968.
[20] A.I. Vogel, A Text Book of Quantitative Inorganic Analysis, Longmans Green, ELBS London, 1962.
[21] H.B. Gray, C.J. Ballhausen, J. Am. Chem. Soc. 85 (1963) 260–263.
[22] K. Sharma, R. Singh, N. Fahmi, R.V. Singh, Spectrochim. Acta Part A 75 (2010) 422–427.
[23] N.E. Borisova, M.D. Reshetova, Y.A. Ustynyuk, Chem. Rev. 107 (2007) 46–79.
[24] A.J. Downard, A.M. Bond, A.J. Clayton, L.R. Hanton, D.A. McMorran, Inorg. Chem. 35 (1996) 7684–7690.
[25] S. Gaur, N. Fahmi, R.V. Singh, Phosphorus Sulfur Silicon Relat. Elem. 182 (2007) 853–862.
[26] E.W. Koneman, S.D. Allen, W.C. Winn, Colour Atlas and Textbook of Diagnostic Microbiology, Lippincott Raven Publishers, Philadelphia, USA, 1997, pp. 86–856.
[27] Z.A. Siddiqi, M. Khalid, S. Kumar, M. Shahid, S. Noor, Eur. J. Med. Chem. 45 (2010) 264–269.
[28] K. Shanker, R. Rohini, V. Ravinder, P. Reddy, Y.P. Ho, Spectrochim. Acta Part A 73 (2009) 205–211.
[29] P.M. Davidson, M.E. Parish, Food Technol. 43 (1989) 148–155.
[30] C.H. Collins, Antibiotics and antibacterial substances, in: Microbiological Methods, Butterworths, London, 1964, pp. 296–305.
[31] W.S. Abbott, A method of computing the effectiveness of an insecticide, J. Econ. Entomol. 18 (1925) 265–267.
[32] D.J. Finney, Probit Analysis, third ed., Univ Press, Cambridge, UK, 1971, p. 333.
[33] B.G. Tweedy, Phytopathology 55 (1964) 910–914.
[34] B. Keshavan, H. Kempe Gowda, Turk. J. Chem. 26 (2002) 237–243.
[35] A.W. Varnes, R.B. Dodson, E.L. Wehry, J. Am. Chem. Soc. 94 (1972) 946–950.
[36] A. Guerrero, G. Rosell, Curr. Med. Chem. 12 (2005) 461–469.