Synthesis, Spectral Characterization, Cyclic Voltammetry, Molecular Modeling and Catalytic Activity of Sulfa-Drug Divalent Metal Complexes

Safaa N Abdou1, Abeer A Faheim1,2 and Abdel-Nasser MA Alaghaz3,4*

1Chemistry Department, College of Education and Science (Khumra), Taif University, Al-Khumra, Taif, Saudi Arabia
2Chemistry Department, Faculty of Science (Girl’s), Al-Azhar University, P.O. Box 11754, Nasr-City, Cairo, Egypt
3Chemistry Department, Faculty of Science (Boy’s), Al-Azhar University, P.O. Box 11754, Nasr-City, Cairo, Egypt
4Chemistry Department, Faculty of Science, Jazan University, Jizan, Saudi Arabia

Abstract

Complexes of cobalt(II), nickel(II), copper(II), zinc(II) and Hafnium(II) of general composition [M(L)2(Cl)2] (L = 4-(phenylphosphinylideneamino-N-thiazolyl benzene-sulfonamide) have been synthesized. The elemental analysis, molar conductance measurements, magnetic susceptibility measurements, mass, IR, UV, NMR, SEM, EDX, thermal and EPR spectral studies of the compounds led to the conclusion that the ligand acts as a bidentate manner. The molar conductance of the complexes in fresh solution of DMSO lies in the range of 7.46–9.13 Ω-1 cm2 mol-1 indicating their non-electrolytic behavior. On the basis of analytical and spectrocopic techniques, octahedral geometry of the complexes was proposed. The ligand binds in a bidentate manner, coordinated through sulfonamide oxygen and thiazole nitrogen atoms. The ligand field parameters were calculated for Co(II), Ni(II) and Cu(II) complexes and their values were found in the range reported for a octahedral structure. The catalytic activities of the divalent metal complexes have been studied in the oxidation of cyclohexane by hydrogen peroxide, an environmental friendly oxidant. The molecular modeling parameters of the ligand and its Co(II) and Hf(II) complexes have been calculated.

Keywords: Schiff base; Complexes; Spectroscopic; Catalytic activities; Molecular modeling parameters; SEM/EDX

Introduction

Currently available methods for the removal of phenol/phenolic compounds from wastewaters (chemical oxidation, reverse osmosis, adsorption and others) are expensive, have regeneration problems and may produce themselves wastewaters with a high environmental impact [1,2]. Particularly contaminating waste waters are those generated by textile and paper mill industries. These wastewaters include medium to low concentrations of dyes or pigments. The degradation of dyes is one of the most important research fields in wastewater treatments. Researchers have recently focused on enzymatic treatments. Many peroxidases such as lignin peroxidase, manganese peroxidase, soybean peroxidase, horseradish peroxidase (HRP), laccase, polyphenol oxidases, micro peroxidases and azo peroxidases have been used for the removal of dyes in industrial effluents [3,4]. One of the most studied substrates is phenol, which is frequently used as a simple model compound of more complex pollutants such as dyes, pigments and others. Among the most toxic phenolic compounds are the chloro- or nitro-substituted phenols. The compounds are used as pesticides and anti-bacterial [5]. Phenol is present in wastewaters discharged by resin manufacturing, petrochemical, oil-refining, paper mill, coking, and iron melting industries [6]. Phenol derivatives include anilquinone dyes, an important group of dyes. Phenolic groups, besides being part of many dyes and pigments, are also the main moiety of lignin. Nowadays, high amounts of ligno-cellulosic wastes from paper and wood industries are generated, of which only 1–2% are reused. Therefore, their accumulation represents a serious environmental problem. Moreover, high-value products potentially obtainable from lignin degradation are misspent [7]. The enzymatic complex (Li-peroxidase, Mn-peroxidase and laccase) produced by white-rot fungi is able to degrade lignin up to mineralization. Hence, the application of well-known, commercially available and robust enzymes such as HRP is an attractive approach for lignin degradation. Recent studies on totally chlorine-free processes for pulping and bleaching involve the use of oxygen, ozone or hydrogen peroxide as oxidants, and enzymes or biomimetics as catalysts [8]. There are three main research fields in the heterogeneous catalytic degradation of phenols: the catalytic wet-peroxide oxidation [9], the catalytic ozonation [10] and the catalytic wet oxidation [11]. The catalysts used in wet-peroxide oxidation include metal-exchanged zeolites, hydrotalcite-like compounds, metal-exchanged clays and resins. The catalysts used in catalytic wet oxidation are transition metal oxides and supported noble metals [12].

The development of new methodologies for the deposition of high-j materials based on HfO2 is of increasing importance for applications in microelectronics [13]. Generally, these depositions are performed using metal–organic chemical vapor deposition (MOCVD), which requires precursors with very special characteristics as thermal stability, high volatility, and low cost/toxicity [14]. The precursor of choice for the deposition of HfO2 is most often tetrakis (dimethylamido) hafnium(IV) [14]; however, its high reactivity and premature decomposition issues have led to interest in the development of new precursors with the potential of fine-tuning their volatility characteristics.

Thus, in this paper we synthesized a new tridentate Schiff base containing N2O donor atoms and its cobalt(II), nickel(II), copper(II), zinc(II) hafnium(II) complexes. The HL ligand and its complexes were characterized by the FT-IR, 1H NMR, 13C NMR, mass, SEM, EDX, UV–Vis spectroscopy, elemental analysis, magnetic susceptibility, molar
conduction and thermal analysis. The geometry of the complexes is characterized by means of spectral and magnetic measurements.

Materials and Methods

Metal salts, Sulfathiazole, phenyldichlorophosphine, were either Aldrich, BDH or Merck products. EDTA disodium salt, ammonium hydroxide, murexide and nitric acid were either BDH or Merck products. Organic solvents (methanol, absolute ethanol, diethylether, dimethylformamide (DMF) and dimethylsulfoxide (DMSO)) were reagent grade chemicals and were used without further purification.

Analytical and physical measurements

The percentage of carbon, hydrogen, nitrogen and sulfur contents were analysed using Carlo Erba 1108 model elemental analyser using sulphanilamide as a reference standard. Analysis of the metal(II) ions followed the dissolution of the solid complexes in concentrated HNO3, neutralizing the diluted aqueous solutions with ammonia and titrating the metal solutions with EDTA. Infrared spectra were recorded by using a 1% of the sample on KBr pellet with 16 scans and 2 cm⁻¹ resolutions in a Jasco FT-IR/4100 spectrophotometer equipped with ATR accessory in the range of 4000–400 cm⁻¹. The electronic spectra of the complexes in UV–Vis region were obtained in DMSO solutions using a Shimadzu UV-1601 spectrophotometer in the range of 200–800 nm. Magnetic susceptibility measurements were computed on a modified HertzSGB-5H model Gouy magnetic balance using CuSO₄.5H₂O as the calibrant. Magnetic susceptibility measurements were computed on a modified HertzSGB-5H model Gouy magnetic balance using CuSO₄.5H₂O as the calibrant.

Isolation of ligand

Sulfathiazole [N1-4-amino-thiazolylbenzenesulfonamide] (0.1 mol) in 100 ml cold dry benzene was added in small portions to a well stirred cold solution of dichlorophenylphosphine (0.1 mol) in 100 ml cold dry benzene during half an hour at 15°C under dry conditions. After completion of the reaction (HCl gas ceased to evolve), the reaction mixture was filtered while hot and the solid obtained was washed several times with dry benzene, diethyl ether and dried in vacuo to give the corresponding 4-phenylphosphinylidenamino-N-thiazolyl benzene-sulfonamide (HL) (Figure 1).

\[ C₆H₉N₂O₃PS; \] yellow, yield; 86%, m.p. = 150-152°C, Calculated C, 49.85; H, 3.35; N, 11.63; P, 8.57; S, 17.75; found C, 49.58; H, 3.29; N, 11.54; P, 8.55; S, 17.63.

Isolation of complexes

Metal(II) (Co, Ni, Cu, Zn and Hf) chlorides (0.1 mol) was dissolved in ~40 ml absolute ethanol, then added to 0.2 mol of the prepared ligand phenyldichlorophosphine-N-thiazolyl benzene-sulfonamide (HL) dissolved in ~40 ml absolute ethanol. The mixture was heated under reflux for ~2 h. The precipitate was filtered off and finally washed with hot ethanol several times.

Analytical data

Complex 1: \([\text{CoC}₃₀\text{H}₂₄\text{Cl}_₂\text{N}_₆\text{O}_₄\text{P}_₂\text{S}_₄]\); Yield-55%, dark blue, m.p. > 300°C, Calc. C, 42.26; H, 2.84; Cl, 8.32; Co, 6.91; N, 9.86; P, 7.27; S, 15.04; Found C, 42.21; H, 2.82; Cl, 8.24; Co, 6.90; N, 9.84; P, 7.25; S, 15.00; ^M=2.28, μeff=5.32 B.M.

Complex 2: \([\text{NiC}₃₀\text{H}₂₄\text{Cl}_₂\text{N}_₆\text{O}_₄\text{P}_₂\text{S}_₄]\); Yield-54%, dark green, m.p.>300°C, Calc. C, 42.27; H, 2.84; Cl, 8.32; N, 9.86; Ni, 6.89; Found C, 42.14; H, 2.78; Cl, 8.18; Ni, 6.89; N, 9.76; P, 7.20; S, 14.93; ^M=4.86, μeff=3.24 B.M.

Complex 3: \([\text{CuC}_₃₀\text{H}_₂₄\text{ClN}_₆\text{O}_₄\text{P}_₂\text{S}_₄]\); Yield-58%, dark brown, m.p.>300°C, Calc. C, 42.03; H, 2.82; Cl, 8.27; Cu, 7.41; N, 9.80; P, 7.23; S, 14.96; Found C, 41.93; H, 2.78; Cl, 8.22; Cu, 7.34; N, 9.75; P, 7.25; S, 14.87; ^M=2.89, μeff=2.12 B.M.

Complex 4: \([\text{ZnC}_₃₀\text{H}_₂₄\text{ClN}_₆\text{O}_₄\text{P}_₂\text{S}_₄]\); Yield-50%, yellow, m.p.>300°C, Calc. C, 41.94; H, 2.82; Cl, 8.25; N, 9.78; Zn, 7.21; S, 14.93; Zn, 7.61; Found C, 41.87; H, 2.76; Cl, 8.19; N, 9.72; P, 7.17; S, 14.68; Zn, 7.58; ^M=2.89, μeff=diamagnetic.

Complex 5: \([\text{HCC}_₃₇\text{H}_₂₄\text{ClN}_₆\text{O}_₄\text{P}_₂\text{S}_₄]\); Yield-52%, yellow, m.p.>300°C, Calc. C, 37.06; H, 2.49; Cl, 7.29; Hf, 18.36; N, 8.64; P, 6.37; S, 13.19; Found C, 36.96; H, 2.41; Cl, 7.24; Hf, 18.35; N, 8.58; P, 6.35; S, 13.14; ^M=2.89, μeff=diamagnetic.

Figure 1: Proposed structure of HL ligand.
Oxidation reactions

The aerobic oxidation reactions were carried out in a 25 ml flask at room temperature and at 70 ºC under atmospheric pressure conditions. 0.05 g of the catalyst ([Co(L)2(Cl)2], [Ni(L)2(Cl)2], [CuL(Cl)2], [ZnL(Cl)2] or [Hf(L)2(Cl)2]) was taken in 10 ml of acetonitrile. To this, 10 mmol of the oxidant, 30% H2O2 solution and 5 mmol of cyclohexane were added successively and the reaction solution was magnetically stirred for 8 and 12 h. Aliquots of the reaction mixture were taken separately at 8 h and 12 h for product analysis. The blank experiments were also run individually without catalyst and oxidant by following the same reaction procedure. All samples were analysed by Hewlett-Packard gas chromatography (HP 6890) having FID detector, a capillary column (HP-5), with a programmed oven temperature from 50 to 200 ºC and a 0.5 cm3 min−1 flow rate of N2 as a carrier gas. The conversion of cyclohexane and selectivity for cyclohexanol and/or cyclohexanone was calculated as follows:

\[
\text{Conversion} \% \text{ of cyclohexane} = 100 \times \left[ \frac{\text{Initial} \% - \text{Final} \%}{\text{Initial} \%} \right] \\
\times \Sigma \text{Peak area of total products.}
\]

Results and Discussion

The ligand

HL ligand is formed via the condensation of the sulfa drug under study with dichlorophenylphosphine. It is characterized based on elemental analyses (C, H, N, S and P). The results obtained are in good agreement with those calculated for the suggested formula (Figure 1).

The 1H NMR spectra of the ligand HL revealed its formation by exchangeable with D2O). This is further supported by the appearance of stretching vibration band \(\nu(-NH)\) sulfonamide at 3310 cm\(^{-1}\). Also, the 1H NMR of the ligand exhibits signals at \(\delta (\text{ppm})=6.5\) (d, \(J=10.2\) Hz, 2H, Ph), 6.64 (d, \(J=10.2\) Hz, 2H, Ph), 6.8 (d, \(J=10.2\) Hz, 2H, Ph), 7.5 (d, \(J=10.2\) Hz, 2H, Ph), 7.8 (d, \(J=3.7\) Hz, 1H, Ph), 8.0 (t, \(J=3.9\) Hz, 1H, thiazole-H3) and 8.1 (d, \(J=3.9\) Hz, 1H, thiazole-H4).

In the 13C NMR spectrum three peaks at 165.9 ppm and 168.3 ppm, 25.6 ppm and 7.7 ppm were observed, being assigned to C=N and C=S respectively. In the 31P NMR spectrum the 31P (C=N) signal is observed at 25.6 ppm.

The mass spectrum of ligand HL showed molecular ion peak at (361, 28%) which corresponding to its molecular formula C15H12N3O2PS2, and base peak at m/z (%)=99 (100%), peak at 165 (71%), peak at 186 (75%), peak at 297 (3%) which confirms the suggested structure.

Further insight concerning the structure of the ligand is obtained from IR, UV-vis. The IR and UV-vis measurements, of HL ligand will be discussed with its metal complexes.

Metal complexes and characterization

IR spectra and mode of bonding: In the absence of a powerful technique such as X-ray crystallography, IR spectra have proven to be the most suitable technique to give enough information’s to elucidate the nature of bonding of the ligand to the metal ion. The IR spectra of the free ligand and metal complexes were carried out in the range 4000–400 cm\(^{-1}\).

The \(\nu (C=N)\) of the thiazole ring occurs at 1620 cm\(^{-1}\) after complexation indicating the coordination of the thiazole nitrogen to metal ions [15]. In addition, the ligand exhibits two bands at 1314 and 1166 cm\(^{-1}\) due to v asym (SO\(_2\)) and v sym (SO\(_2\)) stretching vibrations, respectively. Also, it has a band at 3412 cm\(^{-1}\) which attributed to \(\nu (NH)\) of the amine group. The bands due to asymmetric and symmetric SO\(_2\) group are shifted to lower frequencies upon complexation. While the \(\nu (NH)\) is disappeared or hidden under the broad bands at 3450–3300 cm\(^{-1}\) in the spectra of the complexes as the result of the presence of coordinated molecules which is turns make it difficult to confirm the enolization of the sulfonamide group. In the far IR spectra of all the complexes, the non-ligand bands observed at 500-503, 455-459 and 412-415 cm\(^{-1}\) regions can be assigned to \(\nu (M-O)\), \(\nu (M-N)\) and \(\nu (M-Cl)\), respectively [16]. From the infrared spectra, it is apparent that, the chelation of the divalent metal ions to the ligand occurs from the HL ligand through the oxygen atom of the sulfonamide group and the nitrogen atom of the thiazole ring in the ligand.

NMR spectra: Unfortunately, the insolubility of either Zn(II) or Hf(II) complexes in CDCl\(_3\), CD\(_3\)COCD\(_3\), or DMSO-d6 make it difficult to carry out \(^1\)H NMR, 13C NMR and 31P NMR spectra of the complexes to further clarify the way of binding of HL ligand to the metal ions.

Molar conductance measurements: The observed very low molar conductance of the complex in DMSO (10-2M) solution at room temperature was consistent with non-electrolyte nature of the complexes [17]. Thus the complexes may be formulated as \([\text{ML}_2(\text{Cl})_2]\), where M=Co(II), Ni(II), Cu(II), Zn(II) and Hf(II), L=ligand.

Mass spectra: The mass spectrum of the Ni complex showed a molecular ion NiC\(_{15}\)H\(_{15}\)Cl\(_{2}\)N\(_{10}\)P\(_{5}\)S\(_{2}\)+ peak at m/z 852.36 amu and Hf(II) complex showed molecular ion peak at m/z 676 amu. The calculated mass of Hf(II) complex was 972.15 amu, therefore, the molecular ion peak may be corresponding to the M+ peak. The observed data were in good agreement with the proposed molecular formula that is \([\text{M(C}_{15}\text{H}_{15}\text{Cl}_{2}\text{N}_{10}\text{P}_{5}\text{S}_{2}] \text{Cl}_{2}\]) and suggest the monomeric nature of the complexes. In addition to the molecular ion peaks, the spectra exhibit other peaks assignable to various fragments arising from the thermal cleavage of the complexes.

Electronic and magnetic moment measurements: The Co(II) complex showed the magnetic moment 5.32 B.M. for complex (4) at room temperature where that of the usual octahedral complexes are 4.8–5.4 B.M [15,18]. The electronic spectrum of the Co(II) complex displays three bands at 13,256, 15,856 and 24,477 cm\(^{-1}\). These bands may be assigned to following transitions \(4T_{1g} \rightarrow 4T_{2g}(F)\) (v1), \(4T_{1g} \rightarrow 4A_{2g}(F)\) (v2) and \(4T_{1g} \rightarrow 4T_{1g}(P)\) (v3), respectively. The position of bands suggest octahedral geometry of Co(II) complex [18].

The magnetic moment was measured which gave 3.24 B.M., for complex (5), which lies in the range (2.9-3.3 \(\mu\)B) of the Ni(II) octahedral complexes [15,18]. Electronic spectrum of Ni(II) complex displays bands at 14,439, 15,225 and 21,745 cm\(^{-1}\). These bands may be assigned to \(3A_{2g}(F) \rightarrow 3T_{1g}(F)\) (v1), \(3A_{2g}(F) \rightarrow 3T_{2g}(F)\) (v2) and \(3A_{2g}(F) \rightarrow 3T_{1g}(P)\) (v3) transitions, respectively. It suggests octahedral geometry of Ni(II) complex [15,18].

The observed magnetic moment of the Cu(II) complex is 2.21 B.M., which confirms the octahedral structure of this complex [15,18]. For octahedral Cu(II) complex, the expected transition is 2B1g→2A1g with respective absorption at 15,398 cm\(^{-1}\). Due to Jahn–Teller distortions, Cu(II) complexes give a broad absorption between 600 and 700 nm.

Ligand field parameters: Various ligand field parameters are calculated for the complexes (Table 1). The value of Dq in Co(II) complexes were calculated from transition energy ratio diagram
using the \(v_3/v_2\) ratio [18]. The nephelauxetic parameter \(\beta\) was readily obtained by using the relation \(\beta = B_{\text{complex}}/B_{\text{free}}\), where \(B_{\text{free}}\) is the free ion) for Ni(II) is 1042 cm\(^{-1}\) and for Co(II) is 1117 cm\(^{-1}\) [18]. The value of \(\beta\) lies in the range 0.47–0.95. These values indicate the appreciable covalent character of metal ligand \(\sigma\) bond. The \(g\) values are almost equal to free electron \(g\) value.

**EPR spectrum of Cu(II) complex:** The spectrum of the Cu(II) complex exhibits two broad band with \(g_{||} = 2.18\) and \(g_{\perp} = 2.06\) so, \(|g_{||} - g_{\perp}| = 0.12\). In axial symmetry, the \(g\) values are related to the G-Factor by the expression \(G = |g_{||} - g_{\perp}| = 0.12\). The G values of the Cu(II) complex arc <4 suggesting that the considerable exchange interaction in the solid state. Further, the shape of the ESR spectrum of Cu(II) complex indicates that the geometry around the Cu(II) ions are elongated octahedral. The lower value of \(g_{\perp}\) (0.46) compared to \(g_{||}\) (1.04) in Cu(II) complex indicate that the covalent in-plane \(\sigma\)-bonding is more pronounced than the covalent in-plane \(\pi\)-bonding character [18].

**Kinetics of thermal decomposition:** In order to characterize the metal complexes more fully in terms of thermal stability, their thermal behaviors were studied. In the present investigation, the correlations between the different decomposition steps of the complexes with the corresponding weight losses are discussed in terms of the proposed formula of the complexes. The weight losses for each complex are calculated within the corresponding temperature ranges.

The [Hf(L)\(_2\)(Cl)\(_2\)] complex with the molecular formula [Hf C\(_{20}\)H\(_{18}\)Cl\(_4\)H\(_6\)N\(_6\)O\(_4\)P\(_2\)S\(_4\)] is thermally decomposed in four successive steps. The first estimated mass loss 24.42% (calculated mass loss=25%) within the temperature range 58–186°C can be attributed to the loss of (C\(_{12}\)H\(_{10}\)P\(_2\)N\(_2\)). The DTG curve gives an exothermic peak at 214°C (the maximum peak temperature). The second estimated mass loss 15.39% (calculated mass loss=15.63%) within the temperature range 186–324°C could be attributed to the liberation of (C\(_{6}\)H\(_6\)N\(_4\)) fragment. The DTG curve gives an exothermic peak at 333°C (the maximum peak temperature).

The thermodynamic activation parameters (Table 2) of decomposition processes of the metal (Co(II), Ni(II), Cu(II) and Zn(II)) complexes namely activation energy (E\(_a\)), entropy (\(\Delta S^*\)) and Gibbs free energy change of the decomposition (\(\Delta G^*\)) were evaluated graphically by employing three methods, Coats–Redfern [19] (CR), Horowitz–Metzger [20] (HM), and Piloyan–Novikova [21] (PN). From the results obtained, the following remarks can be pointed out:

1. The high values of the energy of activation, E\(_a\) of the complexes reveal the high stability of such chelates due to their covalent bond character [22].

2. The positive sign of \(\Delta G^*\) for the investigated complexes reveals that the free energy of the final residue is higher than that of the initial compound, and all the decomposition steps are non spontaneous processes. Also, the values of the activation, \(\Delta G^*\) increases significantly for the subsequent decomposition stages of a given complex. This is due to increasing the values of \(\Delta S^*\) significantly from one step to another which overrides the values of \(\Delta H\) [23].

3. The negative \(\Delta S^*\) values for the decomposition steps indicate that all studied complexes are more ordered in their activated states [24].

**Powder XRD:** Single crystals of the complexes could not be prepared to get the XRD and hence the powder diffraction data were obtained for structural characterization. Structure determination by X-ray powder diffraction data has gone through a recent surge since it has become important to get to the structural information of materials, which do not yield good quality single crystals. The indexing procedures were performed using (CCP4, UK) CRYSFIRE program [18] giving tetragonal crystal system for [Co(L)\(_2\)(Cl)\(_2\)] having M(9)=11, F(6)=8, which do not yield good quality single crystals. The indexing procedures were performed using (CCP4, UK) CRYSFIRE program [18] giving tetragonal crystal system for [Co(L)\(_2\)(Cl)\(_2\)] having M(9)=11, F(6)=8, and the tetragonal crystal system for [Cu(L)\(_2\)(Cl)\(_2\)] having M(6)=19, F(6)=8, as the best solutions. Their cell parameters are shown in Table 3.

**SEM and EDX spectra:** A representative energy dispersive x-ray analysis (EDX) and scanning electron microscopy (SEM) results of the residue obtained from thermal decomposition of all complexes are shown in Figures 2 and 3. They provide insights on the surface morphology and the composition. The EDX spectra (Figure 2a-f) show

---

**Table 1:** Ligand field parameters of the complexes.

| Compound | Stage | TG range (°C) | DTGA peak (°C) | \(E_a\) (kJ/mol) | \(\Delta H\) (kJ/mol) | \(\Delta S^*\) (kJ/mol K) | \(\Delta G^*\) (kJ/mol) |
|----------|-------|---------------|----------------|----------------|-----------------|-----------------|----------------|
| [Hf(L)\(_2\)(Cl)\(_2\)] | 1st  | 58–186 | 214 | 46.34×10^6 | 125.33 | -0.009 | 125 |
| 166–324 | 333 | 78.87×10^8 | 142.78 | 132.12 | -0.025 | 144 |
| [Ni(BHDAB)(H\(_2\)O)\(_2\)](Cl)\(_2\) | 3rd | 324–589 | 563 | 77.22×10^3 | 154.68 | -0.034 | 169 |
| 589–798 | 675 | 45.92×10^3 | 164.68 | 174.56 | -0.048 | 224 |
| [Hf(L)\(_2\)(Cl)\(_2\)] | 1st  | 58–186 | 214 | 46.34×10^6 | 124.34 | -0.084 | 128 |
| 186–324 | 333 | 78.87×10^8 | 147.16 | 132.08 | -0.024 | 147 |
| [Ni(BHDAB)(H\(_2\)O)\(_2\)](Cl)\(_2\) | 3rd | 324–589 | 563 | 77.22×10^3 | 155.84 | -0.038 | 169 |
| 589–798 | 675 | 45.92×10^3 | 168.79 | 173.33 | -0.044 | 228 |

**Table 2:** Kinetic parameters \([\text{Hf(L)}(\text{Cl})_2]\).
Table 3: Crystallographic data for the Schiff base complexes [Cu(L)_2(Cl)_2], [Ni(L)_2(Cl)_2] and [Co(L)_2(Cl)_2].

| Data          | [Cu(L)_2(Cl)_2] | [Ni(L)_2(Cl)_2] | [Co(L)_2(Cl)_2] |
|---------------|-----------------|-----------------|-----------------|
| Empirical formula | CuC_{30}H_{24}Cl_{2}N_{6}O_{4}P_{2}S_{4} | NiC_{30}H_{24}Cl_{2}N_{6}O_{4}P_{2}S_{4} | CoC_{30}H_{24}Cl_{2}N_{6}O_{4}P_{2}S_{4} |
| Formula weight (g/mol) | 857.21 | 852.36 | 852.6 |
| Wavelength (Å)                      | 1.49998 | 1.49998 | 1.51998 |
| Crystal system                      | Tetragonal | Cubic | Triclinic |
| Space group                         | P4/m | P4/m | P4/m |
| Unit cell dimensions (Å,°)           |                                           |                                           |                                           |
| a(Å)                                | 8.200358 | 16.1056 | 7.301455 |
| b(Å)                                | 8.200417 | 16.1048 | 7.301455 |
| c(°)                                | 16.02308 | 16.1048 | 7.301455 |
| α(°)                                | 90 | 90 | 90 |
| β(°)                                | 90 | 90 | 90 |
| γ(°)                                | 90 | 90 | 90 |
| Volume (Å³)                          | 1097.63 | 5168.52 | 856.46 |
| (Calc.) density (g/cm³)             | 1.92584 | 1.28 | 1.93 |
| 2θ range                            | 13.22–56.38 | 16.18–64.75 | 12.48–68.08 |
| Limiting indices                    | 0 ≤ h ≤ 3, 0 ≤ k ≤ 1, 1 ≤ l ≤ 7 | 3 ≤ h ≤ 10, 1 ≤ k ≤ 6, 3 ≤ l ≤ 10 | 2 ≤ h ≤ 8, 1 ≤ k ≤ 8, 0 ≤ l ≤ 2 |
| Z                                     | 2 | 6 | 6 |
| Rf                                    | 0.0000801 | 0.000011 | 0.0000698 |
| Temperature (K)                      | 298 | 298 | 298 |

Figure 2: EDX spectrum of (a) Co(II), (b) Ni(II), (c) Cu(II), (d) Zn(II), and (e) Hf(II) complexes (a-f), respectively.
that the residues majorly consist of metal (cobalt, nickel, copper and hafnium), carbon, phosphorus and sulfur. The SEM micrographs of ligand and its complexes are shown in Figure 3a-f. The Co(II) complex shows bar like structure. The Ni(II) complex shows faceted microcrystal. Agglomerated morphology was seen for the Cu(II) complex. For Hf(II) complex bar with layered structure was present.

**Cyclic voltammetry:** The cyclic voltammogram (Figure 4) of metal(II) complexes were recorded in DMSO at room temperature. The Co(II) and Ni(II) complexes showed well distinguished cathodic peak in the range of -622 mV and the corresponding anodic peak at the range of -947 mV. The measured ΔEp values (ΔEp=-325) clearly indicated that these redox couples were found to be less stable. The Cu(II) complex also showed redox couples with anodic peak at -668 mV and cathodic peak -497 mV respectively and ΔEp: -188 mV. The ipa/ipc values for complexes cobalt and copper 1.12 and 2.07 respectively, which clearly confirmed the involvement of one and two electron redox process. The measured ΔEp values for these complexes are -325 and -188 mV which clearly indicated that the redox couples are quasi-reversible process.

**Catalytic activity:** The catalytic activity of cyclohexane oxidation was performed over the five synthesized complexes ([Co(L)]2(Cl)2), [Ni(L)]2(Cl)2, [Cu(L)2(Cl)2], [Zn(L)2(Cl)2] or [Hf(L)2(Cl)2]) at room temperature (RT) and 70ºC for 8 and 12 h. The complexes have not showed any conversion of cyclohexane to cyclohexanol and cyclohexanone at RT. Though all synthesized complexes have not yielded any product at RT, cyclohexane conversion can be achieved at
particular temperature which is almost close to the boiling point of the reactant. The cyclohexane boiling point is ~79°C and thus the reaction temperature fixed at 70°C.

**Molecular modeling:** The ligand–M(II) complexes [M=Co(II), Hf(II)] were modeled by material studio DMOL3 program [25]. Ligand containing metal ion was optimized using molecular mechanic methods. Several cycles of energy minimization had to be carried out for each of the molecules. The root mean square gradient for the molecules was less than one.

The Co(II) complex has octahedral geometry with auto optimized energy 1438.32 kJ/mol. The equatorial positions being occupied by the four N atoms. The equatorial Co(II)-N distance being 1.87 Å. The axial position is occupied by chlorine ligand at Co(II)-Cl distance of 2.37 Å. These values are close to the ideal distance of 1.86 Å and 2.32 Å, respectively. The N–Co–O and Cl–Co–Cl angles are 86.26 Å and 89.75 Å, respectively (Figure 5).

The Hf(II) complex also has octahedral geometry with auto optimized energy 2014.74 kJ/mol. The equatorial Hf(II)-N distance being 1.81 Å. The axial position is occupied by chlorine ligand at Hf(II)-Cl distance of 2.38 Å. These values are close to the ideal distance of 1.86 Å and 2.37 Å, respectively. The N–Hf–O and Cl–Hf–Cl angles are 83.17 Å and 87.45 Å, respectively (Figure 6).

Finally, the previous findings indicated that the coordination...
occurs through the nitrogen of the thiazole ring and the oxygen of the sulfonamide –SO₂NH– group to give the structures shown in Figure 7.

**Conclusion**

In the present research studies, our successful efforts are in contribution in the field of mycology to design and development of novel molecular systems. On the basis of various physico-chemical and spectral data presented and discussed above, the complexes may tentatively be suggested to have octahedral geometry. The magnetic activities of the divalent metal complexes have been studied in the presence one unpaired electron metal(II) complexes. The catalytic activities of the divalent metal complexes have been studied in the oxidation of cyclohexane by hydrogen peroxide, an environmental friendly oxidant. The molecular parameters of the ligand and its Co(II) and Hf(II) complexes have been calculated.

**References**

1. Pignatello JJ, Oliveros E, MacKay A (2006) Advanced Oxidation Processes for Organic Contaminant Destruction Based on the Fenton Reaction and Related Chemistry. Crit Rev Environ Sci Technol 36: 1-84.
2. Derek F, Laine L, Cheng IF (2007) The destruction of organic pollutants under mild reaction conditions: A review Microchem J 85: 183-193.
3. Bhunia A, Durani S, Wangikar PP (2001) Horseradish peroxidase catalyzed degradation of industrially important dyes. Biotechnol Bioeng 72: 562-567.
4. Levin L, Papinutti L, Forchiassin F (2004) Evaluation of Argentinian white rot fungi for their ability to produce lignin-modifying enzymes and decolorize industrial dyes. Biorec Technol 94: 169-176.
5. Kang N, Lee DS, Yoon J (2002) Kinetic modeling of Fenton oxidation of phenol and monochlorophenols. Chemosphere 47: 915-924.
6. Huang CP, Huang YH (2008) Comparison of catalytic decomposition of hydrogen peroxide and catalytic degradation of phenol by immobilized iron oxides. Appl Catal A: Gen 346: 140-148.
7. Sinchez C (2009) Lignocellulosic residues: Biodegradation and biocconversion by fungi. Biotechnol Adv 27: 185-194.
8. Crestini C, Saladino R, Tagliatela P, Boschi T (1999) Biomimetic degradation of lignin and lignin model compounds by synthetic anionic and cationic water soluble manganese and iron porphyrins. Bioorg Med Chem 7: 1897-1905.
9. Santos A, Yustos P, Rodriguez S, Simon E, Garcia-Ochoa F (2007) Abatement of phenolic mixtures by catalytic wet oxidation enhanced by Fenton’s pretreatment: Effect of H₂O₂ dosage and temperature. Jnat Hazard Mater146: 596-601.
10. He K, Dong YM, Li Z, Yin L, Zhang AM, et al. (2008) Geopolymers for immobilization of Cr⁶⁺, Cd²⁺, and Pb²⁺. Jnat Hazard Mater 159: 587-592.