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Spectroscopic analysis, DNA binding and antimicrobial activities of metal complexes with phendione and its derivative

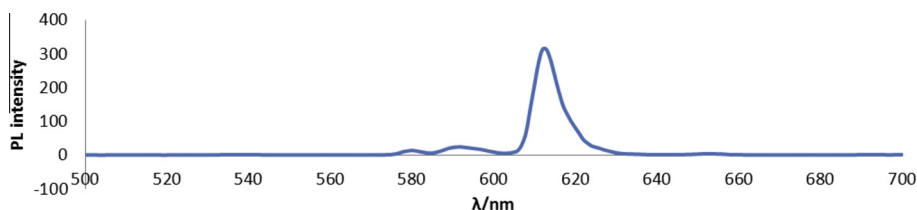
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HIGHLIGHTS

- We report on synthesis of some new phendione containing metal complexes.
- Complexes are characterized by spectroscopic methods.
- The strong red emission with narrowed band (half width <10 nm) of Eu-complexes observed at ~615 nm.
- Interactions of phendione-metal complexes with DNA have been studied.
- Phendione-metal complexes are potential anti-microbial agents.

GRAPHICAL ABSTRACT

PL spectra of [Eu(HFT)₃(Phendione)]. The synthesized ligands and metal complexes have been characterized by FTIR, UV-Visible spectroscopy and PL spectra. DNA binding studies showed that Fe complex of the synthesized ligand is more potent DNA binding and damaging agent compare to other compounds under study. The lanthanide complexes of phendione showed high antibacterial activities.



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ABSTRACT

A novel ligand (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10] phenanthroline(L) has been synthesized from 1,10-phenanthroline-5,6-dione. Its transition metal complexes, [FeLCl₄][L-H] and [CuL₂](NO₃)₂ have also been synthesized. Besides, three mixed ligand lanthanide metal complexes of Phendione and β-diketones have been synthesized, namely [Eu(TFN)₃(Phendione)] (TFN = 4,4,4-trifluoro-1-(2-naphthyl)-1,3-butanedione), [Eu(HFT)₃(Phendione)] (HFT = 4,4,5,5,6,6,6-heptafluoro-1-(2-thienyl)-1,3-hexanedione), [Yb(HFA)₃(Phendione)] (hfa = hexafluoroacetylacetonate). The synthesized ligands and metal complexes have been characterized by FTIR, UV-Visible spectroscopy and PL spectra. DNA binding activities of the complexes and the ligands have been studied by DNA gel electrophoresis. DNA binding studies showed that Fe complex of the synthesized ligand is more potent DNA binding and damaging agent compare to others under study. The synthesized compounds were also screened for their antimicrobial activities by disc diffusion method against three microbes, namely *Escherichia coli*, *Staphylococcus aureus*, *Proteus penneri*. The lanthanide complexes of phendione showed great antibacterial activities.

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Introduction

The development of new materials that exhibit extensive biological activities such as DNA binding, DNA cleaving, antimicrobial sensibility have become potential for the last few decades in the medicinal and pharmaceutical fields. The ongoing interests in the pharmacological field for the development of better therapeutic

agents which can bind and damage DNA is rationalized by the fact that many diseases, including cancer occur because of aberrant gene expression. Transition and rare earth metal complexes are the potential candidates in this field due to their tunable coordination environments and versatile physiochemical properties for designing highly sensitive diagnostic agents for medicinal applications as exemplified by the chemotherapeutic agents like the cis-platin or bleomycins [1–3]. In our present work we intended to synthesized some transition metal complexes of phenanthroline derivative as imidazo-[4,5-f] ligand and some lanthanide com-

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plexes of phendione along with the lanthanide diketones. We have chosen 3d transition metals namely Cu and Fe in our present work because these metals are bio-essential metals and ubiquitous in biological systems [4–13]. The reason for choosing the imidazo-[4,5-f] ligand is that metal complexes of these phenanthroline derivatives have been reported to show huge biological activities such as DNA binding and photocleavage activities and also their metal complexes have been reported to show NLO properties for device applications [14–18]. Besides this we have also synthesized and studied the biological activities of lanthanide metal complexes. We have synthesized Europium and Ytterbium metal diketone complexes incorporating 1,10-phenanthroline-5,6-dione. Our interests for the lanthanide metal chemistry emerged from the versatile interesting characteristics shown by the complexes. Lanthanide ions have distinct spectroscopic properties. In contrast to the broad bands of transition metals they exhibit narrow emission lines with characteristic emission and absorption spectra for each lanthanide ion. Lanthanide ions are interesting tools in the design of optical materials such as OLEDs, optical amplifiers and lasers [19–24]. They can be used as inorganic materials where they exhibit high quantum yields or as complexes with organic chromophores; in the latter case, the inherent low absorption of the lanthanide ions can be overcome by an energy transfer from the organic ligand to the central lanthanide ion (antenna effect) [25] which highly increases the luminescence intensity of the lanthanide ion. Lanthanide complexes are also potential candidates for DNA binding, antitumor, antibacterial, antifungal activities [26–30]. Encouraged by the high potential of the lanthanide complexes, in our present work, we have synthesized three lanthanide complexes namely [Eu(TFN)₃(Phendione)] (TFN = 4,4,4-trifluoro-1(2-naphthyl)-1,3-butanedione), [Eu(HFT)₃(Phendione)] (HFT = 4,4,5,5,6,6,6-heptafluoro-1-(2-thienyl)-1,3-hexanedione), [Yb(HFA)₃(Phendione)] (hfa = hexafluoroacetylacetonate). These lanthanide metal diketone complexes have been reported to show interesting luminescent properties [31]. Our intention in phendione metal complexes is because phendione is a biologically active and fantastic chelating ligand which can form monomeric as well as polymeric coordination complexes. Phendione has free quinoid functional group with redox properties which can cause the bacterial cell breaking and binding to the protein synthesizing enzyme thus inhibiting the protein synthesis for bacterial propagation. Here we report on synthesis of some new phendione containing metal complexes of both transition metals and lanthanides and their interaction with DNA as well as antibacterial activity.

Materials and methods

All the materials used for the research work were reagent grade and collected from Merck. UV–Visible spectra of the ligand and complexes were recorded with a UV–Visible spectrophotometer (Model No: UV-SHIMADZU UV-1800 series, Japan). Infrared spectra were recorded on KBr pellets with an IR spectrometer (model No-SHIMADZU IP Prestidge-21, FTIR spectrometer, Japan) in the 4000–400 cm⁻¹. Photoluminescence spectra were measured by a spectrofluorophotometer (Shimadzu Corp., model RF-5301).

General procedure for the synthesis of the ligands and metal complexes

Phendione has been synthesized according to the literature [32,33].

Synthesis of (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10]phenanthroline (L)

It was synthesized by the modified Redziszewski reaction [34,14–18]. A mixture of Zimtaldehyde (cinnamaldehyde) (0.1982 g, 1.5 mmol), 1,10-phenanthroline-5,6-dione (0.32 g, 1.5 mmol), ammo-

niacetic acid (2.31 g, 30 mmol) and glacial acetic acid (30 cm³) was refluxed for about 2 h, then cooled to room temperature and diluted with water (ca. 60 cm³). Dropwise addition of concentrated aqueous ammonia gave a yellow precipitate, which was collected and washed with water. The crude product in ethanol was purified by silica gel filtration (60–100 mesh, ethanol). The principal yellow band was collected. A yellow crystalline solid was obtained by slow evaporation of the solution, which was then dried in vacuo. Yield 0.35 g, 65%.

Synthesis of Eu(hft)₃·2H₂O, Eu(tfn)₃·2H₂O and Yb(hfa)₃·2H₂O

Eu(hft)₃·2H₂O, Eu(tfn)₃·2H₂O and Yb(hfa)₃·2H₂O were synthesized according to the literature [31]. These compounds were characterized by the IR and UV visible spectral analysis.

[Eu(tfn)₃(Phendione)] synthesis

Phendione (0.0148 g, 0.07 mmol) dissolved in chloroform was dropwise added to an ethanolic solution of Eu(tfn)₃·2H₂O (0.07 g, 0.07 mmol). This solution was then stirred at room temperature for 3 h. After completion of the reaction the solution was kept for the evaporation of the solvent or solvent was reduced by a rotary evaporator. Reduction of the solvent produced a reddish brown precipitate. The precipitate was collected and washed with n-hexane, and recrystallized from a mixture of toluene and n-hexane.

[Eu(hft)₃(Phendione)] synthesis

Phendione (0.0126 g, 0.06 mmol) dissolved in chloroform was dropwise added to an ethanolic solution of Eu(hft)₃·2H₂O (0.07 g, 0.06 mmol). This solution was then stirred at room temperature for 3 h. After completion of the reaction the solution was kept for the evaporation of the solvent or solvent was reduced by a rotary evaporator and allowed to stand for several days. After several days fade yellow colored crystalline solid was obtained. This was collected and washed with n-hexane, and recrystallized from a mixture of toluene and n-hexane.

[Yb(hfa)₃(Phendione)] synthesis

Phendione (0.0126 g, 0.06 mmol) dissolved in chloroform was dropwise added to an ethanolic solution of Yb(hfa)₃·2H₂O and the solution was then refluxed for 3 h. Sky blue colored solution was obtained, which produced sky blue colored precipitate on slow evaporation of the solvent. Product was separated by filtration.

Synthesis of [Fe(L)Cl₄][L-H]

(E)-2-styryl-1H-imidazo [4, 5-f] [1, 10] phenanthroline(L) ligand (0.626 g, 2 mmol) in 0.1 M aqueous HCl solution (20 ml) was added to a solution of FeCl₃·6H₂O (0.27032 g, 1 mmol) in water (15 mL) and the resulting red solution stirred at 55–60 °C for 3 h. The red precipitate obtained was collected by filtration.

Synthesis of [Cu(L)₂](NO₃)₂

Ligand L(2 mmol) dissolved in 15 ml of ethanol was added dropwise to a solution of Cu(NO₃)₂·3H₂O in 20 ml ethanol while the solution changes its color from blue to green and stirred at room temperature for 30 min. Then the volume of solvent was reduced and kept at room temperature for several days. After several days a green precipitate was obtained, which was filtered and collected.

DNA binding studies

DNA was extracted prior to binding studies from goat blood manually by utilizing minicolumn preparation method and also by using EZ-10 Spin Genomic DNA Minipreps extraction Kit from human Blood. Then binding study was conducted by agarose gel electrophoresis method as follows:

5 μL of each of the metal complex solutions dissolved in suitable solvents were taken into a 0.5 ml of eppendorf centrifuge tubes. 12 μL of DNA solution dissolved in TE buffer was added to the tubes containing the metal complexes; for DNA control just the DNA solutions were taken into the tubes. The tubes were incubated at 37 $^{\circ}\text{C}$ for 30 min to 2 h for short time interaction studies and 16 h for long time interaction studies. After incubation the tubes containing the solutions were put into a refrigerator at 0 $^{\circ}\text{C}$ for few minutes. The tubes were then taken out and 3 μL of gel loading buffer was added into each tube before running electrophoresis.

Results and discussion

Characterization by UV–Visible spectra

Characterization of 1,10-Phenanthroline-5,6-dione has been accomplished by melting point, UV–Visible and IR spectroscopic methods [33,35–39]. Melting point of 1,10-Phenanthroline-5,6-dione was found to be 258–260 $^{\circ}\text{C}$ which is consistency with the literature. Physical properties of the synthesized compounds were also recorded (Supplementary Table S1).

The UV–Visible spectra of the ligand (**E**)-2-styryl-1H-imidazo [4, 5-f] [1, 10]phenanthroline (**L**) in DMSO shows three characteristic bands. The three bands at around 270 nm, 288 nm and 348 nm are ascribed as the bands for $\pi\text{-}\pi^*$ (C=C), $\pi\text{-}\pi^*$ (C=N) and $n\text{-}\pi^*$ transitions respectively as shown in Fig. 1.

For starting Europium complexes $\text{Eu}(\text{tfn})_3\cdot 2\text{H}_2\text{O}$ and $\text{Eu}(\text{hft})_3\cdot 2\text{H}_2\text{O}$ we found characteristic absorption peaks at around 464.5 nm, 534.5 nm and 615 nm are assigned as ${}^7\text{F}_0\text{-}{}^5\text{D}_2$ and ${}^7\text{F}_1\text{-}{}^5\text{D}_1$, ${}^7\text{F}_2\text{-}{}^5\text{D}_0$ transitions respectively as shown in Fig. 2. For the $[\text{Eu}(\text{hft})_3(\text{Phendione})]$ and $[\text{Eu}(\text{tfn})_3(\text{Phendione})]$ complex we found the existence of these absorption peaks and that proves the presence of europium in the complex. The molar absorption coefficient at 464.5 nm for $[\text{Eu}(\text{hft})_3(\text{Phendione})]$ complex was found to be $1.015 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$ and that of $[\text{Eu}(\text{tfn})_3(\text{Phendione})]$ was found to be $6.581 \times 10^2 \text{ M}^{-1} \text{ cm}^{-1}$.

Yb has the most unique absorption among the rare earth series. The unique f–f transitions of Yb(III) from ground states ${}^2\text{F}_{7/2}$ to excited state ${}^2\text{F}_{5/2}$ are split by the crystal field into four and three doubly degenerate sublevels, respectively. This is magnetically allowed ($\Delta J = 1$). For each of the Yb(III) complexes within f^{13} electronic configuration, three absorption bands may be observed at around 930 nm, 960 nm and 975 nm [31]. If the absorption spectrum is taken in acetone then all the bands are well resolved (Fig. 3). But in DMSO the bands are not well resolved and the spectrum is dominated by the band at 975 nm. This behavior is consistent with ground-state stabilization of the complex's permanent dipole by the solvent.

The molar absorption coefficient at 975 nm for this complex was found to be $1.711 \times 10^2 \text{ M}^{-1} \text{ cm}^{-1}$.

According to the Tanabe–Sugano diagram for low spin d^5 configuration, the bands for the $[\text{FeCl}_4][\text{L-H}]$ (Fig. 4) at the regions

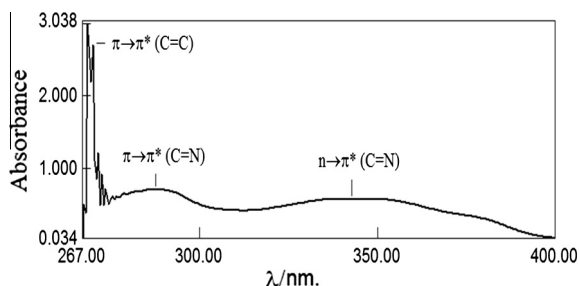


Fig. 1. UV–Visible absorption spectrum of the ligand (**E**)-2-styryl-1H-imidazo [4, 5-f] [1, 10]phenanthroline.

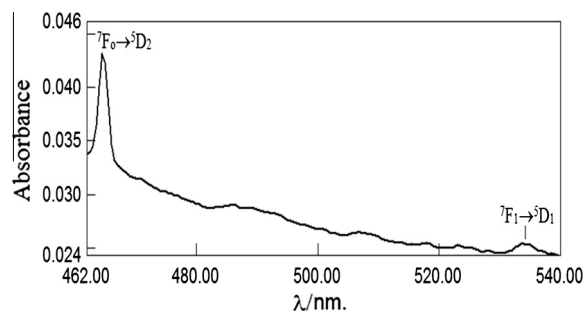


Fig. 2. Absorption spectrum of the $\text{Eu}(\text{tfn})_3\cdot 2\text{H}_2\text{O}$ complex.

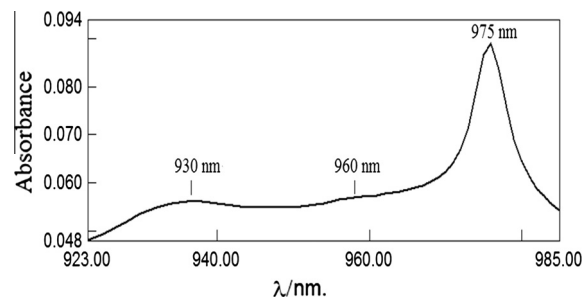


Fig. 3. Absorption spectrum of $\text{Yb}(\text{hfa})_3\cdot 2\text{H}_2\text{O}$ in acetone.

529 nm and 487 nm were assigned to the ${}^2\text{T}_{2g}\text{-}({}^2\text{A}_{2g}\text{ or }{}^2\text{T}_{1g})$ and ${}^2\text{T}_{2g}\text{-}{}^2\text{E}_g$ transitions, respectively [40]. The ligand centered bands for the $\pi\text{-}\pi^*$ (C=N) and $n\text{-}\pi^*$ in the complex appear at around 293.5 nm and 349 nm [40]. These bands show red shift from those in the free ligand due to the MLCT from the metal t_{2g} to ligand empty π orbital.

For Cu (II) systems with square planar geometry the ground term is ${}^2\text{B}_{1g}$ and three d–d bands corresponding to the transitions ${}^2\text{B}_{1g}\text{-}{}^2\text{B}_{2g}$, ${}^2\text{B}_{1g}\text{-}{}^2\text{A}_{1g}$ and ${}^2\text{B}_{1g}\text{-}{}^2\text{E}_g$ are observed. In both square planar and tetragonal geometries the transitions are not well resolved. The copper (II) complex $[\text{CuL}_2](\text{NO}_3)_2$ also showed a very weak and broad MLCT band at around 678 nm (Fig. 5A) [18]. We also found absorption bands at near IR region (989 nm, 890 nm and 865 nm) (Fig. 5B) and these can be assigned to the ${}^2\text{B}_{1g}\text{-}{}^2\text{B}_{2g}$, ${}^2\text{B}_{1g}\text{-}{}^2\text{A}_{1g}$ and ${}^2\text{B}_{1g}\text{-}{}^2\text{E}_g$ transitions respectively, which is reasonable for the square planar Cu(II) complexes. Intense absorption in the ultraviolet region is a feature common to the Cu(II) complex and is attributed to intra-ligand charge-transfer transition. We found the ligand centered transitions at 296.5 nm for the $\pi\text{-}\pi^*$ of C=N and at around 350.50 nm for the $n\text{-}\pi^*$ of C=N (Fig. 5A). These bands showed red shift from those of the ligands because of the MLCT from filled t_{2g} orbital of Cu to empty π^* orbital of the ligand. For the Cu complex the bands showed higher red shift that shown by the Fe complexes. This can be

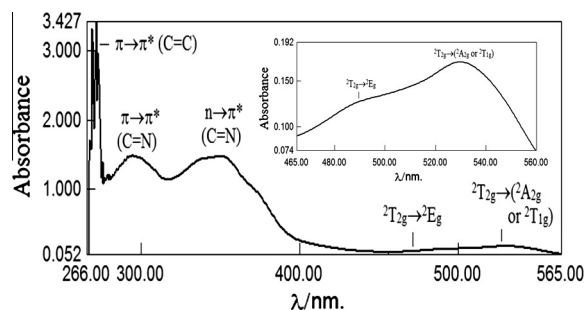


Fig. 4. UV–Visible absorption spectrum of $[\text{FeCl}_4][\text{L-H}]$.

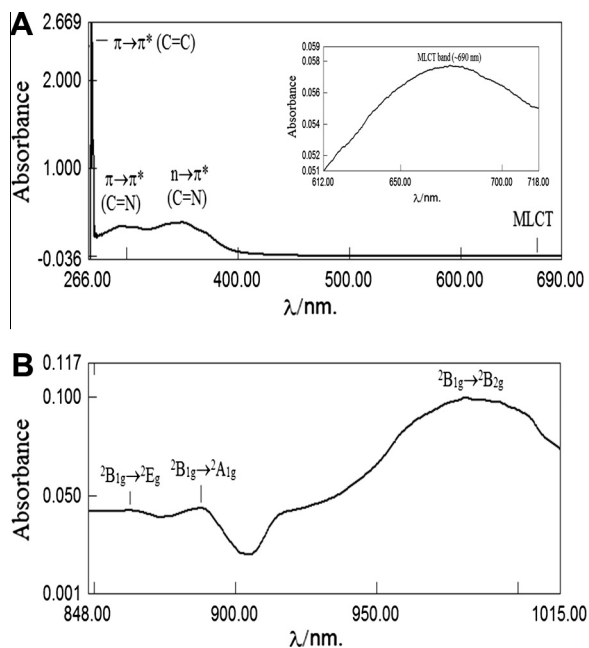


Fig. 5. Electronic absorption spectrum for $[\text{CuL}_2](\text{NO}_3)_2$ complex. (A) Ligand centered and MLCT band (upper right side) and (B) Absorption bands for the square planar $[\text{CuL}_2](\text{NO}_3)_2$ complex.

rationalized in terms of Fe^{3+} having d^5 configuration and Cu^{2+} having d^9 configuration and that charge transfer from Cu^{2+} centered t_{2g} orbital thus becomes easier.

PL spectra of Eu(III) complexes

Photoluminescence spectra of $[\text{Eu}(\text{HFT})_3(\text{Phendione})]$ and $[\text{Eu}(\text{TFN})_3(\text{Phendione})]$ were measured in acetone. Both the complexes showed PL spectra in visible region. Emission bands were observed at around 580, 590, 615 and 650 nm, and are attributed to the f-f transitions $^5\text{D}_0 \rightarrow ^7\text{F}_j$ ($J = 0, 1, 2, 3$, respectively) when excited at 370 nm [31]. The strongest emission band at around 615 nm ($^5\text{D}_0 \rightarrow ^7\text{F}_2$) was due to the electronic dipole transition as shown in Figs. 6 and 7. The strong red emission with narrowed band (half width <10 nm) of complexes $[\text{Eu}(\text{HFT})_3(\text{Phendione})]$ and $[\text{Eu}(\text{TFN})_3(\text{Phendione})]$ were observed by excitation at 370 nm.

Characterization of ligands and metal complexes by IR

FTIR spectra of the ligand (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10]phenanthroline (L) showed (Table 1 and Supplementary

Fig. S1) characteristic bands for the C=N at around 1564 cm^{-1} for the diimino C=N and at around 1645 cm^{-1} , 1620 cm^{-1} for the imidazo C=N. As it has been derived from phendione, no peak for the C=O in the region of around 1689 cm^{-1} was observed. The results proved that the ligand formation by removing C=O of phendione and creating imidazo group has been successful.

IR spectral data of the metal complexes are provided in Table 1 (Figs. S2–S6). For $[\text{Eu}(\text{tfn})_3(\text{Phendione})]$ complex (Fig. S2), coordination of phendione ligand to the metal was proved by the FTIR spectra of the complex. The IR spectra of phendione clearly exhibits stretching frequency of the C=O band at 1689 cm^{-1} . This band was seen to be not shifted much in the $[\text{Eu}(\text{tfn})_3(\text{Phendione})]$ complex and found at 1692 cm^{-1} which is reasonable since the C=O moieties are far removed from the site of coordination of this ligand with the metal ion [38,39]. In IR spectra of the starting europium complex $\text{Eu}(\text{tfn})_3 \cdot 2\text{H}_2\text{O}$ this new band was absent. This result verifies the presence of phendione in coordination to europium in the $[\text{Eu}(\text{tfn})_3(\text{Phendione})]$ complex.

FTIR spectra of $[\text{Eu}(\text{hft})_3(\text{Phendione})]$ complex proves the existence of the phendione ligand coordinated to the Eu(III) (Fig. S3). The stretching frequency of the C=O of phendione band was found at around 1697 cm^{-1} in the $[\text{Eu}(\text{hft})_3(\text{Phendione})]$ complex. In IR spectra of the starting europium complex $\text{Eu}(\text{hft})_3 \cdot 2\text{H}_2\text{O}$ this new band was absent. The result ascertained the presence of phendione in coordination to europium in the $[\text{Eu}(\text{hft})_3(\text{Phendione})]$ complex.

In $[\text{Yb}(\text{hfa})_3(\text{Phendione})]$ complex the existence of the phendione ligand coordinated to the complex is evidenced by the stretching frequency of the C=O of phendione at around 1693 cm^{-1} in the $[\text{Yb}(\text{hfa})_3(\text{Phendione})]$ (Fig. S4). In IR spectra of the starting europium complex $\text{Yb}(\text{hfa})_3 \cdot 2\text{H}_2\text{O}$ this new band was not found. Similarly the result indicates the presence of phendione in coordination moiety of Ytterbium in the $[\text{Yb}(\text{hfa})_3(\text{Phendione})]$ complex.

As shown in Table 1, FTIR spectra of the complex, $[\text{FeLCl}_4][\text{L-H}]$ indicates the bond formation between the ligand L and Fe^{3+} (Fig. S5). The original peaks for the C=N double bond in the ligand shifted to the lower wavenumber due to the bond formation with the metal ion and the fact that the charge delocalization or conjugation increases due to coordination of the ligand to the metal ion. The peaks at 1639 cm^{-1} and 1606 cm^{-1} are ascribed to be the bands for the C=N of the imidazo group. The diimino C=N shows peak at 1544 cm^{-1} , which is at lower wavenumber than that in the free ligand due to the bond formation with the metal [14–18].

In case of $[\text{CuL}_2](\text{NO}_3)_2$ complex (Table 1) the ligand coordination to the metal ion Cu^{2+} is also apparent from the FTIR spectra of the complex (Fig. S6). The original peaks for the C=N bond in the ligand shifted to the lower wavenumber in the metal complex due to the bond formation with the metal ion and the fact that the charge delocalization or conjugation increases due to coordina-

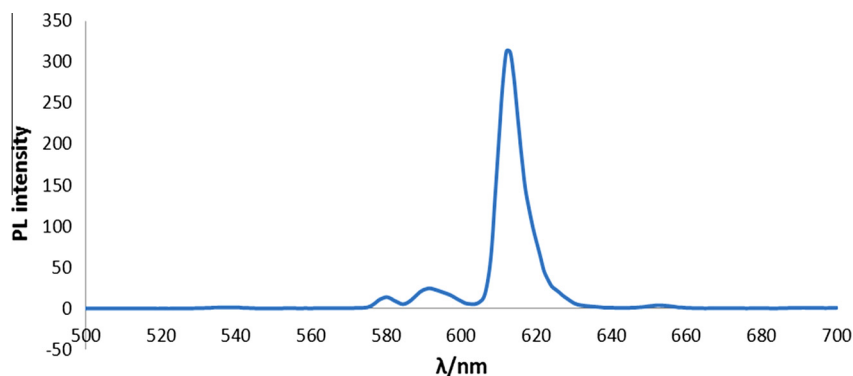


Fig. 6. PL spectra of $[\text{Eu}(\text{HFT})_3(\text{Phendione})]$.

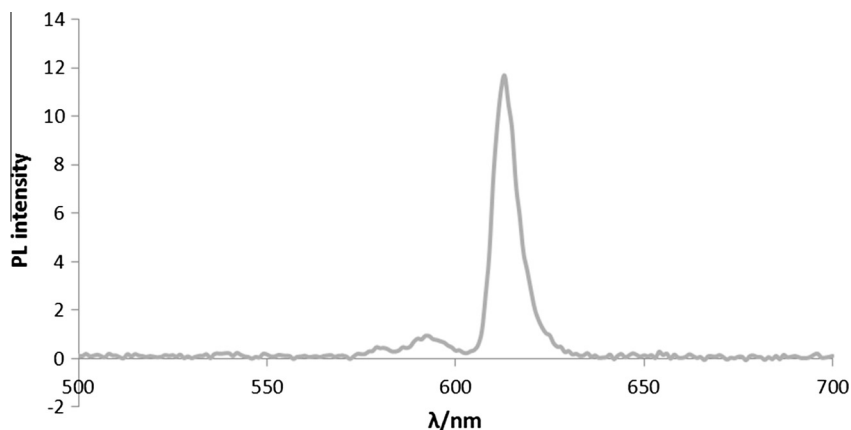


Fig. 7. PL spectra of [Eu(TFN)₃(Phendione)].

tion of the ligand to the metal ion. The peaks at 1641 cm^{-1} and 1608 cm^{-1} are attributed to be the bands for the C=N of the imidazo group. The diiminic C=N shows peak at 1543 cm^{-1} , which is at lower wavenumber than that in the free ligand due to the bond formation with the metal [14–18].

Biological activities assay

DNA binding studies

We have studied the DNA binding activities of the synthesized ligand (Phendione, (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10]phenanthroline (L) as well as the Metal (Eu, Yb, Cu, Fe) complexes by agarose gel electrophoresis (Supplementary Figs. S7–S10).

DNA was extracted from Goat blood manually and from human blood sample by extraction kit. We studied the binding activity of the synthesized products to both the DNA samples.

There was a substantial decrease in the intensity of the DNA bands from DNA control to metal complexes with ligand L (Cu, Fe) i.e. intensity varies, DNA control \cong Ligand + DNA > Cu complex + DNA > Fe complex + DNA (Fig. S7). The decreased intensity of the DNA bands may be attributed to the fact that, ligand and also the metal complexes bind to DNA such that ethidium bromide cannot intercalate into DNA. Fe complex of the ligand L showed the less intense band. This implies that Fe complex intercalated into the DNA more efficiently than the Cu complex and the ligand. The DNA band for (Cu complex + DNA) and (Fe complex + DNA) showed increased mobility. This is due to the fact that Cu and Fe complexes not only intercalate into DNA also causes DNA degradation or cleavage thus making the DNA band running fast. For the Fe complex the DNA degradation efficiency was higher. We also studied the DNA binding activities of the metal (Fe, Cu) complexes and the ligand after 2.5 h of incubation (Fig. S8). We observed that DNA band for (Ligand + DNA) was more intense than that of the DNA itself. There was no DNA band visible in for the Cu and Fe complexes. This indicated that Fe as well as Cu complexes intercalated to DNA effectively. Band for the (ligand + DNA) specifies that ligand bind to DNA mostly through electrostatic interaction between the phosphate groups of DNA and the N–H group of the ligand.

DNA binding activities of phendione and its lanthanide diketone complexes with human genomic DNA extracted from blood samples were studied (Fig. S9). We found that the DNA bands for the metal complexes were less intense than that for the DNA control. For Eu(hft)₃(Phendione), Eu(tfn)₃(Phendione) the DNA bands were less intense than those for Eu(hft)₃·2H₂O and Eu(tfn)₃·2H₂O. Between Eu(hft)₃(Phendione) and Eu(tfn)₃(Phendione) DNA band for Eu(hft)₃(Phendione) was less intense, almost absent. And in comparison with Eu(hft)₃·2H₂O, Eu(tfn)₃·2H₂O the DNA band for

Eu(hft)₃·2H₂O was less intense. The DNA bands for the complexes show increased mobility in the high molecular weight DNA region.

The DNA bands for the Yb(hfa)₃·2H₂O and Yb(hfa)₃(Phendione) were less intense than that for the DNA control. And also increased mobility in the high molecular weight DNA region of these DNA bands with the metal complexes were seen (Fig. S10).

These apparent results can be rationalized in terms of both intercalation and degradation of DNA by the metal complexes. Among the Eu-complexes the most effective intercalator is Eu(hft)₃Phendione (Fig. S9), whose intercalation to DNA causes the inhibition of DNA intercalation of Ethidium Bromide. And thus the DNA band appeared to be almost absent. Among the Yb-complexes, Yb(hfa)₃(Phendione) is the most effective binding and degrading agent (Fig. S10). All the metal complexes also effectively degrade or cleave DNA strands which were apparent from increased mobility of the DNA bands.

Antibacterial activity assay

We have tested our synthesized compounds for their antibacterial activities against three bacterium; namely, *Escherichia coli*, *Staphylococcus aureus* and *Proteus penneri*. Antibacterial activity of the synthesized ligands and complexes were performed by disk diffusion method. We measured the annular radius of the inhibitory zones created by the antibacterial agents (tested compounds). The results for the antibiogram sensing ability of the synthesized compounds are given below in the following table (Table 2).

It is obvious from the antibacterial activity testing result that phendione and its related complexes (Eu, Yb) show huge antibacterial activities and they showed highest antibacterial activities against *P. penneri*. In contrast, our synthesized ligand, (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10] phenanthroline(L) and its Fe and Cu complexes are not antibacterial agents.

The enormous antibacterial activities of the phendione related compounds can be attributed to the fact that phendione has free quinoid functional group with redox properties which can cause the bacterial cell breaking and binding to the protein synthesizing enzyme thus inhibiting the protein synthesis for bacterial growth resulting in the death of microbes. Ligand L does not have this quinoid functional group, thus is not antibacterial active.

Conclusion

Novel phenanthroline derivative, (E)-2-styryl-1H-imidazo [4, 5-f] [1, 10] phenanthroline (Ligand, L) was synthesized from 1,10-phenanthroline-5,6-dione. Transition metal (Fe and Cu) complexes of the ligand, L and mixed ligand lanthanide (Eu and Yb) complexes of phendione and β -diketones have also been synthesized. The

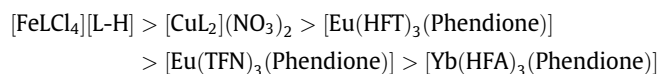
Table 1
UV–Visible and IR spectroscopic data for the synthesized compounds.

| Complex name | IR | | | | UV–Visible | | | | | |
|--|---------------------------|----------|---------------------------|----------------|----------------|-----------------------------------|----------------|---------------------------------|----------------|--|
| | ν (cm ⁻¹) | Group | ν (cm ⁻¹) | Group | λ (nm) | Types of bond & transition (nm) | λ (nm) | Types of bond & transition (nm) | λ (nm) | Types of bond & transition (nm) |
| Phendione [Eu(tfn) ₃ (PD)] | 1689 | C=O | 1566 | C=N | 324 | π - π^* for C=C | 364 | $\pi \rightarrow \pi^*$ for C=N | 479 | $n \rightarrow \pi^*$ for C=N |
| | 1692 | C=O (PD) | 1610 | C=O (tfn) | 464.5 | $^7F_0 \rightarrow ^5D_2$ | 534.5 | $^7F_1 \rightarrow ^5D_1$ | - | - |
| Eu(tfn) ₃ ·2H ₂ O [Eu(hft) ₃ (PD)] | - | - | 1612 | C=O (tfn) | 464.5 | $^7F_0 \rightarrow ^5D_2$ | 534.5 | $^7F_1 \rightarrow ^5D_1$ | - | - |
| | 1697 | C=O (PD) | 1602 | C=O (hft) | 464.5 | $^7F_0 \rightarrow ^5D_2$ | 534.5 | $^7F_1 \rightarrow ^5D_1$ | - | - |
| Eu(hft) ₃ ·2H ₂ O [Yb(hfa) ₃ (PD)] | - | - | 1612 | C=O (hft) | 464.5 | $^7F_0 \rightarrow ^5D_2$ | 534.5 | $^7F_1 \rightarrow ^5D_1$ | - | - |
| | 1693 | C=O (PD) | 1660 | C=O (hfa) | 975 | $^2F_{7/2} \rightarrow ^2F_{5/2}$ | - | - | - | - |
| Yb(hfa) ₃ ·2H ₂ O | - | - | 1651 | C=O (hfa) | 960 | | - | - | - | - |
| | | | | | 930 | | | | | |
| | | | | | 975 | $^2F_{7/2} \rightarrow ^2F_{5/2}$ | | | | |
| | | | | | 960 | | | | | |
| | | | | | 930 | | | | | |
| (E)-2-styryl-1H-imidazo[4,5-f][1,10]phenanthroline (L) | 1602 | C=C | 1564 | C=N (diiminic) | 270 | π - π^* for C=C | 288 | $\pi \rightarrow \pi^*$ for C=N | 348 | $n \rightarrow \pi^*$ for C=N |
| | 1562 | | | | | | | | | |
| | 1431 | | 1645 | C=N (imidazo) | | | | | | |
| [FeLCl ₄][L-H] | 1404 | | 1620 | | | | | | | |
| | 1575 | C=C | 1544 | C=N (diiminic) | 293 | $\pi \rightarrow \pi^*$ for C=N | 349 | $n \rightarrow \pi^*$ for C=N | d-d transition | |
| | 1501 | | | | | | | | 529 | $^2T_{2g} \rightarrow (^2A_{2g} \text{ or } ^2T_{1g})$ |
| | 1445 | | 1639 | C=N (imidazo) | | | | | 487 | $^2T_{2g} \rightarrow ^2E_g$ |
| [CuL ₂](NO ₃) ₂ | 1404 | | 1606 | | | | | | | |
| | 1575 | C=C | 1543 | C=N (diiminic) | 296 | $\pi \rightarrow \pi^*$ for C=N | 351 | $n \rightarrow \pi^*$ for C=N | 678 | MLCT |
| | 1502 | | | | | | | | 989 | Transitions for the square planar geometry |
| | 1445 | | 1641 | C=N (imidazo) | | | | | 890 | |
| | | | 1608 | | | | | | 865 | |

Table 2
Antibacterial activity of the synthesized compounds (annular radius of the inhibitory zone).

| Tested compounds | Bacterium (annular radius of the inhibitory zone in mm) | | | | | |
|--|---|------------|------------------------------|-------------|------------------------|-------------|
| | <i>E. coli</i> | Comments | <i>Staphylococcus aureus</i> | Comments | <i>Proteus penneri</i> | Comments |
| Phendione | 5.5 | Resistance | 6 | Susceptible | 7 | Susceptible |
| Eu(hft) ₃ ·2H ₂ O | 0.5 | Resistance | 0.50 | Resistance | 3 | Resistance |
| Eu(hft) ₃ Phendione | 4.25 | Resistance | 3.25 | Resistance | 7.25 | Susceptible |
| Eu(tfn) ₃ ·2H ₂ O | 0.75 | Resistance | 0.5 | Resistance | 2 | Resistance |
| Eu(tfn) ₃ Phendione | 3.25 | Resistance | 4 | Resistance | 7.25 | Susceptible |
| Yb(hfa) ₃ ·2H ₂ O | 0.5 | Resistance | 1 | Resistance | 1.5 | Resistance |
| Yb(hfa) ₃ Phendione | 4.25 | Resistance | 3.25 | Resistance | 8 | Susceptible |
| Ligand | – | – | – | – | – | – |
| [CuL ₂](NO ₃) ₂ | – | – | – | – | – | – |
| [FeLCl ₄][L-H] | – | – | – | – | – | – |

ligands (L and Phendione) as well as the complexes were characterized by UV–Visible, IR spectroscopy and PL study. The intense red emission with narrowed band (half width <10 nm) of complexes [Eu(HFT)₃(Phendione)] and [Eu(TFN)₃(Phendione)] were observed by excitation at 370 nm. DNA binding studies of the synthesized compounds showed that the metal complexes are strong DNA binding and cleaving agent. The [FeLCl₄][L-H] complex was the most effective DNA binding and cleaving agent. DNA binding studies showed the following trend.



Antimicrobial activity studies revealed that, all the lanthanide metal complexes of phendione and phendione itself showed efficient resistance to bacteria. The lanthanide metal complexes and phendione showed most antimicrobial activities to the bacteria *P. penneri*. Phendione and related metal complexes can cause the bacterial cell breaking and binding to the protein synthesizing enzyme thus inhibiting the protein synthesis for bacterial growth resulting in the death of microorganisms.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.saa.2013.09.110>.

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