Experimental and theoretical studies on new organotin(IV) complexes with oxygen donor ligand: DNA binding, molecular docking and antimicrobial activity

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Abstract. In the present paper, oxygen donor ligand having carboxylate moiety and two new tri-organotin(IV) carboxylates, (Ph3Sn)2L(1) and (n-Bu3Sn)L(2) were prepared successfully and characterized by FT-IR, NMR and UV-visible spectroscopic analysis. FT-IR results for complexes (1) and (2) with Δν values 216 and 188 cm−1 indicated bidentate binding mode of ligand leading to trigonal bipyramidal geometry. NMR spectral results of ligand and complexes were compared and complex formation was confirmed by disappearance of carboxylic acidic proton in the range 13.14-13.10 ppm. DFT studies were performed for comparative spectroscopic studies i.e., FT-IR, UV-Vis and to reveal the structural geometrical parameters of ligand and complexes which showed an outstanding collaboration between the DFT-based results and attained experimental results. The antimicrobial potential of newly synthesized ligand and complexes were evaluated and results exhibited significant potential by these compounds. The antibacterial molecular docking results revealed that complex (Ph3Sn)2L(1) has excellent binding capability with the target protein (2EX9) and the complex (n-Bu3Sn)L(2) has the least binding with protein. The antifungal docking results revealed that metal presence enhances the anti-fungal activity of the compounds and the results are in good agreement with experimental results. The DNA binding results revealed that organotin(IV) complexes interact with DNA better than ligand via an intercalative mode of interaction as indicated by hypochromism.

Keywords. DFT; Docking; Antibacterial; Antifungal; Activity.

1. Introduction

Organometallic chemistry has become significant due to its tremendous value and applications.1-4 Numerous organometallic compounds have been formulated. A lot of series of organotin(IV) compounds have been introduced to organometallic chemistry.4-7 Due to the unique physical, chemical, and biological properties of organotin complexes, tin and its compounds have gained a lot of importance in commercial uses than any other element.8-10 Compounds containing Sn-O bonds are called organotin carboxylates.11,12 Oxygen donor ligands bind to organotin compounds in different modes like monodentate, bidentate, and aniso-bidentae fashion.13 Organotin compounds display considerable biocidal activity, presumably as a result of having lipid solubility, which makes them more transportable to the sites of reaction in comparison to equivalent inorganic tin compounds.14 Organotin (IV) carboxylates are very special among all organotin(IV) compounds because of their potential biological activities.15 The organotin(IV) carboxylates are

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substantially more efficient than cisplatin. The antiproliferative action of di-, tri-, or aryltin(IV) carboxylate complexes is significantly affected by the attachment of the carboxylato ligands and aryl or alkyl substituted molecules at tin(IV). Triorganotin(IV) carboxylates have exhibited superior anti-cancer activity compared to their mono- and diorganotin(IV) counterparts which are linked to their capacity to bind to proteins. Organotin(IV) carboxylates are highly active against microorganisms, even at very small concentrations. This toxicity action depends upon the ligand-metal, the coordination number of the tin metal atom, and the geometry of the complex. The biological activity of organotin(IV) carboxylates mainly depends upon the nature of ligands and their structure. The role of organic ligand in the transportation of organotin(IV) moiety to the target area for biocidal activity has been pronounced. The structural diversity due to the presence of additional coordinating sites along with carboxylate moiety plays important role in enhanced biological activity of organotin(IV) complexes. The microbial evolution and adaptation with increasing consumption of antibiotics especially in developing countries resulted early antibiotic resistance problems. The tumor is also increasing threat which is also one of the main causes of casualties in the World. This is very alarming along with the increasing population of the World. Keeping this scenario, the research on searching for new potential compounds like organotin(IV) carboxylates has very much significance. The main significance and aim of the present work was to find out new potential antimicrobial and anti-tumor organotin(IV) complexes. So, because of the great importance and tremendous applications of organotin(IV) carboxylates, we report here the synthesis, characterization, DFT studies, molecular docking, and biological application of organotin(IV) complexes with oxygen donor ligand. The choice of ligand has been made considering the structural diversity due to the presence of additional coordinating sites along with two carboxylate moiety groups which can develop multinuclear coordination with organotin centers and play important role in increasing antimicrobial and antitumor potential of organotin(IV) complexes. The synthesized ligand and complexes have been characterized by FTIR, 1H and 13C NMR and UV-Visible spectroscopies. The synthesized complexes have been screened against various bacterial and fungal strains and it is evaluated that they are highly active even at very small concentration. Computational studies of newly synthesized compounds for investigation of their kinetic properties and determining their electronic structures are getting popular. The stability, structure of newly synthesized organic compounds and potential of non-covalent interactions are investigated by calculations of density functional theory (DFT) by connecting their magnetic and electronic properties. The antitumor potential of ligand and its complexes were also determined using UV-Visible DNA interaction studies.

2. Experimental

2.1 Chemicals and instrumentation

Triphenyltin(IV) chloride, tributyltin(IV) chloride, maleic anhydride, 4-amino-2-hydroxy-benzoic acid and sodium hydroxide were purchased from Sigma Aldrich and used without any further purification. Analytical grade solvents methanol, glacial acetic acid, acetone, chloroform, and DMSO were purchased from Merck, Lab Scan, and used as such. Gallen Kamp (UK) electrothermal melting point apparatus was used to record melting point of samples. Thermo Scientific Nicolet FTIR Spectrophotometer was used to take absorption spectra. Shimadzu 1800 UV-Visible spectrophotometer was used to take absorption spectra. 1H and 13C NMR NMR spectra of ligand and complexes were recorded on 300 MHz and 75 MHz, respectively, Bruker Advance Digital Spectrometer made in Switzerland equipped with 5 mm BBO probes at 7.05 Tesla using TMS as internal standard and DMSO as solvent. The ligand H2L and complexes tested for antimicrobial activities against four strains of bacteria (two-gram positive, S. aureus and M. luteus and two gram negative, B. septic and E. coli) and four strains of fungi (F. solani, A. fumigatus, A. Niger, A. flavus) by agar diffusion method to test their biological activities.

2.2 Synthesis

2.2a Synthesis of ligand: The stoichiometric ratio of precursors, maleic anhydride (0.25 g, 2.55 mmol), and 4-amino-2-hydroxy-benzoic acid (0.39 g, 2.55 mmol) were dissolved in glacial acetic acid...
NaOH and ligand $H_2L$ salt of ligand was prepared using molar ratio of 2:1 of Na$_2$L (Na$_2$L represents as disodium carboxylate ligand) with molar ratio of 1:2 with sodium salt of ligand $Na_2L$ (0.30 g, 1.0 mmol) and triphenyltin (IV) chloride (0.77 g, 2.0 mmol) into 100 mL of methanol as solvent. Then, methanolic solution of sodium hydroxide was poured slowly into the methanolic solution of ligand and the resultant solution was stirred constantly at room temperature for 5 hours. When the clear solution was formed, it was rotary evaporated to get pure solid mass product (30 mL) separately. Both solutions were mixed up and stirred for 3-4 h at room temperature until the formation of yellow-colored precipitates. Then, these precipitates were filtered and dried to get pure mass product. The structure and numbering for $^1$H NMR interpretation of $H_2L$ (H-representing two acidic protons from two carboxylic acid groups) are given in Scheme 1.

Physical data: M.P. 212 °C, Yield: 76%. CHN Analysis: Cald for C$_{11}$H$_9$NO$_6$: C 52.6, H 3.59, N 5.56. FT-IR (cm$^{-1}$): 1666 vOCO$_{asym}$, 1422 vOCO$_{sym}$, ($\Delta v$=244 cm$^{-1}$), 3500 v-N-H, 3399 vO-H. Proton-NMR (DMSO, ppm): 13.14 (s,1H, O-H), 6.46 (d, 1H, H9), 6.30 (d, 1H, H10), 7.07 (s, 1H, H4Ar), 7.65 (s, 1H, H6Ar), 7.88 (d, 1H, H7Ar), 11.40 (s, 1H, N-H), 11.35 (s, 1H, N-H). 13C NMR (DMSO, ppm): 178.29 (C1), 115.77 (C2), 119.57 (C3), 116.06 (C4), 129.67 (C5), 129.78 (C6), 131.13 (C7), 161.98 (C8), 142.86 (C9), 131.18 (C10), 165.30 (C11)

2.2b Synthesis of sodium salt of ligand: Sodium salt of ligand was prepared using molar ratio of 2:1 of NaOH and ligand $H_2L$ and dissolving them into methanol (30 mL) separately. Then, methanolic solution of sodium hydroxide was poured slowly into the methanolic solution of ligand and the resultant solution was stirred constantly at room temperature for 5 hours. When the clear solution was formed, it was rotary evaporated to get pure solid mass product through rotary evaporator to remove solvent and to get a pure solid product. Chloroform was used to recrystallize the product.

Physical data: M.P. 90-93 °C, Yield: 72%. CHN Ana for C$_{47}$H$_{57}$NO$_6$Sn$_2$: Cald, C 59.47, H 3.93, N 1.48. Found: C 59.61, H 3.94, N 1.49. FT-IR (cm$^{-1}$): 1645vOCO$_{asym}$, 1429vOCO$_{sym}$, ($\Delta v$=216), 3426 v-N-H, 3349vO-H, 460 vSn-O, 510 vSn-C. Proton-NMR (DMSO, ppm): 6.30 (d, 1H, H9), 6.46 (d, 1H, H10), 7.08 (d, 1H, H4 Ar), 7.36 (s, 1H, H6Ar), 7.72 (d, 1H, H7Ar), 7.79-7.97 (m, Ph-30H), 10.54 (s, 1H, O-H), 11.35 (s, 1H, N-H), 13C-NMR (CDCl$_3$, 75 MHz): 173.89 (C1), 115.63 (C2), 115.92 (C3), 116.06 (C4), 129.95 (C5), 130.49 (C6), 131.13 (C7), 158.77 (C8), 133.97 (C9), 130.61 (C10), 162.08 (C11), 123.59-123.91 (Ph-C).

2.2d Synthesis of complex (2): Complex (2) was synthesized by using same method$^{23}$ as complex (1) with molar ratio of 1:2 with sodium salt of ligand $Na_2L$ (0.30 g, 1.0 mmol) and tributyltin (IV) chloride (0.65 g, 2.0 mmol) in 100 mL of methanol as solvent.

Physical data: M.P. = 110 °C, Yield: 78%. CHN Ana for C$_{35}$H$_{61}$NO$_6$Sn$_2$: Cald: C 50.69, H 7.41, N 1.69. Found: C 50.71, H 7.42, N 1.68. FT-IR (cm$^{-1}$): 1610 vOCO$_{asym}$, 1422 vOCO$_{sym}$, ($\Delta v$=188), 3316 v-N-H, 3250 vO-H, 420 vSn-O, 593 vSn-C. Proton-NMR (DMSO, ppm): 6.30 (d, 1H, H10), 6.51 (d, 1H, H9), 7.05 (d, 1H, H4 Ar), 7.65 (s, 1H, H6Ar), 7.88 (d, 1H, H7Ar), 10.13 (s, 1H, O-H), 11.40 (s, 1H, N-H), 1.64-0.78 (Bu-H), 13C NM R (CDCl$_3$, ppm): 178.29 (C1), 115.39 (C2), 125.33 (C3), 127.77 (C4), 131.78 (C5), 132.08 (C6), 134.47 (C7), 160.94 (C8), 139.26 (C9), 137.88 (C10), 164.25 (C11), 13.62-27 (Bu-C)

2.3 Antimicrobial study

2.3a Antibacterial study: The synthesized oxygen donor ligand $H_2L$ along with organotin(IV) complexes (1) and (2) were tested against four different strains of bacteria: two Gram-positive bacteria (S. aureus & M. luteus) and two Gram-negative bacteria (B. septic & E. coli). Agar well diffusion method was used to carry out antibacterial activity.$^{3}$ At the temperature of 45 °C, 0.75 mL broth culture was added to that agar medium. Then the mixture containing a culture of colony-forming units of ca.10$^6$/mL of test strains was stirred well. Then the mixture was transferred to a petri dish. After that medium was set to be hardened than 8mm wells were put in by the help of sterile metallic borer. Then DMSO solution of newly synthesized tin

Scheme 1. Numbering for $^1$H NMR interpretation of $H_2L$. 

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complexes at the quantity of 1 mg/mL was added to the prepared wells. Ciprofloxacin was used as a standard drug. For negative control DMSO was used. Triplicates plates of bacterial strains were incubated at 37 °C for 24 h. The antibacterial activity was determined by the diameter of zones of inhibition in millimeters with reference to positive control.

2.3b Antifungal study: Antifungal investigation of oxygen donor ligand $\text{H}_2\text{L}$ along with organotin(IV) complexes (1) and (2) was carried out by using the agar tube dilution method. Four different fungal strains (F. solani, A. fumigatus, A. Niger, A. flavus) were used in this method. Terbinafine was used as a reference antifungal drug. Solutions of all the pure compounds were prepared in DMSO. Medium was applied to sabouraud dextrose sugar (SDA). Into screw-caped test tubes having 4 mL of these SDA compounds were prepared in DMSO. Medium was reference antifungal drug. Solutions of all the pure dock 4.2 24,25 software using the Lamarckian genetic algorithm to understand the types of interaction and binding orientation of the synthesized compounds responsible for antibacterial activity and anti-fungal activity. X-ray crystal structure of penicillin-binding protein (PBP) 4 was obtained from PDB (PDB ID 2EX9) with penicillin V as a native ligand and *Candida albicans* (3N9K) were obtained from PDB. All the needless parts including solvent molecules, and co-crystallized ligands were removed and the Gasteiger charges for all the atoms were assigned using UCSF Chimera. The grid box was set using a grid map of $46 \times 46 \times 44$ xyz dimensions with 0.375A spacing and center of the grid was centered on the center of the ligand i-e 83.635, -4.260, 40.542 along x, y, and z axis respectively for 2EX9. The selected grid centers for 3N9K were -3.192, -7.731, and 10.932 along x, y, and z axis respectively with a grid map of $60 \times 6 \times 60$ xyz. Throughout the whole docking procedure, the selected receptor was kept rigid, while ligand and metal complexes were flexible. The docking process was performed by selecting following parameters: GA runs was 25, maximum number of generations was 27000 for a single population of 150 individuals and rate of gene mutation was 0.02. The three-dimensional structure of ligand and synthesized metal complexes were drawn using Marvin Sketch (http://www.chemaxon.com/products/marvin/marvinsketch/) and optimized by Avogadro version 1.2. The parameter file of Auto dock was changed to incorporate metal needed parameters http://autodock.scripps.edu/resources/parameters/AD4.1_bound.dat/view. To estimate the validation of the docking protocol the co-crystallized ligand was removed from the pocket and re-docked into the active site of 2EX9. A good agreement was observed between docked and crystal structure as it further confirmed the interaction region of the PBP. Docking results was evaluated by PyMOL and BIOVIA Discovery studio.

2.5 DNA interaction studies

DNA interaction studies of ligand $\text{H}_2\text{L}$, complexes (1) and (2) using Salmon Sperm DNA (SS-DNA) was performed using a UV-Visible spectrophotometer (Shimadzu 1800). For this purpose, 0.2 g DNA powder was dissolved in double deionized (DD) water and placed at 4.0 °C for 48 h. DNA Solution was made in 20 mM Tris-hydrochloride and a ratio of absorbance at 260 and 280 nm was determined as 1.86 which showed that DNA solution is protein free. The concentration of DNA solution was determined as $7.45 \times 10^{-5}$ M using a molar absorption coefficient of 6600 M$^{-1}$ cm$^{-1}$ at 260 nm. The working solution of 4, 8, and 12 μM was prepared from the above stock DNA solution. The ligand and complexes/compounds were dissolved in 10% DMSO solution. First of all, UV absorbance of the compound (ligand/complex) was determined without DNA and then with DNA by varying its concentration while keeping the concentration of the
compound constant. To eliminate the absorbance of DNA itself, an equivalent amount of DNA was added to the reference solution. Incubation of compound-DNA solution was made for 30 min before measurement at room temperature. Binding mode of interaction of compound with DNA was also determined by keeping DNA concentration constant and varying the concentration of compound. The absorption spectra of the interaction of SS-DNA with the prepared compounds have been recorded for a constant SS-DNA concentration (7.45 \times 10^{-4}) and varying compound concentrations (5 \times 10^{-5}, 4 \times 10^{-5}, 3 \times 10^{-5}, 2 \times 10^{-5} and 1 \times 10^{-5} M).

The interaction of the compounds with SS-DNA was also carried out via viscosity measurement in order to know the binding mode of interaction. An Ubbelohde viscometer with a digital stopwatch was used for the viscosity measurement at room temperature. The relative viscosity \[ [(\eta/\eta_0)^{1/3}] \] was plotted against the \( r ([\text{Compound}]/[\text{DNA}]) \) where \( \eta \) and \( \eta_0 \) represent the DNA viscosity measured in the presence of the compound and absence of the compound, respectively. The viscosity was measured using the equation: \( \eta = t - t_0 \).

### 3. Results and Discussion

#### 3.1 Synthesis of organotin (IV) carboxylates

The complexes were prepared by reacting a methanolic solution of organotin (IV) trichloride with \( \text{Na}_2\text{L} \) as given in the synthesis section. The synthesized complexes were in the form of solids. These compounds were stable in the air and show sharp melting points. Different organic solvents like acetone, methanol, ethanol, DMSO, and chloroform were used for the solubility of organotin (IV) carboxylates. Different analytical techniques such as FTIR, NMR, and UV-Visible spectroscopy were used for the characterization of these complexes. Antibacterial and antifungal studies have also been done on these complexes.

#### 3.2 FT-IR analysis

The IR spectra of ligand \( \text{H}_2\text{L} \) and tri-organotin (IV) complexes (1) and (2) were recorded in the range of 4000-400 cm\(^{-1}\) using KBr discs. The values of IR data of ligand acid \( \text{H}_2\text{L} \) were compared with their corresponding organotin(IV) complexes. It was done for the confirmation of complexation and the identification of binding mode of acid to tin (IV). Following the literature, complexes showed lesser IR values which are the confirmation of the formation of organotin (IV) complexes. The decrease in the frequencies of \( \text{asym}(\text{COO})^- \) and increase in the frequencies of \( \text{sym}(\text{COO})^- \) values also confirms the formation of metal-ligand bonds. Moreover, the appearance of new peaks in the IR spectra of complexes in the range of 495-420 cm\(^{-1}\) is also a confirmation of the Sn-O bond, because this peak was absent in the IR spectra of the parent ligand acid. Band in the range of 590-520 cm\(^{-1}\) shows the presence of Sn-C bonds. It is very important to note the binding mode of ligand (COO)\(^-\) moiety with the tin metal atom. The coordination mode depends upon the difference \( \Delta \nu \) between symmetric and asymmetric values of (COO)\(^-\) and their respective position of bands. According to literature,\(^{31,32}\) if the value of \( \Delta \nu \) (COO)\(^-\) is greater than 350 cm\(^{-1}\), then it shows monodentate. If the value of \( \Delta \nu \) (COO)\(^-\) is less than 250 cm\(^{-1}\) then such compounds contain a bidentate binding mode of carboxylate to the tin metal atom. Moreover, if the value of \( \Delta \nu \) (COO)\(^-\) is between the range of 350-200 cm\(^{-1}\) then such compounds have an intermediate state called anisobidentate. In the present study, complex (1) shows anisobidentate binding mode as its \( \Delta \nu \) values are 216 cm\(^{-1}\) while complex (2) shows bidentate coordination mode (\( \Delta \nu =188 \) cm\(^{-1}\)) and trigonal bipyramidal geometry of both complexes has been proposed in solid state.

#### 3.3 NMR analysis

DMSO was used as a solvent for the measurement of \(^1\text{H}-\text{NMR} \) spectra of newly synthesized ligand \( \text{H}_2\text{L} \) and their novel complexes (1) and (2). Signals were assigned on the basis of signal patterns involving multiplicity and intensity in coordination with \( ^7J \) values to account for \((^{1}\text{H}, ^{119}\text{Sn})\) coupling.\(^{33,34}\) The carboxylic acid proton seemed at 13.14-13.10 ppm. A singlet was observed for N-H proton at 11.40 ppm. The complex formation was confirmed by the disappearance of carboxylic acid proton singlet in complexes. For complexes (1) and (2), a complex pattern of \(^1\text{H}-\text{NMR} \) peaks was observed. The multiplets of phenyl protons of triphenyltin(IV) (IV) appeared at 7.97 ppm. Moreover, the butyl group proton appeared in the range of 0.78-1.64 ppm.

The synthesis of ligand \( \text{H}_2\text{L} \) and complexes (1) and (2) was further confirmed by \(^{13}\text{C} \) NMR analysis in which a change in carboxylate group carbon was observed from 171.94 ppm \( \text{H}_2\text{L} \) to 173.89 (complex (1)) and 178. 29 ppm complex (2). The co-ordination behavior of tin (IV) atom in complexes in solution was
found out by calculating $^1J^{(119}\text{Sn}-^{13}\text{C})}$ coupling values using Holecek’s equation and C-Sn-C angle using Lockhart’s equation. The $^1J^{(119}\text{Sn}-^{13}\text{C})}$ value of 648-640 Hz and C-Sn-C angle 146-135° of complexes indicated five coordinated behavior of the Sn atom hence, its proposed geometry is trigonal bipyramidal in solution state. The results are comparable to literature reports.\textsuperscript{35,36}

In conclusion, the FTIR studies showed that the mode of coordination of ligand $\text{H}_2\text{L}$ with the organotin center showed bidentate binding mode in complex (1) and (2) leading to five coordinated trigonal bipyramidal geometry of both complexes. While the $^1J^{(119}\text{Sn}-^{13}\text{C})}$ values of NMR studies ($^{13}\text{C}$) showed five coordinated behavior around the tin center. Thus the proposed structures of complex (1) and (2) are represented below in Figure 1.

### 3.4 UV-visible spectroscopy

Ultraviolet-visible studies were performed for determination of electronic transitions of newly synthesized ligand $\text{H}_2\text{L}$ and organotin(IV) complexes (1) and (2). The choice of a good solvent is very important for spectroscopic investigations otherwise solvents may interfere here. For this purpose, DMSO was used as a solvent because it does not interfere with the important bands of spectroscopy. 0.001 M concentration of synthesized ligand $\text{H}_2\text{L}$ and organotin(IV) complexes was used to make solutions. UV-Visible light of wavelength of 200-800 nm was used for this purpose. In organotin(IV) complexes, tin shows no d-d transition because it has $d^{10}$ system so no electron is available for tarnation. Tin shows only n-$\pi^*$ transition. Referring to literature\textsuperscript{35,36} if the wavelength of 200-400 nm is observed then these transitions can be assigned for $\pi - \pi^*$ and n-$\pi^*$ transitions. UV-Visible spectra and data of ligand $\text{H}_2\text{L}$ and organotin(IV) complexes are given in Table 1.

### 3.5 Computational studies

Gaussian 09 program package [U1] was utilized to perform the overall quantum chemical calculations with the help of DFT. Geometrical optimization of newly synthesized ligand $\text{H}_2\text{L}$, complex (1) and (2) and was done without symmetry restrictions by applying CAM- B31YP/6-31+ G(d, p) level of DFT. The fully optimized structure of $\text{H}_2\text{L}$, organotin(IV) complexes (1) and (2) are shown in Figure 2. The nonlinear optical analysis, frontier molecular orbital, and natural bond orbital analysis were conducted on the aforementioned level of DFT. The UV-Vis analysis was performed utilizing time-dependent density functional theory (TDDFT) calculations at CAM-B31YP/6-31+ G (d, p) level of theory for estimation of photophysical characteristics of ligand $\text{H}_2\text{L}$, complexes (1) and (2). The GaussSum, Avogadro [U3], and Chemcraft [U4] programs were employed for interpreting output files.

### 3.5a NBO analysis (natural bond orbital analysis)

Orbital interaction, hybridization and atomic charges are described in NBO analysis. At the same time, it helps to examine the transfer of charge density from donor to acceptor orbitals.\textsuperscript{26} Enormous interaction between donor and acceptor orbital results in greater stabilization energy. CAM- B31YP/6-31+ G (d, p) level of DFT was used to carry out the NBO analysis for oxygen donor ligand $\text{H}_2\text{L}$, complex (1) and complex (2). The results are mentioned in Tables S1 (Supplementary Information) (a-c). The stabilization energy formula according to second order perturbation approach is represented by equation 3.

![Figure 1. Structure of triphenyltin complex 1 (a) and tributyltin complex 2 (b).](image-url)
\[ E^{(2)} = \frac{q_i \left| F_{ij} \right|^2}{\varepsilon_j - \varepsilon_i} \]  \hfill (3)

where \( E^{(2)} \) is the stabilization energy, \( q_i \) is the occupancy of donor, \( \varepsilon_j \) and \( \varepsilon_i \) are off diagonal \( F(i,j) \) = diagonal and NBO Fock matrix elements, respectively.

Commonly, five types of interactions were present in the investigated compounds such as \( \sigma \rightarrow \sigma^*, \pi \rightarrow \pi^*, \pi \rightarrow \pi^*, \text{ LP } \rightarrow \sigma^* \), \( \text{ LP } \rightarrow \pi^* \). Considering Ligand \( H_2L \), showed the most important \( \pi \rightarrow \pi^* \) interaction as \( \pi(C4-C5) \rightarrow \pi^*(C1-C6) \) having highest stabilization energy 25.83 kcal/mol. Whereas, the interaction such as \( \pi(C19-C21) \rightarrow \pi^*(C18-O24) \) yield lowest stabilization energy of 0.53 kcal/mol. Similarly, some other prominent interactions were also observed as \( \pi(C19-C21) \rightarrow \pi^*(C23-O25) \) and \( \pi(C2-C3) \rightarrow \pi^*(C10-O11) \) with stabilization energies of 22.70 and 23.90 kcal/mol, respectively. For complex (1), the interaction \( \pi(C4-C5) \rightarrow \pi^*(C1-C6) \) with the highest stabilization energy of 26.60 kcal/mol, and the interaction \( \pi(C22-O24) \rightarrow \pi^*(C52-C55) \) with lowest stabilization energy in the range of 0.05 kcal/mol were observed. Additionally, some other important transitions were also observed as \( \pi(C5-C6) \rightarrow \pi^*(C17-O18) \) and \( \pi(C3-C4) \rightarrow \pi^*(C5-C6) \) with stabilization energies 22.64 and 23.91 kcal/mol, respectively. For complex (2), the interaction such as \( \pi(C5-C6) \rightarrow \pi^*(C1-C2) \) had the highest stabilization energy of 24.80 kcal/mol, and the interaction like \( \pi(C12-O22) \rightarrow \pi^*(C13-C15) \) yielding the lowest stabilization energy in the range of 0.67 kcal/mol. Other important transitions were also observed such as \( \sigma \rightarrow \sigma^*(C5-C6) \rightarrow \pi^*(C17-O18) \) and \( \pi(C3-C4) \rightarrow \pi^*(C5-C6) \) affording stabilization energies 22.64 and 23.91 kcal/mol, respectively. Similarly, ligand \( H_2L \sigma \rightarrow \sigma^* \) interactions were found as \( \sigma(O14-H15) \rightarrow \sigma^*(C2-C3) \) with the highest stabilization energy of 5.49 kcal/mol. While the interaction \( \sigma(N16-C18) \rightarrow \sigma^*(N16-H17) \) showed the lowest stabilization energy of 0.51 kcal/mol. In addition to that, some other transitions were also present as \( \sigma(C19-H20) \rightarrow \sigma^*(C21-H22) \) and \( \sigma(O12-H22) \rightarrow \sigma^*(C3-C10) \) showing stabilization energies within the range of 5.05 and 5.24 kcal/mol, respectively. At the same time complex (1) showed \( \sigma \rightarrow \sigma^* \) interaction with stabilization energy 7.08 kcal/mol showing transition \( \sigma(Sn26-C39) \rightarrow \sigma^*(Sn26-C50) \) and the lowest stabilization energy 0.05 kcal/mol exhibited by the interaction like \( \sigma(Sn26-C50) \rightarrow \sigma^*(C22-O25) \). Other noticeable transitions exhibited by this compound were \( \sigma(Sn27-C50) \rightarrow \sigma^*(Sn27-C72) \) and \( \sigma(Sn26-C50) \rightarrow \sigma^*(Sn26-C39) \) with stabilization energies 6.84 and 7.05, respectively. \( \text{ LP } \rightarrow \sigma^* \) transition for ligand was found as \( \text{ LP2(O25)} \rightarrow \sigma^*(C23-O26) \) exhibiting the highest stabilization energy of 34.21 kcal/mol. While several significant transitions were also present as \( \text{ LP1(O24)} \rightarrow \sigma^*(N16-H17) \) having the lowest stabilization energy of 0.58 kcal/mol and the other interactions are \( \text{ LP2(O24)} \rightarrow \sigma^*(N16-C18) \) and \( \text{ LP2(O11)} \rightarrow \sigma^*(C10-O12) \) with stabilization energy in the range of 25.03 and 32.30 kcal/mol correspondingly. At the same time complex (2) showed the highest stabilization energy for \( \sigma \rightarrow \sigma^* \) interaction within the range of 8.52 kcal/mol having transition \( \sigma \)

Table 1. UV-Visible results of Ligand \( H_2L \) and complexes 1 and 2.

<table>
<thead>
<tr>
<th>Ligand/complex</th>
<th>( \lambda_{max} )(nm)</th>
<th>Possible transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2L )</td>
<td>280</td>
<td>( n \rightarrow \pi^* )</td>
</tr>
<tr>
<td>(Ph(_3)Sn)(_2)L(1)</td>
<td>240, 260</td>
<td>( \pi \rightarrow \pi^* ), ( n \rightarrow \pi^* )</td>
</tr>
<tr>
<td>(Bu(_3)Sn)(_2)L(2)</td>
<td>250, 270</td>
<td>( \pi \rightarrow \pi^* ), ( n \rightarrow \pi^* )</td>
</tr>
</tbody>
</table>

![Figure 2. Fully optimized structure of \( H_2L \) (a), complex 1 (b) and complex 2 (c).](image-url)
Non-Linear Optical Properties (NLO)

Inorganic compounds are potential candidates for designing Non-linear optical (NLO) material used for making optical memory devices, optical switches, and signal processing and communication technology. Compounds having pi-electron conjugated systems are considered strong candidates for non-linear optical (NLO) and electro-optic applications. Polarizability and hyperpolarizability had major contributions towards the strength of optical responses (linear and non-linear) and electronic properties. Therefore, polarizability and hyperpolarizability were evaluated to determine NLO properties of ligand $H_2L$, complex (1), and complex (2) separately. To evaluate the variation in the $\pi$ conjugated polarizability values of the ligand $H_2L$, complex (1) and complex (2) are mentioned in Tables (2, 3).

The ligand linear polarizability along the three-axis $x$, $y$, and $z$ were obtained as 207.277, 165.438, and 129.243 $\alpha.u.$, respectively, which gives $\alpha_{total}$ value of 167.319 $\alpha.u.$ Complex (1) shows the linear polarizability along the three-axis $x$, $y$, and $z$ as 686.081, 520.525, and 543.154, respectively, and results in the total value of 583.253 $\alpha.u.$ Complex (2) shows the linear polarizability along the $x$, $y$, and $z$ axis was calculated as 539.272, 492.191, and 418.06 $\alpha.u.$ respectively, which results in $\alpha_{total}$ value of 483.174 $\alpha.u.$ The second-order polarizability ($\beta_{total}$) values for ligand $H_2L$, complex (1), and complex (2) were calculated as 656.80, 1285.33, and 1195.69 $\alpha.u.$ respectively. The second order polarizability participating tensors are $\beta_{xxx}$, $\beta_{xxy}$, $\beta_{xyy}$, $\beta_{yyz}$, $\beta_{yzz}$, and $\beta_{zzz}$. A total sum of all these tensors for ligand $H_2L$, complex (1), and complex (2) were mentioned in the table. The standard molecule in this technology is frequently applied urea with $\beta_{total}$ 43. The ($\beta_{total}$) values of ligand $H_2L$, complex (1), and complex (2) are much greater than standard compound urea. The total dipole moment of ligand $H_2L$, complex (1), and complex (2) was calculated as 2.2453, 0.9731, and 2.0635 correspondingly. The dipole moment of ligand $H_3L$ is the highest of all of these three compounds at 2.2453 and complex (1) has the least at 0.9731.

3.5b Frontier molecular orbital (FMO): In chemical quantum mechanics, energy gaps and frontier molecular orbitals (FMOs) consisting of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) are considered effective parameters. During molecular interactions, FMOs play a vital role. Stability and chemical reactivity are determined by FMOs energy

(Sn25- C40) $\rightarrow$ $\pi^*$(Sn25-C27) and the lowest stabilization energy was 0.08 kcal/mol exhibited by the interaction $\sigma$ (Sn25- C40) $\rightarrow$ $\sigma^*$(C6-C17). Other noticeable transitions exhibited by complex (2) were seen as $\sigma$ (Sn25- C27) $\rightarrow$ $\sigma^*$(Sn25-C40) and $\sigma$ (Sn25-C27) $\rightarrow$ $\sigma^*$(Sn25-C53) with stabilization energies 7.67 and 7.80 kcal/mol, respectively. LP$\rightarrow$ $\sigma^*$ transitions for complex (1) were present as LP2(O23) $\rightarrow$ $\sigma^*$(N15-C17) exhibiting the highest stabilization energy of 24.95 kcal/mol and the transition with the lowest stabilization energy was LP1(O25) $\rightarrow$ $\sigma^*$(Sn26-C50) having stabilization energy 0.05 kcal/mol. Other significant transitions are LP2(O11) $\rightarrow$ $\sigma^*$(C10-C12) and LP2(O23) $\rightarrow$ $\sigma^*$(C17-C18) stabilization energies within the range of 17.39 and 18.86 kcal/mol. The highest stabilization energy of LP$\rightarrow$ $\pi^*$ transition for ligand was 47.39 kcal/mol exhibited by the transition LP2(O12) $\rightarrow$ $\pi^*$(C10-O11) and the lowest stabilization energy level was 22.38 kcal/mol given by the interaction LP1(N16) $\rightarrow$ $\pi^*$(C1-C6). Some other considerable transitions are LP1(N16) $\rightarrow$ $\pi^*$(C1-C2), LP2(O14) $\rightarrow$ $\pi^*$(C2-C3), and LP2(O26) $\rightarrow$ $\pi^*$(C23-C25) consisting of stabilization energies of 39.62, 31.96 and 45.32 kcal/mol. LP$\rightarrow$ $\sigma^*$ transitions for complex (2) was present as LP2(O20) $\rightarrow$ $\sigma^*$(N10-C12) exhibiting the highest stabilization energy of 24.53 kcal/mol and the transition with the lowest stabilization energy was LP1(O22) $\rightarrow$ $\sigma^*$(Sn25-C40) having stabilization energy 0.05 kcal/mol. Other significant transitions are LP2(O18) $\rightarrow$ $\sigma^*$(C17-C22) and LP2(O19) $\rightarrow$ $\sigma^*$(C16-O21) stabilization energies within the range of 22.37 and 24.47 kcal/mol. At the same time, the highest stabilization energy for LP$\rightarrow$ $\pi^*$ transition for complex (1) was LP3(O12) $\rightarrow$ $\pi^*$(C10-O11), and this transition had the maximum value of stabilization energy 69.46 kcal/mol. The lowest stabilization energy value was 0.06 kcal/mol and the transition was LP1(O25) $\rightarrow$ $\pi^*$(C39-O41). Some other transitions were LP1(N15) $\rightarrow$ $\pi^*$(C17-C23) and LP3(O25) $\rightarrow$ $\pi^*$(C22-O24) with stabilization energy values of 40.68 and 66.79 kcal/mol respectively. At the same time, the highest stabilization energy for LP$\rightarrow$ $\pi^*$ transition for complex (2) was LP1(O21) $\rightarrow$ $\pi^*$(C16-19), and this transition had the maximum value of stabilization energy 55.12 kcal/mol. The lowest stabilization energy value was 1.57 kcal/mol and the transition was LP2(O22) $\rightarrow$ $\pi^*$(C17-O18). Some other transitions were LP1(N10) $\rightarrow$ $\pi^*$(C3-C4), LP2(O23) $\rightarrow$ $\pi^*$(C5-C6), LP2(O26) $\rightarrow$ $\pi^*$(C23-C25) and LP1(N10) $\rightarrow$ $\pi^*$(C12-O20) with stabilization energy values 25.74, 32.07 and 40.69 kcal/mol, respectively.
By DFT studies frontier molecular orbitals were determined for ligand $H_2L$, complex (1), and complex (2) as mentioned in Table 4 and Figure 3.

Global reactivity parameters: The HOMO-LUMO energies and energy gaps were used to demonstrate the reactivity and stability of ligands, complex (1) and complex (2). The ionization potential ($I$) and electron affinity ($A$) are calculated by the following equations 4 and 5, respectively.

$$I = -E_{HOMO}$$  \hspace{1cm} (4)

$$A = -E_{LUMO}$$  \hspace{1cm} (5)

In the above equation, $I =$ Ionization potential; $A =$ electron affinity

The electrophilicity calculations were performed to establish the charge transfer process which describes the energy variations by equation 8.

$$\omega = \frac{\mu^2}{2\eta}$$  \hspace{1cm} (8)

By DFT studies frontier molecular orbitals were determined for ligand $H_2L$, complex (1), and complex (2) as mentioned in Table 4 and Figure 3.

<table>
<thead>
<tr>
<th>Linear polarizability</th>
<th>Ligand $H_2L$</th>
<th>Complex (1)</th>
<th>Complex (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{xx}$</td>
<td>207.277</td>
<td>686.081</td>
<td>539.272</td>
</tr>
<tr>
<td>$\alpha_{yy}$</td>
<td>165.438</td>
<td>520.525</td>
<td>492.191</td>
</tr>
<tr>
<td>$\alpha_{zz}$</td>
<td>129.243</td>
<td>543.154</td>
<td>418.06</td>
</tr>
<tr>
<td>$\alpha_{total(a.u.)}$</td>
<td>167.3193333</td>
<td>583.2533333</td>
<td>483.1743333</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dipole moment</th>
<th>Ligand $H_2L$</th>
<th>Complex (1)</th>
<th>Complex (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_x$</td>
<td>0.8738</td>
<td>0.2443</td>
<td>-0.4923</td>
</tr>
<tr>
<td>$\mu_y$</td>
<td>-1.7883</td>
<td>-0.0026</td>
<td>-1.9756</td>
</tr>
<tr>
<td>$\mu_z$</td>
<td>1.0391</td>
<td>-0.9419</td>
<td>0.3359</td>
</tr>
<tr>
<td>$\mu_{total}$</td>
<td>2.2453</td>
<td>0.9731</td>
<td>2.0635</td>
</tr>
</tbody>
</table>

Table 2. Linear polarizability with major contributing tensor (a.u.) and dipole moments for Ligand $H_2L$, complex (1) and complex (2).

Table 3. Computed first hyper-polarizabilities ($\beta_{tot}$) and major contributing tensor (a.u) for Ligand ($H_2L$), complexes (1) and (2).

<table>
<thead>
<tr>
<th>Hyper polarizability</th>
<th>Ligand $H_2L$</th>
<th>Complex (1)</th>
<th>Complex (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{xxx}$</td>
<td>-206.606</td>
<td>361.12</td>
<td>-312.24</td>
</tr>
<tr>
<td>$\beta_{xxy}$</td>
<td>496.538</td>
<td>-879.51</td>
<td>666.012</td>
</tr>
<tr>
<td>$\beta_{xyy}$</td>
<td>-144.951</td>
<td>386.844</td>
<td>-265.13</td>
</tr>
<tr>
<td>$\beta_{yyy}$</td>
<td>139.307</td>
<td>-201.132</td>
<td>216.524</td>
</tr>
<tr>
<td>$\beta_{xxz}$</td>
<td>146.356</td>
<td>184.391</td>
<td>173.571</td>
</tr>
<tr>
<td>$\beta_{xyz}$</td>
<td>-32.864</td>
<td>-17.987</td>
<td>167.096</td>
</tr>
<tr>
<td>$\beta_{yyz}$</td>
<td>81.822</td>
<td>1.885</td>
<td>-108.855</td>
</tr>
<tr>
<td>$\beta_{yzz}$</td>
<td>-52.781</td>
<td>52.211</td>
<td>20.358</td>
</tr>
<tr>
<td>$\beta_{zzz}$</td>
<td>23.16</td>
<td>12.856</td>
<td>38.247</td>
</tr>
<tr>
<td>$\beta_{total(a.u.)}$</td>
<td>656.80</td>
<td>1285.33</td>
<td>1195.69</td>
</tr>
</tbody>
</table>

Table 4. Computed Energies Title for Ligand ($H_2L$), complex (1) and complex (2).
The Global softness could be calculated by equation 7.

\[
\sigma = \frac{1}{2\eta} \tag{7}
\]

The results obtained from all these equations for ligand \( \text{H}_2\text{L} \), complex (1), and complex (2) are represented in Table 5.

Generally, electron accepting and donating properties were elaborated on electron affinity and ionization potential. The compounds mentioned in the table showed much higher values of ionization potential as compared to electron affinity values. The reactivity, as well as stability of a chemical system, were associated with chemical potential value. The reactivity has an inverse relationship with chemical potential whereas, it has a direct relationship with stability. The chemical potential order was determined as; ligand \( \mu = -4.854 \text{ eV} \); complex (2) \( \mu = 7.5135 \text{ eV} \); complex (1) \( \mu = 7.5375 \text{ eV} \). In the context of these findings, it can be elaborated that complex (1) is more stable and less reactive as compared to complex (2) and ligand \( \text{H}_2\text{L} \).

3.5d Natural population analysis (NPA): NPA analysis is very important for quantum mechanical calculations. It is the best method to obtain electronic distribution and atomic charges within the molecules. The natural population analysis for Oxygen donor ligand \( \text{H}_2\text{L} \), complex (1) and complex (2) was deliberated by using CAM- B31YP/6-31+ G (d, p) level of DFT. NPA of oxygen donor ligand \( \text{H}_2\text{L} \), complex (1), and complex (2) are shown in Figure S1 (SI). In this analysis oxygen donor ligand \( \text{H}_2\text{L} \) shows some carbons like C2, C6, C10, C18, and C23 which are positively charged while all other carbons in this ligand are negatively charged. Similarly, all oxygen atoms O11-O26 in this ligand are negatively charged. All hydrogen atoms are positively charged. The highest positive charge peak in oxygen donor ligand is shown by carbon element C10 with a natural charge of 0.8003 and the lowest negative charge peak is shown by carbon element C4 with a natural charge -0.15819.

In the natural population analysis of complex (1), some carbons like C2, C6, C10, C17, and C22 are positively charged while all other carbons in this complex are negatively charged. Similarly, N15 and all oxygen atoms O11-O25 in this complex are negatively charged. All hydrogen atoms H7-H93 are positively charged. The highest positive charge peaks in complex (1) are shown by Tin elements Sn26 and Sn27 with natural charges of 2.16486 and 2.1651 respectively and the lowest negative charge peak is shown by carbon element C4 with a natural charge of -0.15345.

In the NPA analysis of complex (2), some carbons like C3, C5, C12, C16, and C17 which are positively charged while all other carbons in this complex are negatively charged. Similarly, N10 and all oxygen atoms O11-O25 in this complex are negatively charged. All hydrogen atoms H7-H93 are positively charged. The highest positive charge peaks in complex (2) are shown by Tin elements Sn26 and Sn27 with natural charges of 2.16486 and 2.1651 respectively and the lowest negative charge peak is shown by carbon element C4 with a natural charge of -0.15345.

In the NPA analysis complex (2) shows some carbons like C3, C5, C12, C16, and C17 which are positively charged while all other carbons in this complex are negatively charged. Similarly, N10 and all oxygen atoms O11-O25 in this complex are negatively charged. All hydrogen atoms H7-H93 are positively charged. The highest positive charge peaks in complex (2) are shown by Tin elements Sn26 and Sn27 with natural charges of 2.16486 and 2.1651 respectively and the lowest negative charge peak is shown by carbon element C4 with a natural charge of -0.15345.

![Figure 3. Frontier molecular orbitals diagrams for Ligand \( \text{H}_2\text{L} \) (a), complex (1) (b) and complex (2) (c).](image-url)

Table 5. Global reactivity descriptors for Ligand \( \text{H}_2\text{L} \), complex (1) and complex (2).

<table>
<thead>
<tr>
<th>Compounds</th>
<th>( I )</th>
<th>( A )</th>
<th>( X )</th>
<th>( H )</th>
<th>( M )</th>
<th>( \Omega )</th>
<th>( \Sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligand ( \text{H}_2\text{L} )</td>
<td>6.957</td>
<td>2.751</td>
<td>4.854</td>
<td>2.103</td>
<td>-4.854</td>
<td>5.601</td>
<td>0.237</td>
</tr>
<tr>
<td>Complex (1)</td>
<td>9.004</td>
<td>6.071</td>
<td>7.5375</td>
<td>1.4665</td>
<td>-7.5375</td>
<td>19.370</td>
<td>0.340</td>
</tr>
<tr>
<td>Complex (2)</td>
<td>9.015</td>
<td>6.012</td>
<td>7.5135</td>
<td>1.5015</td>
<td>-7.5135</td>
<td>18.798</td>
<td>0.333</td>
</tr>
</tbody>
</table>
atoms O18-O23 in this complex are negatively charged. All hydrogen atoms H7-H105 are positively charged. The highest positive charge peaks in Complex (2) are shown by Tin elements Sn25 and Sn26 with natural charges 2.16784 and 2.16863, respectively. The lowest negative charge peaks are shown by carbon elements such as C1 and C6 with natural charges -0.16527 and -0.22522, respectively. The natural population analysis (NPA) spectrum for ligand \( \mathbf{H}_2 \mathbf{L} \) shows the inter-nuclear distances in the molecule. FTIR was done for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1), and complex (2) are given in Figure S1 (SI).

3.5e FT-IR analysis: FTIR is the energy analysis used to explain the vibrational modes of compounds. Vibrational modes show the transition distances in the molecule. FTIR was done for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2), and vibrational modes, intensities, and harmonic frequencies were noted by using CAM-B31YP/6-31+G (d, p) level of theory as mentioned in Table S2 (a-c) (SI).

Carbon to hydrogen aromatic and heteroatomic stretching vibrations were observed in the range of 3100-3000 cm\(^{-1}\).\(^{44}\) The stretching (C-H) vibrations for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) for both symmetric and asymmetric vibrational modes were noted. The frequencies were observed at 3215 cm\(^{-1}\) for ligands and complexes in the range of 3103-3097 and 3242-3156 cm\(^{-1}\), respectively. Symmetric and asymmetric stretching (C-H) vibrations in the benzene ring were noted in the range of 3230-3169, 3210-3197, and 3242-3156 cm\(^{-1}\) respectively. The bending vibrations for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) were also noted. The C-H scissoring, wagging, twisting, and rocking vibrations were noted in the range of 1656-1196, 1656-1126, 1514-1462, 1015-852, 1021-754, 1419-1417, 994, 3218, 3210, 1796-1179, 1768-1095, and 1343-1312 cm\(^{-1}\) respectively. The C-C stretching vibrations were noted in the range of 1650-1400 cm\(^{-1}\).\(^{45}\) The calculated C-C stretching vibrational frequencies for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) were noted in the range of 1688-1625, 1677-1656, and 1696-1622 cm\(^{-1}\), respectively. The O-H stretching vibrations were found in the range of 3200-3400.\(^{38}\) The calculated O-H stretching vibrational frequencies for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) were noted in the range of 3818, 3812, and 3811 cm\(^{-1}\) respectively. The C-N stretching vibrations were indicated in the range of 1382-1266 cm\(^{-1}\).\(^{38}\) The calculated C-N stretching vibrational frequencies for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1), and (2) were found in the range of 1349-1274, 1350-1347 and 1389-1223 cm\(^{-1}\), respectively. The N-H stretching vibrations were found in the range of 3300–3500 cm\(^{-1}\).\(^{39}\) Nitrogen to hydrogen vibrational stretching frequencies for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) were noted at 3583, 3590, and 3587 cm\(^{-1}\), respectively. The C-O stretching vibrations were observed in the range of 1710-1652 cm\(^{-1}\).\(^{40}\) The C=O stretching vibrational frequencies for ligand \( \mathbf{H}_2 \mathbf{L} \), complex (1) and (2) were noted at 1796-1688, 1768-1656 and 1736-1622 cm\(^{-1}\), respectively. The Sn-O calculated stretching vibrational frequencies for complex (1) and (2) were observed in the range of 600-402 and 641-449 cm\(^{-1}\), respectively. The calculated Sn-C stretching vibrational frequencies for complex (1) and (2) were noted in the range of 672-665 and 607-587 cm\(^{-1}\), respectively. All the results showed good support to the literature and experimental values as indicated in Table S2 (a-c) (SI).

UV-visible analysis for the oxygen donor ligand \( \mathbf{H}_2 \mathbf{L} \)

UV-visible spectroscopy is used for the absorption properties, and vertical excitation and to explain the charge transfer of the compounds.\(^{41}\) The UV-visible analysis results of recent oxygen donor ligand \( \mathbf{H}_2 \mathbf{L} \) were derived at comfortable indoor temperatures. On the basis of DFT studies, the deliberation of results of excitation energy (E), maximum absorption wavelength (\( \lambda_{\text{max}} \)), oscillator strength (F), and molecular orbital contribution are shown in Table S3 (SI). According to UV-visible spectroscopy experimental data for oxygen donor ligand \( \mathbf{H}_2 \mathbf{L} \), the \( \lambda_{\text{max}} \) value is 280 nm, whereas by computed study for maximum absorption (DFT peaks, \( \lambda_{\text{max}} \)) of Oxygen donor ligand \( \mathbf{H}_2 \mathbf{L} \) in the gas phase were achieved to be 357.259, 322.009, 301.581 and 283.435nm. The major orbital contributions HOMO → LUMO (H→L) for aforesaid values are 99%, 96%, 84%, and 83%, respectively given in the Table S3 and the spectrum are shown in Figure S2 (SI) for oxygen donor ligand \( \mathbf{H}_2 \mathbf{L} \).

3.6 Antimicrobial investigations

3.6a Antibacterial investigations: Four bacterial strains, two Gram +ve (Staphylococcus aureus & Micrococcus luteus) and two Gram –Ve (Bordetella bronchiseptica & Escherichia Coli) were used to investigate ligand \( \mathbf{H}_2 \mathbf{L} \) and complex (1) and (2). The common agar well diffusion method was adopted using DMSO solvent.\(^{17}\) The standard antibiotic drugs ciprofloxacin (1 mg/mL) were used as positive control and DMSO as negative control. The obtained antibacterial results are summarized in Table 6 which is based on the calculation of the area of
inhibition zone in mm. Zero to increasing inhibition zone represent insignificant to significant antibacterial activity. More than 20 mm zone of inhibition is considered significant, 20-18 mm as better, 17-15 as poor, and below 10 as insignificant antibacterial activity. The tested complexes showed significant/better antibacterial activity in comparison to precursor organic ligand \( \text{H}_2\text{L} \) as shown in Table 6. Various mechanisms for killing bacteria have been suggested such as Tweedy Chelation, enzyme inhibition, cellular wall dysfunctioning, etc.\(^{18}\)

3.6b Anti-fungal investigation: Four fungal strains, Aspergillus Niger, Aspergillus fumigates, Aspergillus flavus and Fusarium solani, were used to test ligand \( \text{H}_2\text{L} \) and complex (1) and (2) for antifungal investigation using Agar Tube Dilution method.\(^{17,18}\) Terbinafine standard drug was used as positive control. The results were given in Table 7 which were based on % age growth inhibition. The four activity parameters, significant (> 70%), good (70-60%), moderate (60-50%) and non-significant (<50%) have been used to explain the antifungal activity of ligand \( \text{H}_2\text{L} \) and complex (1) and (2). The obtained data showed that complexes are more active than ligand \( \text{H}_2\text{L} \) and complex (1) is more active than complex (2) which may be because of more lipophilic character due to phenyl groups.

3.7 Molecular docking

Molecular docking was completed for the synthesized ligand \( \text{H}_2\text{L} \), complexes (1) and (2) to determine the possible binding interaction in the catalytic site of the penicillin-binding protein. The bacterial cell wall is considered an important target in the drug discovery process because the enzyme involved in its manufacturing has no counterpart in mammalians. Penicillin V was used as a standard drug in antibiotic studies, and inhibits the peptidoglycan in the cell wall.\(^{42}\) Keeping in view the mode of action of the standard drug, we performed docking studies on binding protein. According to the binding energies and binding orientation of the synthesized compounds, it could be concluded that all the compounds fit well in the active site.

Visual inspection of the docked complex (1) substituted with the tri-phenyl tin group, showed that pi-alkyl, pi-pi stacking, and pi-donor hydrogen bond of the phenyl group stabilized the penicillin complex in the active site. On the other hand, although \( \text{H}_2\text{L} \) which didn’t have metal and substituted groups was able to form four conventional hydrogen bonds through hydroxyl and carboxylic groups (Figure 4), it presented less binding energy and affinity. This desirable effect of substituted tri-phenyl tin could be attributed to additional van der Waals interaction which stabilized the complex in the pocket of 2EX9. Complex (1)
showed the lowest binding energy of -8.65 Kcal/mol and was considered the best inhibitor of penicillin-binding protein. This complex oriented itself in such a way that it formed one conventional hydrogen bond with Ser398 and pi-pi stacking interaction with Phe160. Leu359 and the pi-alkyl interaction with Leu421 while Asn308, Thr418 formed the pi-donor hydrogen bond with complex (1). Along with this, a pool of hydrophobic contact was also observed by Tyr425, Tyr401, Arg402, Ser306, Ser420, Arg171, Lys417, Ser62, and Asp307 that stabilized the complex in the active site (Figure 5). Compound complex (2) exhibited one conventional hydrogen bond with Ser306 by the carbonyl group of the complex. Alkyl, pi-alkyl, and Van der Waals interaction stabilized the complex in the pocket (Figure 6). Docking results revealed that complex (1) has excellent binding capability with the target protein (2EX9) and complex (2) has the least binding with the protein. Overall, the experimental results are in good agreement with the docking results. Table 8 presents a molecular docking analysis of the synthesized and the native ligand H2L which showed antibacterial activity.

3.7a Docking studies on antifungal target Candida albicans: Table 8 shows binding energies between the target and the synthesized compounds. Compounds with lower docking scores and lower inhibition constant are considered stronger drug candidates. Table 9 presented the binding pose of the synthesized compounds in the binding pocket of the 3N9K that favors the hydrophobic interactions. Complex (1) showed the highest antifungal activity and the estimated free binding energy of the complex (1) was -10.48 Kcal/Mol. It showed the pi-anion interactions with Asp318 and pi-alkyl interactions with pro196, Val197, Leu194 while a core of hydrophobic contact with active residues of Tyr153, Glu262, Tyr255, Asp227, His254, His253, His226, Val231, Gln230, Val231, Arg312, Phe144, Ser259. The binding energies of complex (2) was -8.33 Kcal/mol (Figure 7) which was less efficient than complex (1) but more efficient than H2L.
The complete description of a mode of interactions was presented in Figure 8. It was clear from the docking results that metal presence enhances the antifungal of the compounds and the results are in good agreement with experimental results.

3.8 DNA-compound interaction studies via UV-visible spectrophotometer

The antitumor properties of organotin (IV) compounds have been known due to their one of the important properties of binding capacity with DNA through

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**Table 8.** Molecular docking analysis of native ligand $H_2L$ and the synthesized complex (1) and complex (2) against 2EX9.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Compound</th>
<th>Binding energy ($\Delta G$)</th>
<th>Ligand $H_2L$ efficiency</th>
<th>Intermolecular energy</th>
<th>VDW-H Bond Desolvation Energy</th>
<th>Inhibition Constant $Ki$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2EX9</td>
<td>Native ligand</td>
<td>-4.68</td>
<td>-0.19</td>
<td>-5.55</td>
<td>-5.51</td>
<td>372.94 $\mu M$</td>
</tr>
<tr>
<td></td>
<td>$H_2L$</td>
<td>-6.22</td>
<td>-0.35</td>
<td>-7.27</td>
<td>-4.15</td>
<td>27.36 $\mu M$</td>
</tr>
<tr>
<td></td>
<td>Complex (1)</td>
<td>-8.65</td>
<td>-0.15</td>
<td>-8.26</td>
<td>-8.36</td>
<td>454.48 $\mu M$</td>
</tr>
<tr>
<td></td>
<td>Complex (2)</td>
<td>-4.3</td>
<td>-0.1</td>
<td>-9.45</td>
<td>-9.36</td>
<td>699 $\mu M$</td>
</tr>
</tbody>
</table>

**Table 9.** Molecular docking analysis of native ligand $H_2L$ and the synthesized compounds against 3N9K.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Compound</th>
<th>Binding energy ($\Delta G$)</th>
<th>Kcal/Mol</th>
<th>Ligand $H_2L$ efficiency</th>
<th>Intermolecular energy</th>
<th>VDW-H Bond Desolvation Energy</th>
<th>Inhibition Constant $Ki$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3N9K Candida Albicans</td>
<td>$H_2L$</td>
<td>-4.09</td>
<td>-0.23</td>
<td>-5.34</td>
<td>-6.73</td>
<td>1.0 $mM$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complex (1)</td>
<td>-10.48</td>
<td>-0.19</td>
<td>-10.03</td>
<td>-9.97</td>
<td>20.84 $nM$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complex (2)</td>
<td>-8.33</td>
<td>-0.19</td>
<td>-13.77</td>
<td>-13.76</td>
<td>786.78 $nM$</td>
<td></td>
</tr>
</tbody>
</table>
intercalation, groove binding, or electrostatic interaction. Keeping in view of this, the anti-tumor potential of newly prepared ligand $\text{H}_2\text{L}$ and its organotin (IV) compounds were determined using a UV-Visible spectrophotometer.

The absorbance of ligand $\text{H}_2\text{L}$/organotin (IV) compounds was determined first without DNA and then with various concentrations (4 $\mu$M, 8 $\mu$M, and 12 $\mu$M) of DNA while keeping the concentration of ligand $\text{H}_2\text{L}$ or complex constant. The results showed (Figures 9, 10, 11) a decrease in absorbance known as a hypochromic effect with no significant shift in wavelength. This observation suggested that ligand $\text{H}_2\text{L}$/complex may bind with DNA through intercalation and lead to lengthening and separation of base pairs. The results were taken again after 24 hours and found out same that sowed stability of compound-DNA adduct. To find out the binding strength of compound-DNA adduct, the intrinsic binding constant

![Image](image-url)

Figure 8. (L-R, A-C). Two-dimensional presentations of the binding interactions of the synthesized compound $\text{H}_2\text{L}$ (A), complex (1) (B), complex (2) (C), generated by discovery studio.

![Image](image-url)

Figure 9. UV-Visible spectrum of Ligand $\text{H}_2\text{L}$ without DNA a and with DNA (b-d); [4 $\mu$M (b), 8 $\mu$M (c), 12 $\mu$M (d)].
(K) was determined using the Benesi Hildebrand equation

\[
\frac{A_0}{A - A_0} = \frac{\epsilon_G}{\epsilon_{H-G} - \epsilon_0} + \frac{\epsilon_G}{\epsilon_{H-G} - \epsilon_G} \times \frac{1}{K[\text{DNA}]}
\]

Where \(A_0\) and \(A\) represent absorbance of the compound without DNA and with DNA respectively, \(\epsilon_G\) and \(\epsilon_{H-G}\) absorption co-efficient of compound and compound-DNA adduct respectively. The binding constant value was obtained from intercept to slope ratio of \(A_0/A_0\) versus 1/DNA plot and found as 1.26 x 10^2 M\(^{-1}\), 1.087 x 10^5 M\(^{-1}\), 2.73 x 10^4 M\(^{-1}\) for ligand \(H_2L\), complex (1) and (2), respectively.

Gibb’s free energy accounts for spontaneous or non-spontaneous reactions and is determined as

\(\Delta G = -RT \ln K\). Where, \(R\), \(T\), and \(K\) represent, the general gas constant, room temperature in Kelvin, and binding constant, respectively.

Figure 10. UV-Visible spectrum of complex (1) without DNA a and with DNA (b-d); [4 μM (b), 8 μM (c), 12 μM (d)].

Figure 11. UV-Visible spectrum of complex (2) without DNA a and with DNA (b-d); [4 μM (b), 8 μM (c), 12 μM (d)].
The determined ΔG values are -11.88, -28.52, and -25.12 KJmol⁻¹ for ligand H₂L, complex (1) and (2), respectively. These negative values showed that the interaction of DNA with the compound is a spontaneous process.

The binding mode of interaction of the compound with DNA was also determined by keeping DNA concentration constant and varying the concentration of the compound. The absorption spectra of the interaction of SS-DNA with the prepared compounds have been recorded for a constant SS-DNA concentration (7.45 × 10⁻⁴ M) and varying compound concentrations (5 × 10⁻⁵, 4 × 10⁻⁵, 3 × 10⁻⁵, 2 × 10⁻⁵ and 1 × 10⁻⁵ M). UV spectra of SS-DNA in the presence of complexes (1) and (2) obtained for different concentrations are shown in Figure 12 (a,b). The spectral characteristics of DNA associated with its double helix structure are known as hyperchromism and hypochromism. Hyperchromism refers to the breakdown of DNA secondary structure, while hypochromism denotes that the mode of complex that binds to DNA is an intercalation or electrostatic effect that can stabilize the DNA duplex, whereas the presence of a red-shift indicates that the DNA duplex has been stabilized. The variations in the SS-DNA absorption spectra observed in the presence of complexes (the increase in intensity at λmax = 272 nm) just after mixing to complexes (1) and (2) suggest that the interaction of SS-DNA with compound takes place by an immediate development of an entirely novel complex with double-helical SS-DNA. Because of the compound interaction with DNA, the pyrimidine and purine bases of DNA are exposed, increasing the absorption intensity at 272 nm. A small conformational shift may have been caused in DNA by this type of binding. The observed small red shift is indicative of the stability SS-DNA duplex, and the hypochromism may be attributable to interactions between the complexes’ aromatic chromophores and DNA base pairs. The results obtained are comparable to previous reports.

### 3.9 Viscosity measurement

The clarification of the binding mode of the tested compounds with SS-DNA was further done with the help of the viscometric method. The viscosity of the SS-DNA (Figure 13) was increased with the addition of various concentrations of the tested compounds (H₂L, 1, 2) which is a sign of an intercalative mode of interaction.

### 4. Conclusions

Two new tri-organotin (IV) carboxylate complexes were prepared successfully and characterized by FT-IR, NMR, and UV-visible spectroscopic techniques.
The binding mode and geometry of ligand \( H_2L \) were determined by FT-IR and NMR studies. Five coordinated geometries (trigonal bipyramidal) have been suggested for the complexes. Computational studies were performed for comparative spectroscopic studies i.e., FT-IR, UV-Vis to reveal the structural geometrical parameters, natural population analysis (NPA), natural bond orbitals (NBO), frontier molecular orbital (FMO) analysis, nonlinear and linear optical (NLO) properties of ligand \( H_2L \), complex (2) and complex (1). Consequently, an outstanding collaboration between the DFT-based results and experimental results was attained. The antimicrobial potential of newly synthesized ligand \( H_2L \) and complexes were evaluated and results exhibited significant antimicrobial potential. The antibacterial molecular docking results revealed that complex (1) has excellent binding capability with the target protein (2EX9) than complex (2). The antifungal docking results revealed that complex (1) showed the highest antifungal activity and the estimated free binding energy of complex (1) was \( -10.48 \) Kcal/mol. The organotin (IV) complexes have been shown anti-tumor potential as indicated by binding constant values of \( 1.26 \times 10^2 \) M\(^{-1}\), \( 1.087 \times 10^1 \) M\(^{-1}\) and \( 2.73 \times 10^4 \) M\(^{-1}\) for ligand \( H_2L \), complex (1), and (2), respectively while keeping compound concentration constant and varying DNA concentration. The resultant decrease in intensity or hypochromic effect indicated an intercalative mode of the binding interaction. The mode of intercalation was further elaborated through UV-visible studies by keeping DNA concentration constant and varying compound concentration. The same was also confirmed through viscosity measurement in which the viscosity of the SS-DNA was increased with the addition of various concentrations of the tested compounds (\( H_2L, 1, 2 \)).

Supplementary Information (SI)

Tables S1-S3 and Figures S1-S2 are available at www.ias.ac.in/chemsci.

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Declarations

Conflict of interest There is no conflict of interest to be reported.

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