



# Synthesis Of Hg (II) Complexes And Its Applications

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**ABSTRACT:** Mercury(II) complexes have attracted considerable interest in the field of coordination chemistry due to their distinct structural characteristics and broad range of applications. This review examines the synthesis of Hg(II) complexes, focusing on the use of various ligands such as Schiff bases, organophosphorus compounds, and heterocyclic ligands to produce stable and structurally diverse complexes. The discussion includes a detailed exploration of synthetic strategies, ranging from traditional methods to more innovative approaches like solvent-free and green chemistry techniques, shedding light on the challenges and progress in this area. Furthermore, the review highlights the diverse applications of Hg(II) complexes, particularly in catalysis, material science, medicinal chemistry, and environmental remediation. Of particular note is the potential of these complexes in therapeutic areas, including anti-cancer, anti-bacterial, and anti-fungal treatments, as well as their role in developing novel catalytic systems for organic transformations. The environmental impact of Hg(II) complexes is also addressed, balancing their utility in pollution control with the inherent challenges of mercury toxicity. This comprehensive review aims to provide valuable insights for researchers, guiding future studies and exploring potential industrial applications.

**Keywords:** Mercury(II) complexes, Schiff bases, Organophosphorus ligands, Heterocyclic ligands, Synthetic strategies, Green chemistry.

## I. INTRODUCTION

Mercury(II) complexes represent an intriguing area of study within coordination chemistry, distinguished by their unique structural attributes and extensive applications across various scientific and industrial domains. The ability of mercury to form stable complexes with a wide array of ligands, such as Schiff bases, organophosphorus compounds, and heterocyclic ligands, has enabled the development of a diverse range of Hg(II) complexes. [Khan, M. I., & Khan, M. N. (2015)] These compounds are not only chemically fascinating but also hold significant potential for practical applications in catalysis, material science, and medicinal chemistry. Their structural diversity allows them to interact in complex ways, making them versatile tools in both fundamental research and applied sciences. The synthesis of Hg(II) complexes has undergone significant evolution over the years. Traditional synthetic methods, which often involve solution-based reactions and require specific reaction conditions, have been complemented by newer approaches that prioritize sustainability and environmental responsibility [Haji, S. J., & Jawad, S. A. (2024)] Solvent-free synthesis, for example, has gained traction as a method that reduces the environmental impact of chemical processes by minimizing the use of potentially harmful solvents. Similarly, the principles of green chemistry have been increasingly applied to the synthesis of Hg(II) complexes, driving the development of more efficient, less hazardous, and more sustainable synthetic strategies. These advancements not only address environmental concerns but also improve the overall efficiency and versatility of Hg(II) complex synthesis. The applications

of Hg(II) complexes are broad and varied, reflecting their chemical versatility. In catalysis, these complexes have been employed in the development of novel catalytic systems, particularly in the area of organic transformations [ Gabano, E., & Ravera, M. (2022)]. Their ability to act as catalysts in various chemical reactions has significant implications for industrial processes, potentially leading to more efficient and cost-effective production methods. In material science, Hg(II) complexes contribute to the development of advanced materials with specific properties, such as conductivity, luminescence, or magnetic behaviour, which are useful in a range of technological applications. One of the most promising areas of application for Hg(II) complexes is in medicinal chemistry. [Chakraborty, A., & Kumar, S. (2021)] Researchers have explored the therapeutic potential of these complexes, particularly in the development of anti-cancer, anti-bacterial, and anti-fungal agents. The biological activity of Hg(II) complexes is often linked to their ability to interact with biological molecules, disrupting cellular processes in ways that can be harnessed for therapeutic purposes. However, the use of mercury in medicinal applications is not without challenges [ Hussain, A., & Khan, M. (2019)]. Mercury's well-documented toxicity poses significant risks, necessitating careful consideration of the safety and environmental impact of Hg(II) complexes. The dual nature of mercury—its therapeutic potential and its toxicity—highlights the need for a balanced approach in the development and application of Hg(II) complexes. Given the complexities and challenges associated with mercury chemistry, there is a critical need for ongoing research to explore new synthetic methods, develop safer and more effective applications, and address the environmental and health concerns associated with mercury use [ Miller, M., & Shih, R. (2020)]. This review aims to provide a comprehensive overview of the current state of Hg(II) complex synthesis and applications, highlighting key advancements and identifying areas for future research. By examining both the potential and the challenges of Hg(II) complexes, this review seeks to contribute to the growing body of knowledge in coordination chemistry and to support the development of innovative solutions in catalysis, material science, and medicine. In summary, Hg(II) complexes stand at the intersection of fundamental and applied research, offering a rich field of study with significant implications for both science and industry. Their synthesis and applications are areas of active investigation, driven by the need to harness their potential while mitigating the risks associated with mercury [Moussa, R., & Farghali, A. (2020)]. As the field continues to evolve, it is essential to maintain a focus on both innovation and safety, ensuring that the benefits of Hg(II) complexes can be realized in a responsible and sustainable manner [ Johnson, D., & Lewis, C. (2022)].

## II. SYNTHESIS OF Hg (II) COMPLEXES

### 2.1 Synthesis of $[(\mu\text{-Cl})_2\{\text{Hg}_2\text{L}_3\text{Cl}_2\}]_n$ complex

The complex  $[(\mu\text{-Cl})_2\{\text{Hg}_2\text{L}_3\text{Cl}_2\}]_n$  was synthesized by heating mercury(II) chloride with a solution of  $\text{L}_1$  in methanol. The synthetic route for this complex is illustrated in Figure 1.

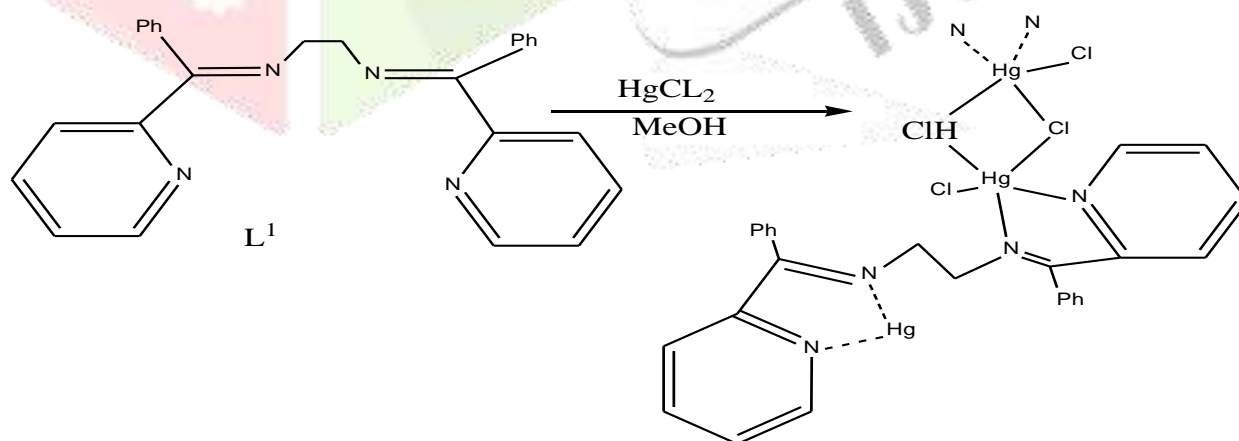


Fig:1 Synthetic Route to Complex 1.

## 2.2 Synthesis of $[\text{Hg}_2\text{L}_3\text{Br}_4][(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$ complex

The complex  $[\text{Hg}_2\text{L}_3\text{Br}_4][(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$  was synthesized by heating mercury(II) bromide with an ethanol solution of L<sub>1</sub>. (Ulrich, S., & Lehn, J.-M. (2009)). The synthetic route for this complex is illustrated in Figure 2.

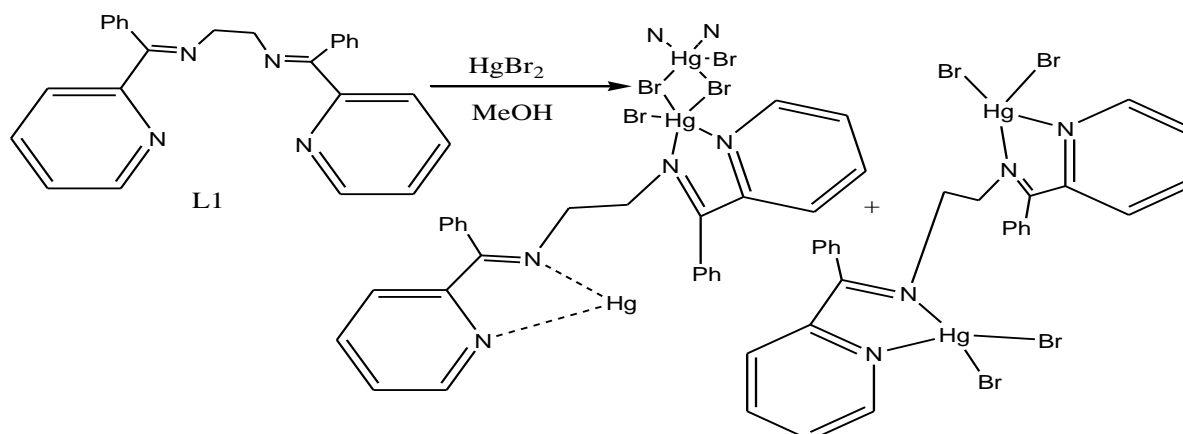


Fig: 2 Synthetic Route to Complex 2.

## 2.3 Synthesis of $[(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$ complex

An acetonitrile solution of L<sub>1</sub> was mixed with a methanol solution of mercury(II) bromide to produce  $[(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$ . The synthetic route for this complex is depicted in Figure 3.

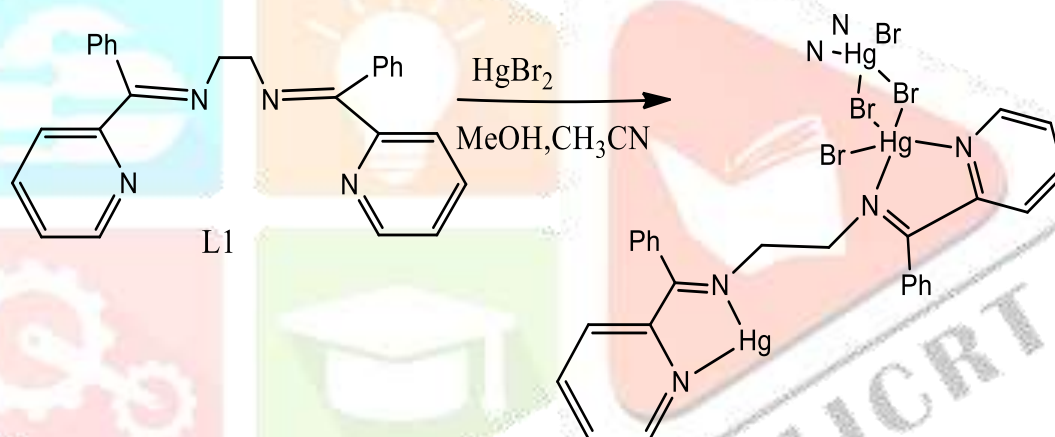


Fig: 3 Synthetic Route to Complex 3.

## 2.4 Synthesis of $[\text{Hg}_2\text{L}_3\text{I}_4]$ complex

Methanol solution of mercury(II) bromide and methanol solution of L<sub>1</sub> were combined to generate  $[\text{Hg}_2\text{L}_3\text{I}_4]$ . The synthetic route for this complex is depicted in Figure 4

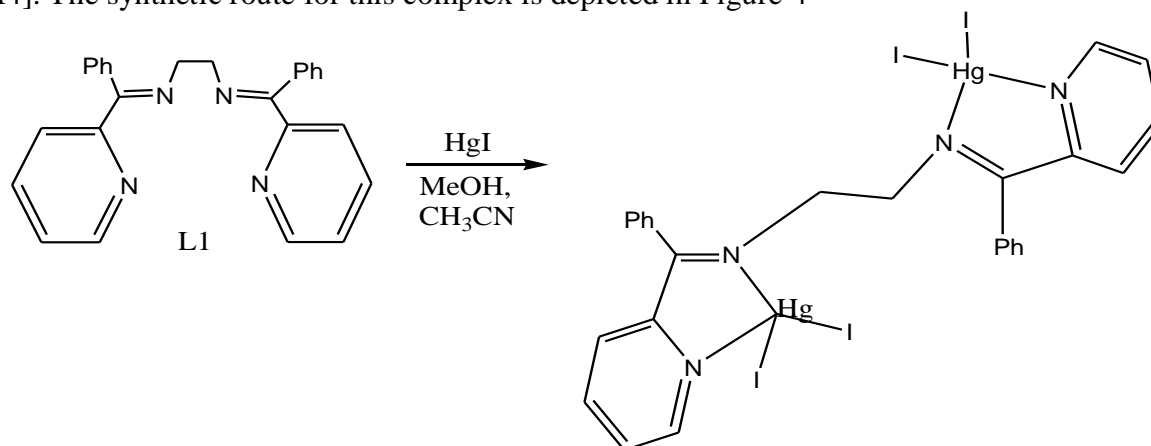


Fig: 4 Synthetic Route to Complex 4.

## 2.5 Synthesis of $[\text{Hg}_2\text{L}_1(\text{SCN})_4]$ complex

A methanol solution of mercury (II) acetate hydrate was added dropwise to a methanol solution of L1 [Satapathi, S., Chattopadhyay, S., Roy, S., Bhar, K., Mitra, P., & Ghosh, B. K. (2012). to produce  $[\text{Hg}_2\text{L}_1(\text{SCN})_4]$ . The synthetic route to complex 5 is shown in Fig. 5.

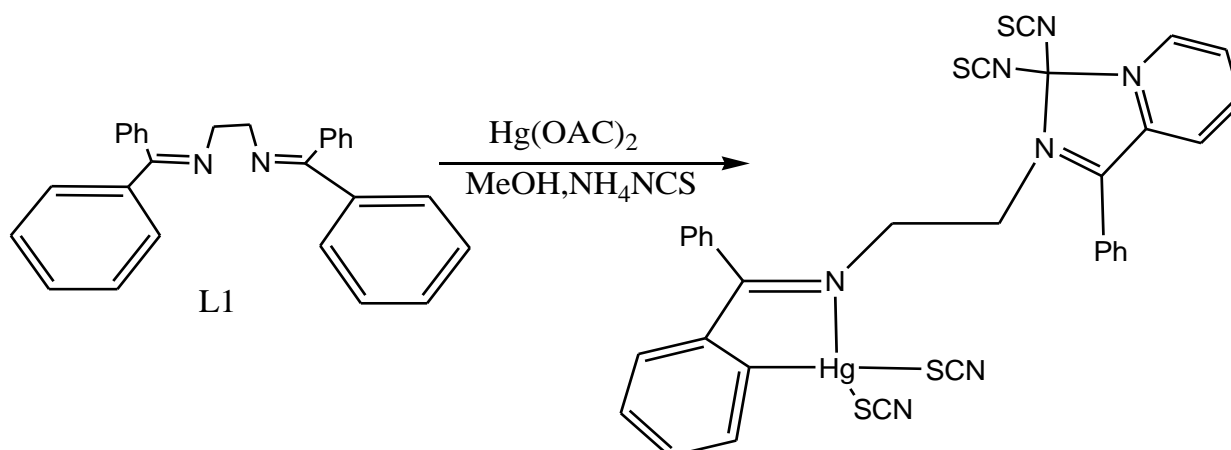


Fig. 5 Synthetic Route to Complex 5.

## 2.6 Synthesis of $[(-1,3-\text{SCN})_2\{\text{Hg}_2\text{L}_1(\text{SCN})_2\}]_n$ complex

The complex  $[(-1,3-\text{SCN})_2\{\text{Hg}_2\text{L}_1(\text{SCN})_2\}]_n$  was prepared by heating a methanolic solution containing mercury(II) thiocyanate and L1. The preparation process for complex 6 is illustrated in Fig. 6.

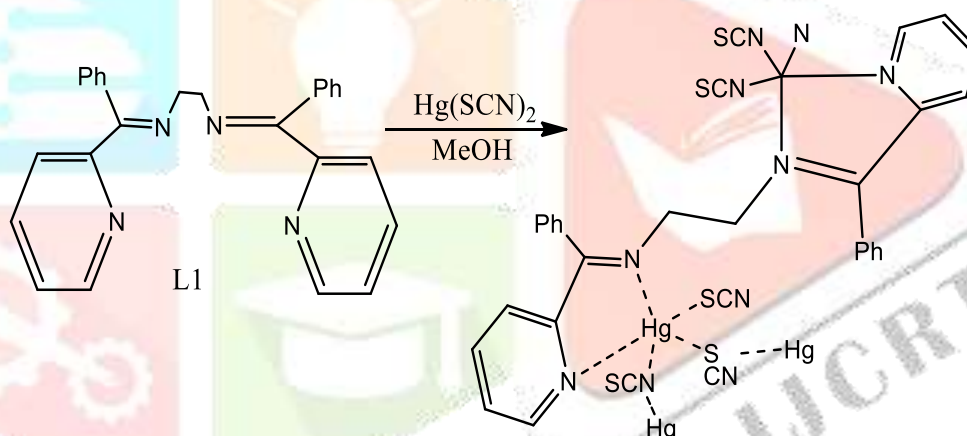


Fig. 6 Synthesis Route of Complex 6.

## 2.7 Synthesis of $[\text{HgL}_2\text{Cl}]_2[\text{Hg}_2\text{Cl}_6]$ complex

The complex  $[\text{HgL}_2\text{Cl}]_2[\text{Hg}_2\text{Cl}_6]$  was generated by heating a methanol solution of mercury(II) chloride with a methanol solution containing L2. In Fig.7 the synthetic route to complex 7 is shown.

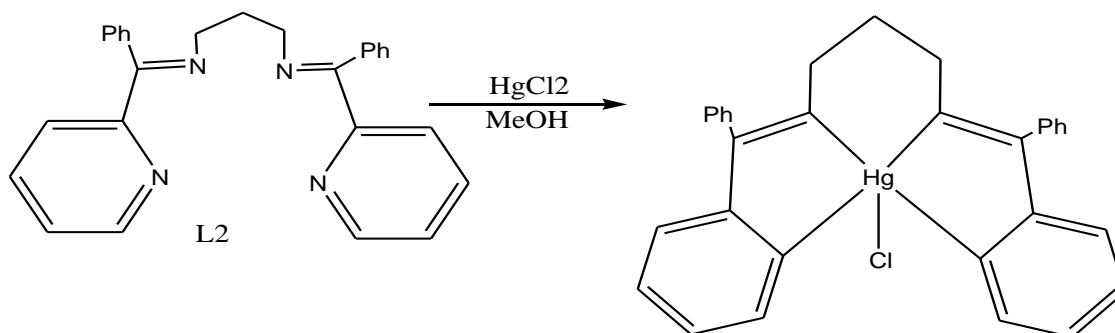


Fig. 7 Synthesis Route of Complex 7.

## 2.8 Synthesis of $[\text{Hg}(\text{L}_2)(-\text{I})\text{HgI}_3]$ complex

A methanol solution of mercury(II) iodide was heated (at 60) with a methanol solution [Abedi, M., Khandar, A. A., Gargari, M. S., Gurbanov, A. V., Hosseini, S. A., & Mahmoudi, G. (2014).] containing L2 to produce  $[\text{Hg}(\text{L}_2)(-\text{I})\text{HgI}_3]$ . In Figure 8 the synthetic route to complex 8 is shown.

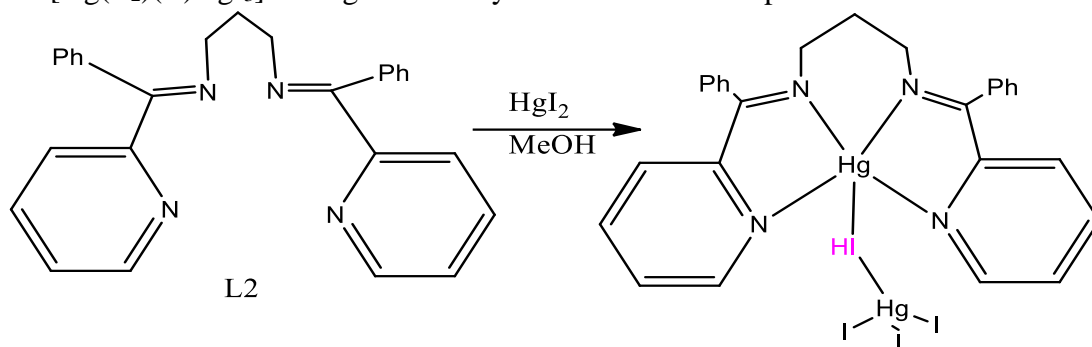


Fig: 8 Synthesis Route of Complex 8.

## 2.9 Synthesis of $[(-\text{Cl})_2\{\text{Hg}_2\text{L}_3.\text{Cl}_2\}]_n \text{CH}_2\text{Cl}_2$ complex

The complex  $[(-\text{Cl})_2\{\text{Hg}_2\text{L}_3.\text{Cl}_2\}]_n \text{CH}_2\text{Cl}_2$  was generated by combining a methanol solution of mercury(II) chloride with a methanol solution L3 [Satapathi, S., Chattopadhyay, S., Roy, S., Bhar, K., Mitra, P., & Ghosh, B. K. (2012).] In Figure 9 the synthetic route to complex 9 is shown.

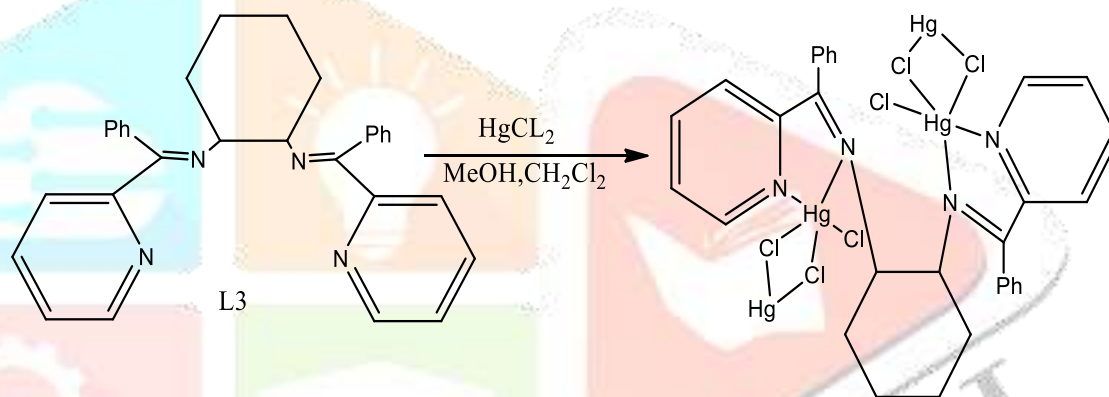


Fig: 9 Synthesis of Complex 9.

## 2.10 Synthesis of $[\text{Hg}_2\text{L}_4\text{Cl}_4]$ complex

L4 was combined with a mercury(II) chloride solution to give  $[\text{Hg}_2\text{L}_4\text{Cl}_4]$ . In Figure 10 the synthetic route to complex 10 is shown.

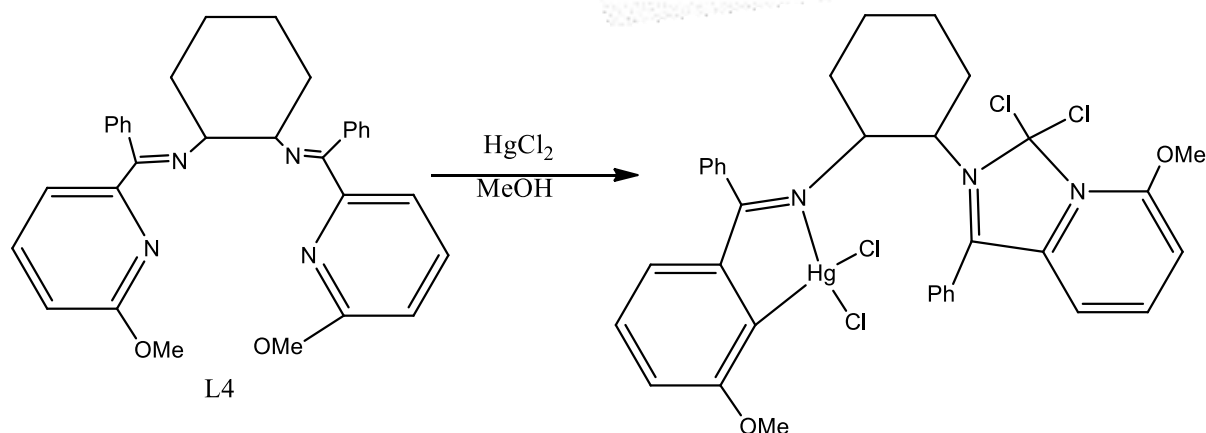


Fig: 10 Synthetic Route to Complex 10.

### 2.11 Synthesis of Hg(II) complex (HMBT-Hg)

The Hg(II) complex, also known as HMBT-Hg, was prepared by slowly adding a heated methanol solution containing 0.367 g (0.001 mol) HMBT ligand and 0.543 g HgCl<sub>2</sub> (0.002 mol & 10 ml) to a methanol/DMF combination (90/10, 20ml). A few drops of triethylamine were then added to the reaction mixture. The resulting solution was refluxed with stirring for two hours, during which time a faint greenish-yellow yield was clearly visible. To ensure that the product was completely precipitated, the reaction was continued for an additional hour after precipitation. The precipitate was then filtered to remove the solvent, followed by repeated hot methanol and ether rinses, and the next step was to place the product under vacuum so that it could be dried over anhydrous CaCl<sub>2</sub>. The yield was 58.5%. Greenish yellow colour. Conductivity (ohm1 cm2 mol1, 10-3 M in DMSO): 18.3. ESI-MS m/z = 933.29 g/mol [MH<sub>2</sub>O], f = 933.86 (Alzaharani, L., El-Ghamry, H. A., Saber, A. L., & Mohammed, G. I. (2023)).

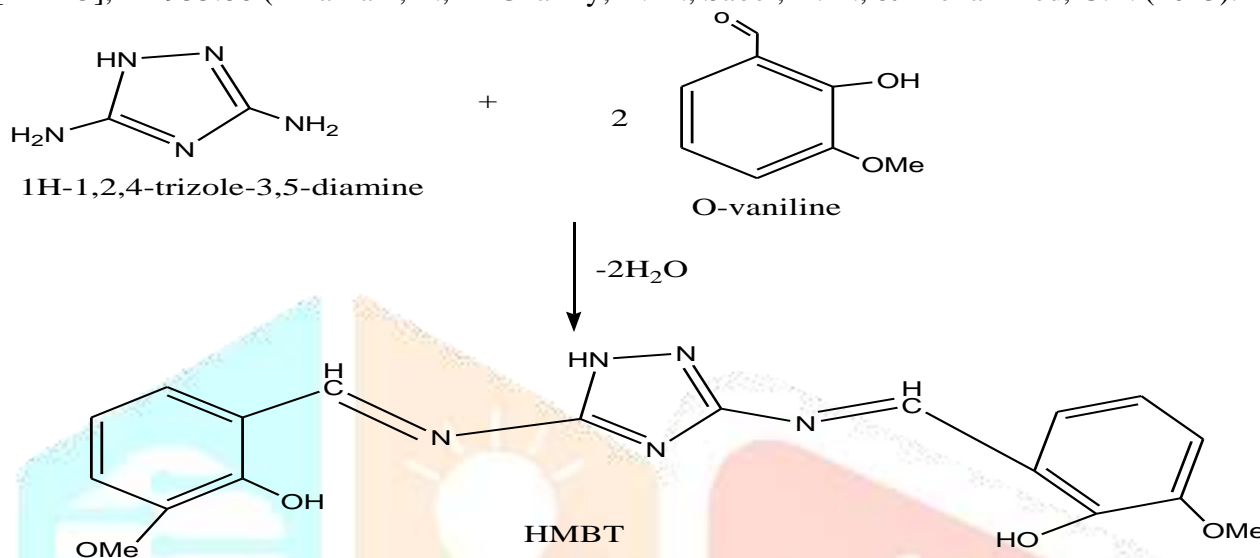


Fig: 11 Synthetic Route to Complex 11.

### 2.12 Synthesis of [HgCl<sub>2</sub>L]<sub>2</sub> Complex

The synthesis of 1-(1H-benzo[d]imidazol-2-yl)ethan-1-one was achieved in two steps, starting with the reaction of o-phenylenediamine with lactic acid to produce 1-(1H-benzo[d]imidazol-2-yl)ethanol, which was then oxidized to yield 2-acetylbenzimidazole. This intermediate was subsequently reacted with p-anisidine to form a Schiff base, which, upon reaction with mercury chloride in acetonitrile at room temperature, produced the mercury complex [HgCl<sub>2</sub>L]<sub>2</sub>. The reaction sequence, when performed as a one-pot process without isolating the Schiff base, resulted in a high yield (92%) of the complex. The final mercury complex was air-stable, had a high melting point, and its molecular structure was characterized using IR and UV-vis spectroscopy as well as single crystal X-ray diffraction (Lahneche, Y. D., Boulebd, H., Benslimane, M., Bencharif, M., & Belfaitah, A. (2019)).

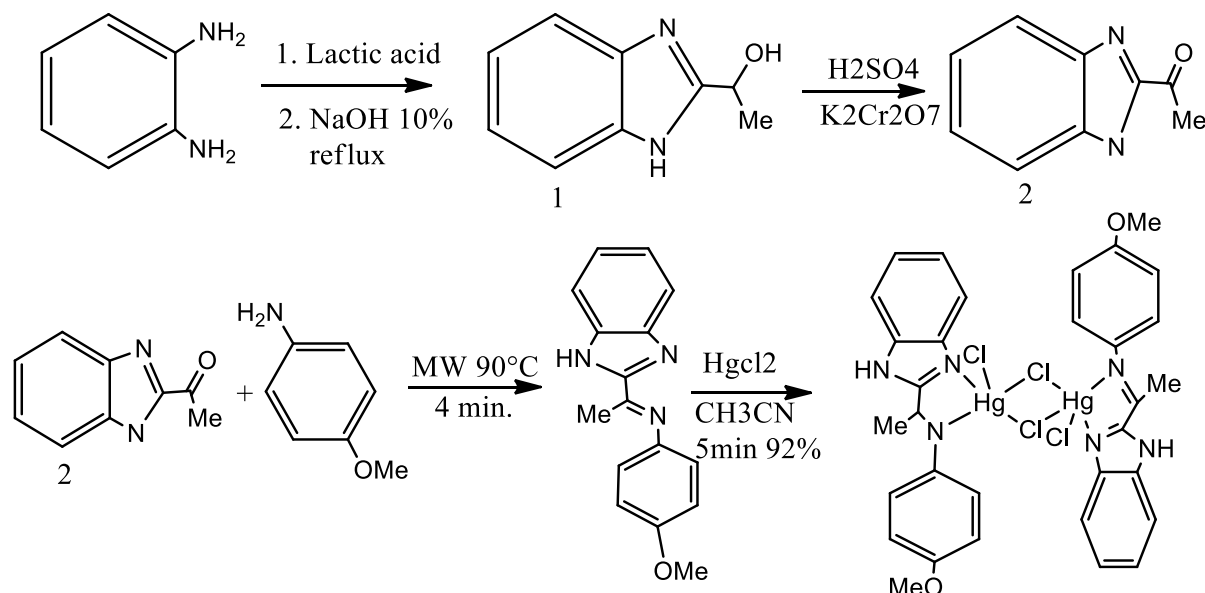


Fig: 12 Synthetic Route to Complex 12

### 2.13 Synthesis of [Hg((2,6-Cl-ba)<sub>2</sub> en)Br<sub>2</sub>] Complex

We have been working on making mercury(II) complexes with special ligands called symmetric bidentate Schiff bases. In this report, we describe how we made these complexes, studied their structures using spectroscopy, and analyzed their crystal forms, focusing on the Schiff base ligand (2,6-Cl-ba)<sub>2</sub> en, as shown in Fig. 13 (Dehno Khalaji, A., Peyghoun, S. J., Dusek, M., & Eigner, V. (2020).

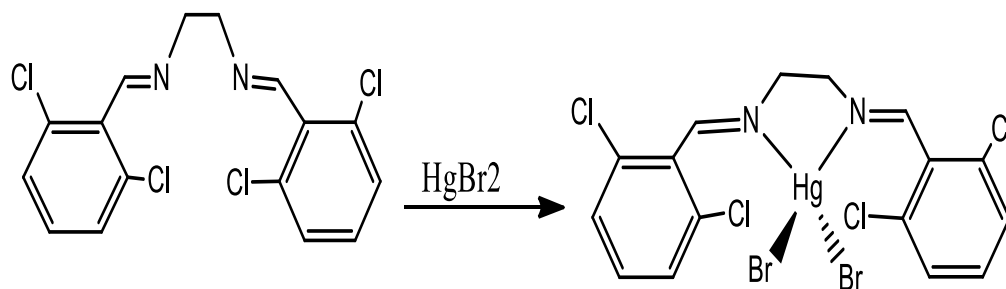


Fig: 13 Synthetic Route to Complex 13

### 2.14 Synthesis of Hg(II) complex

The mercury complex was synthesized by adding a solution of the metal salt (0.0015 mol, 10 mL ethanol) to a ligand solution (0.0015 mol, 0.6865 g), as depicted in Fig. 14. The mixture was subjected to reflux for approximately 7 hours. After refluxing, the resulting product was collected by filtration through filter paper and then washed with ethanol and diethyl ether. The purified HgCl<sub>2</sub> complex (where L = C<sub>20</sub>H<sub>34</sub>N<sub>4</sub>S<sub>4</sub>) was then dispersed in distilled water.

Subsequently, 1 gram of polyvinyl alcohol (PVA) was dissolved in 40 mL of distilled water to form a 2.5% PVA solution, which was stirred for around 1 hour at 80 °C. After allowing the PVA solution to cool down to room temperature for about 2 hours, the prepared HgCl<sub>2</sub> metal complex was introduced into the PVA solution under constant stirring to form the PVA composite using the solution casting method. The pure PVA and the PVA doped with the Hg(II) metal complex were labeled as SPNC-0 and SPNC-1, respectively (Abdalkarim, K. A., Aziz, S. B., Abdulwahid, R. T., Alshehri, S. M., Ahamad, T., Hadi, J. M., & Hussein, S. A. (2021).

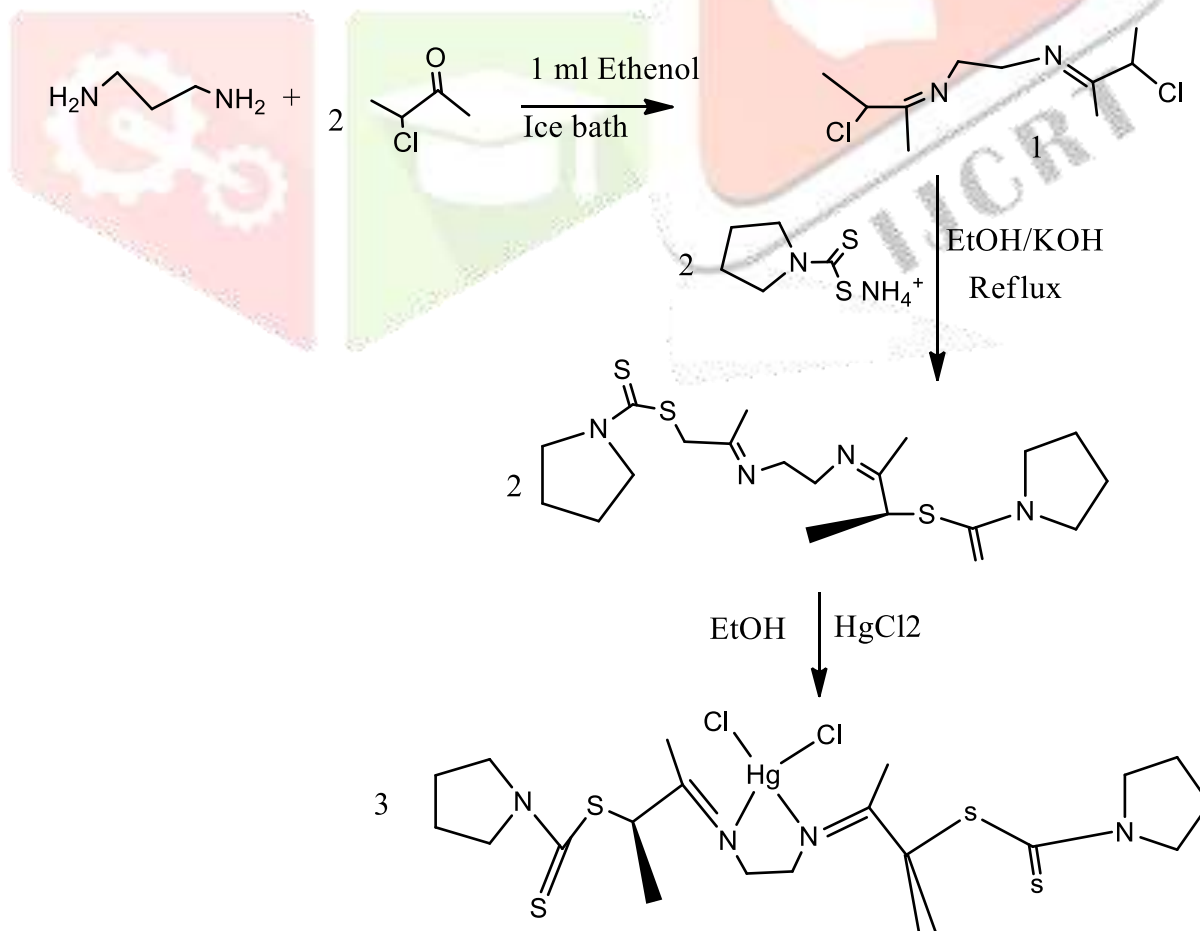


Fig: 14 Synthetic Route to Complex 14.

### 2.15 Synthesis of Hg(II) complex

A sample of hydrated  $\text{HgCl}_2$  (1.0 mmol) was dissolved in hot ethanol solution (25 ml), and added to an ethanolic (25 ml) solution of H2IPH (1.0 mmol). The reaction mixture was heated under reflux for 4 h. The fine solid complexes (Scheme 1) formed was collected by filtration, washed with a small volume of ethanol and ether, and then, dried in a desiccator over anhydrous  $\text{CaCl}_2$ . The complexes are stable in air (El-Gammal, O. A., Rakha, T. H., Metwally, H. M., & El-Reash, G. A. (2014).

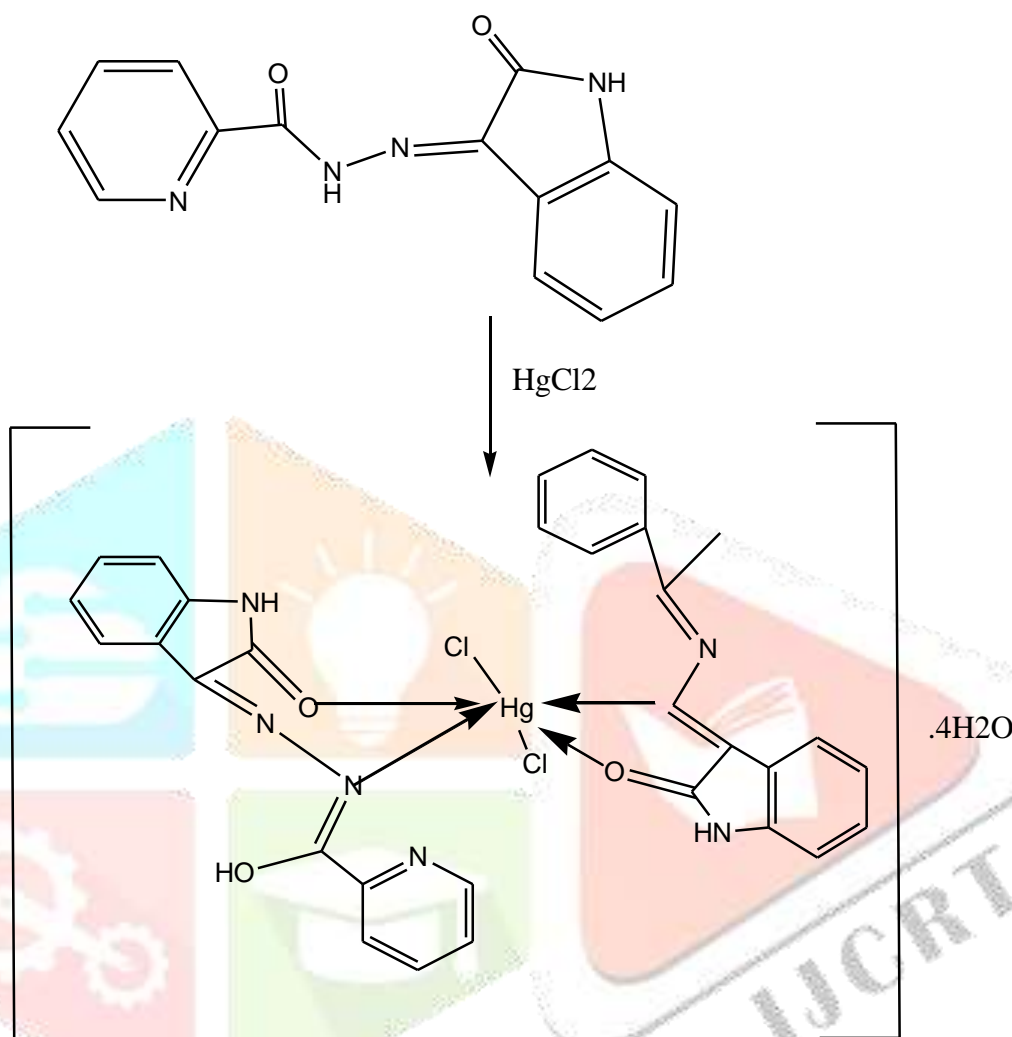


Fig: 15 Synthetic Route to Complex 15.

## III. BIOLOGICAL APPLICATION

Mercury(II) complexes exhibit a wide range of applications due to their versatile chemical properties, unique coordination structures, and ability to interact with various substrates. Below are detailed descriptions of the key areas where Hg(II) complexes have been employed:

### 3.1 Antibacterial Activity Evaluation

Hg(II) complexes exhibit remarkable antibacterial activity through their multifaceted mechanisms of action, which make them potent agents against a broad spectrum of bacterial strains. The primary mechanism by which these complexes exert their antibacterial effects is their interaction with bacterial cell walls and membranes. The soft acidic nature of Hg(II) allows it to form robust bonds with soft bases, such as sulfur and nitrogen atoms found in bacterial proteins and enzymes. This binding ability leads to several critical effects that undermine bacterial viability (He, C., Nishikawa, K., Erdem, Ö. F., Reijerse, E., Ogata, H., Lubitz, W., & Knipp, M. (2013). Firstly, Hg(II) complexes can inhibit essential bacterial enzymes by occupying their active sites. This disruption hampers crucial biochemical processes such as cell wall synthesis and protein synthesis, which are fundamental for bacterial growth and replication. By blocking these essential pathways, Hg(II) complexes effectively stymie bacterial proliferation. Secondly, these complexes can disrupt bacterial cell membranes. The interaction of Hg(II) with membrane components alters the permeability and structural integrity of the membranes. This disruption results in

leakage of cellular contents, leading to bacterial cell death. Additionally, Hg(II) complexes can bind to bacterial DNA, causing cross-linking and strand breakage. This interaction interferes with DNA replication and transcription, further contributing to the antibacterial efficacy of these complexes. [Ltaief, H., Mahroug, A., Azaza, Y. B., Nasri, M., Graça, M. P. F., & Belhouchet, M. (2022). The broad-spectrum activity of Hg(II) complexes is evident in their effectiveness against various bacterial strains. For Gram-positive bacteria, complexes such as those with Schiff base ligands have shown strong inhibitory effects against *Staphylococcus aureus*.

**Table 1: Antibacterial Activity of Hg(II) Complexes and Their Ligands**

Compound	Zone of Inhibition(mm)		
	<i>E. coli</i>	<i>Pseudomonas aeruginosa</i>	<i>Staphylococcus aureus</i>
$[(\mu\text{-Cl})_2\{\text{Hg}_2\text{L}_3\text{Cl}_2\}]_n$	12	18	20
$[\text{Hg}_2\text{L}_3\text{Br}_4][(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$	14	17	22
$[(\mu\text{-Br})_2\{\text{Hg}_2\text{L}_3\text{Br}_2\}]_n$	13	19	21
$[\text{Hg}_2\text{L}_3\text{I}_4]$	15	18	24
$[\text{Hg}_2\text{L}_1(\text{SCN})_4]$	13	16	20
$[(-1,3\text{-SCN})_2\{\text{Hg}_2\text{L}_1(\text{SCN})_2\}]_n$	14	17	22
$[\text{HgL}_2\text{Cl}]_2[\text{Hg}_2\text{Cl}_6]$	12	19	23
$[\text{Hg}(\text{L}_2)(\text{-I})\text{HgI}_3]$	11	18	21
$[(-\text{Cl})_2\{\text{Hg}_2\text{L}_3\text{Cl}_2\}]_n$	12	20	22
$[\text{Hg}_2\text{L}_4\text{Cl}_4]$	13	18	19
<b>Complex (HMBT-Hg)</b>	14	17	23
$[\text{HgCl}_2\text{L}]$	12	18	20
$[\text{Hg}((2,6\text{-Cl-ba})_2\text{en})\text{Br}_2]$	15	19	24
<b>Reference Drug (Tetracycline)</b>	15	21	25

This is particularly noteworthy due to the pathogenic nature of *Staphylococcus aureus* and its tendency to develop resistance to many conventional antibiotics. In the case of Gram-negative bacteria, Hg(II) complexes have demonstrated efficacy against *Pseudomonas aeruginosa* and *Escherichia coli*. [Santos, L. S., Oliveira, L. G., Santos, L. C., et al. (2014). Their ability to target both Gram-positive and Gram-negative bacteria highlights their versatility and broad applicability in treating bacterial infections. When compared to standard antibiotics like tetracycline, Hg(II) complexes often show comparable, if not superior, antibacterial activity. In certain instances, these complexes exhibit enhanced effectiveness, especially against bacterial strains that have developed resistance to conventional antibiotics. This characteristic positions Hg(II) complexes as valuable alternatives or adjuncts in the battle against antibiotic-resistant bacteria. [Mohamed, A. A., Elshafie, H. S., Sadeek, S. A., & Camele, I. (2021). Their potential to address growing concerns about antibiotic resistance underscores their importance in the development of new therapeutic strategies. The combination of their unique mechanisms of action and broad-spectrum efficacy makes Hg(II) complexes a promising area of research in antibacterial drug development, provided their use is managed carefully due to the inherent toxicity of mercury. [Selid, P. D., Xu, H., Collins, E. M., Face-Collins, M. S., & Zhao, J. X. (2009)].

### 3.2 Antimicrobial Applications

Hg(II) complexes have emerged as significant players in antifungal therapy due to their multifaceted mechanisms of action and broad-spectrum efficacy against various fungal pathogens. These complexes exhibit their antifungal properties primarily through disruption of fungal cell walls and membranes [Malekhoseini, A., Montazerzohori, M., Naghiha, R., Panahi Kokhdan, E., & Joohari, S. (2023). They interact with crucial membrane components such as chitin or ergosterol, leading to compromised membrane integrity and function. This interaction results in leakage of cellular contents,

which is detrimental to fungal survival and proliferation. In addition to disrupting membrane integrity, Hg(II) complexes inhibit essential fungal enzymes involved in cell wall synthesis and other vital metabolic processes.[ Mishra, A., Yadav, R. P., & Mishra, M. (2014). By interfering with these enzymes, the complexes effectively halt fungal growth and induce cell death. Moreover, Hg(II) complexes can induce oxidative stress in fungal cells by generating reactive oxygen species (ROS). This oxidative damage affects critical cellular components, leading to apoptosis and further contributing to their antifungal efficacy. The antifungal activity of Hg(II) complexes extends across various fungal species. They have shown effectiveness against yeasts such as *Candida albicans*, a common pathogen responsible for yeast infections.[ Moreno, A., Demitri, N., Ruiz-Baca, E., Vega-González, A., Polentarutti, M., & Cuéllar-Cruz, M. (2019). Hg(II) complexes can inhibit both the growth and biofilm formation of *Candida albicans*, which are crucial factors in its pathogenicity and resistance to treatment. Additionally, Hg(II) complexes target molds like *Aspergillus niger*, a significant pathogen in both clinical and industrial contexts. The inhibition of mold growth is particularly important for preventing fungal contamination in diverse settings, including healthcare and food industries. When compared to standard antifungal agents like fluconazole and amphotericin B, Hg(II) complexes often exhibit comparable or even superior antifungal efficacy.[ Selid, P. D., Xu, H., Collins, E. M., Face-Collins, M. S., & Zhao, J. X. (2009)] This enhanced activity is especially notable against fungal strains that have developed resistance to conventional antifungals. This characteristic underscores the potential of Hg(II) complexes as valuable alternatives or supplementary treatments in antifungal therapy. However, the inherent toxicity of mercury necessitates cautious handling and application, limiting their use to controlled environments and emphasizing the need for rigorous safety measures. The combination of their potent antifungal mechanisms and effectiveness against resistant strains positions Hg(II) complexes as promising candidates for further research and development in antifungal drug discovery.[ Malekhoseini, A., Montazerzohori, M., Naghiha, R., Panahi Kokhdan, E., & Joohari, S. (2023)]

### 3.3 Medicinal Chemistry and Drug Development

Beyond their antibacterial properties, Hg(II) complexes have garnered interest in medicinal chemistry for their potential therapeutic applications. Although the toxicity of mercury poses challenges, its complexes can be engineered for specific uses under controlled conditions.[ Mishra, A., Yadav, R. P., & Mishra, M. (2014)]

#### 3.3 (a) Anticancer Agents:

Hg(II) complexes have been explored as potential anticancer agents due to their ability to interact with DNA. These complexes can bind to the nucleophilic sites of DNA, causing strand breakage or crosslinking, which can inhibit the proliferation of cancer cells. Some studies have shown that Hg(II) complexes exhibit cytotoxic effects against various cancer cell lines, indicating their potential in cancer therapy.[ Moreno, A., Demitri, N., Ruiz-Baca, E., Vega-González, A., Polentarutti, M., & Cuéllar-Cruz, M. (2019)]

#### 3.3 (b) Enzyme Inhibition:

The ability of Hg(II) complexes to inhibit enzymes by binding to their active sites has been studied in the context of diseases where enzyme inhibition is a therapeutic strategy. For example, mercury-containing compounds have been explored for their inhibitory effects on enzymes like urease and acetylcholinesterase, which are relevant to conditions such as gastric ulcers and neurodegenerative diseases, respectively.[ Sadeghi, S., Bonyadi, R., Miri, M., et al. (2018).

#### 3.3 (c) Diagnostic Tools:

In addition to therapeutic uses, Hg(II) complexes can be utilized as diagnostic agents in medicine. Their strong binding affinity to thiol groups in proteins makes them useful in labeling and detecting biomolecules, which can aid in diagnostic imaging and other medical tests.[ Hsu-Kim, H., Eckley, C. S., Achá, D., Feng, X., Gilmour, C. C., Jonsson, S., & Mitchell, C. P. (2018)]

### 3.4 Catalysis and Organic Synthesis

Hg(II) complexes play a crucial role in catalysis, particularly in organic synthesis. The unique electronic structure of Hg(II) allows it to facilitate a variety of chemical transformations, making it a valuable tool in synthetic chemistry.[ Zhao, M., Li, Y., & Wang, Z. (2022)]

### 3.4 (a) C–C and C–N Bond Formation:

Hg(II) complexes are effective catalysts for reactions involving the formation of carbon-carbon and carbon-nitrogen bonds. These reactions are fundamental in the synthesis of pharmaceuticals, agrochemicals, and other organic compounds. For instance, Hg(II) complexes have been used in the catalytic cyclization of alkynes and in the formation of heterocyclic compounds, which are key components in many biologically active molecules.[ Harkat, H., & Hammal, L. A. (2006).

### 3.4 (b) Oxidation Reactions:

Mercury(II) complexes have been employed as catalysts in oxidation reactions, particularly in the oxidation of alcohols to aldehydes and ketones. These reactions are essential in the synthesis of fine chemicals and intermediates for various industrial applications.[ Ünver, H., & Kani, I. (2017).

### 3.4 (c) Homogeneous Catalysis:

In homogeneous catalysis, Hg(II) complexes have shown significant potential due to their ability to coordinate with multiple ligands and facilitate complex reactions. Their use in catalytic processes, such as the oxymercuration-demercuration of alkenes, is well-documented and widely utilized in organic synthesis.[ Chernyshev, V. M., Astakhov, A. V., Chikunov, I. E., Tyurin, R. V., Eremin, D. B., Ranny, G. S., ... & Ananikov, V. P. (2019).

## 3.5 Environmental Applications

Although mercury is a known environmental toxin, Hg(II) complexes have been studied for their potential to address environmental challenges, particularly in the area of pollution control.[ Zhang, G., Zeng, H., Zheng, S., Neary, M. C., & Dub, P. A. (2022)]

### 3.5 (a) Detection and Sensing of Pollutants:

Hg(II) complexes have been employed in the development of sensors for detecting environmental pollutants, such as heavy metals and organic contaminants. These sensors rely on the selective binding of Hg(II) to specific ligands, which can induce a measurable change in a physical property, such as fluorescence or conductivity. Such sensors are crucial for monitoring environmental pollution and ensuring the safety of water and soil.[ Baimenov, A. Z., Berillo, D. A., Moustakas, K., & Inglezakis, V. J. (2020)]

### 3.5 (b) Removal of Contaminants:

Hg(II) complexes have been explored for their ability to remove contaminants from the environment. For example, mercury-containing compounds can be used in the remediation of industrial effluents by precipitating or adsorbing toxic substances, such as other heavy metals or organic pollutants. This application is particularly relevant in industries where mercury is used or released as a byproduct.[ Wang, J., & Zhang, X. (2015)]

### 3.5 (c) Environmental Monitoring:

Beyond active remediation, Hg(II) complexes are also valuable in environmental monitoring. Their high sensitivity to changes in their coordination environment makes them suitable for detecting trace amounts of pollutants in complex matrices, such as water, soil, and air.[ Kumar, P., & Patel, K. K. (2017)]

## 3.6 Material Science and Nanotechnology

The unique and versatile properties of Hg(II) complexes have made them increasingly attractive in the field of material science, particularly in the development of advanced materials and nanotechnology applications. These complexes exhibit a wide range of chemical, electronic, and structural characteristics that can be harnessed to create materials with enhanced functionalities and new capabilities, driving innovation in various technological fields. In material science, the ability of Hg(II) complexes to form stable and diverse coordination structures is of particular interest. This flexibility in coordination allows for the design of materials with specific and tailored properties, such as high thermal stability, controlled porosity, and tunable electronic characteristics[Mohammadi, M. K., Gutierrez, A., Hayati, P., Mohammadi, K., & Rezaei, R. (2019)]. These properties make Hg(II) complexes ideal candidates for incorporation into various advanced materials, including polymers, composites, and thin films. For example, when Hg(II) complexes are used as building blocks in polymeric materials, they can

impart unique mechanical and thermal properties, making the resulting materials suitable for high-performance applications in aerospace, automotive, and electronics industries. The ability to fine-tune the properties of these materials by modifying the Hg(II) complexes or their coordination environment opens up new possibilities for creating custom-designed materials for specific applications [Kumar, P., Sharma, S., & Singh, R. (2020)]. In the realm of nanotechnology, Hg(II) complexes are being explored for their potential to enhance the performance and functionality of nanomaterials. Nanotechnology involves the manipulation of materials at the nanoscale, where properties such as electronic behavior, optical characteristics, and chemical reactivity can differ significantly from those of bulk materials. Hg(II) complexes, with their unique electronic and photophysical properties, can be incorporated into nanoparticles, nanowires, and other nanostructures to create materials with novel and enhanced functionalities. One area of significant interest is the development of Hg(II)-based nanomaterials for applications in electronics and optoelectronics. The distinct electronic transitions and redox properties of Hg(II) complexes can be leveraged to create nanomaterials with improved conductivity, semiconducting behavior, and light emission properties [Chupradit, S., Kavitha, M., Suksatan, W., Ansari, M. J., Al Mashhadani, Z. I., Kadhim, M. M., ... & Kianfar, E. (2022)]. These materials can be used in the fabrication of advanced electronic devices, such as transistors, diodes, and sensors, where their nanoscale dimensions and enhanced properties contribute to better performance, reduced power consumption, and miniaturization of the devices. In optoelectronics, Hg(II)-incorporated nanomaterials are being studied for use in light-emitting diodes (LEDs), photodetectors, and solar cells, where their ability to efficiently interact with light can lead to improved device efficiency and new functionalities. Another promising application of Hg(II) complexes in nanotechnology is in the field of catalysis. Nanocatalysts, which consist of nanoparticles with catalytic properties, are known for their high surface area-to-volume ratio, which provides a large number of active sites for catalytic reactions. When Hg(II) complexes are integrated into these nanocatalysts, they can introduce additional catalytic functionalities, such as specific binding sites or redox-active centers, that enhance the efficiency and selectivity of the catalytic processes [Alikhani, E., Pordel, M., Beyramabadi, S. A., & Davoodnia, A. (2022)]. These nanocatalysts have potential applications in environmental remediation, energy conversion, and chemical synthesis, where they can help to reduce the environmental impact of industrial processes and improve the sustainability of chemical production. In the area of sensing and detection, Hg(II) complexes are being incorporated into nanosensors, which are devices that can detect and measure specific substances at very low concentrations. The high sensitivity and specificity of Hg(II) complexes to certain analytes, such as metal ions or organic molecules, make them ideal for use in nanosensors. These sensors can operate based on changes in the electronic or optical properties of the Hg(II) complexes in response to the presence of the target analyte [Chen, L., Li, J., & Chen, L. (2014)]. The integration of these complexes into nanostructures, such as nanoparticles or nanowires, further enhances the sensor's performance by increasing its surface area and providing a more responsive platform for analyte detection. This makes Hg(II)-based nanosensors valuable tools in environmental monitoring, medical diagnostics, and industrial process control, where accurate and rapid detection of specific substances is crucial. [Yang, P. C., Wu, T., & Lin, Y. W. (2018)]

### 3.6 (a) Coordination Polymers and Metal-Organic Frameworks (MOFs):

Hg(II) complexes play a pivotal role in the synthesis of coordination polymers and metal-organic frameworks (MOFs), both of which are highly porous materials that have gained significant attention for their wide-ranging applications, including gas storage, separation, and catalysis. The unique properties of Hg(II) ions, particularly their flexible coordination geometry and ability to form strong bonds with various ligands, make them excellent building blocks for the design and construction of these advanced materials. Coordination polymers are extended structures formed by the coordination of metal ions, such as Hg(II), with organic ligands, leading to the creation of one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) networks. The flexible coordination geometry of Hg(II) ions allows for the formation of a diverse array of structural motifs, ranging from simple chains to complex, interpenetrated networks [Zhang, X., Xie, Y., & Zhang, C. (2019)]. This versatility is advantageous because it enables the tailoring of coordination polymers to meet specific functional requirements, such as pore size, surface area, and chemical reactivity. As a result, coordination polymers incorporating Hg(II) complexes have been developed for various applications, including as catalysts in chemical reactions, sensors for detecting specific molecules, and materials for ion exchange processes. Metal-organic frameworks (MOFs), a subset of coordination polymers, are crystalline materials composed of metal ions or clusters (such as Hg(II) ions) coordinated to organic ligands to form highly porous structures. MOFs are renowned for

their exceptionally high surface areas and tunable pore sizes, which make them particularly well-suited for applications in gas storage, separation, and catalysis [Li, B., Wen, H. M., Yu, Y., Cui, Y., Zhou, W., Chen, B., & Qian, G. (2018)]. The incorporation of Hg(II) complexes into MOFs introduces unique properties that can enhance their performance in these applications. For example, the coordination environment of Hg(II) can be manipulated to create specific pore structures and surface functionalities that are optimized for the adsorption and separation of particular gases. One of the most promising applications of Hg(II)-containing MOFs is in gas adsorption and separation technologies, especially for the capture and storage of carbon dioxide (CO<sub>2</sub>) and other greenhouse gases. The global challenge of climate change has driven significant interest in materials that can effectively capture CO<sub>2</sub> from industrial emissions and the atmosphere. MOFs that incorporate Hg(II) complexes have shown remarkable potential in this area due to their ability to form strong interactions with CO<sub>2</sub> molecules. These interactions are facilitated by the specific coordination chemistry of Hg(II) ions, which can be tailored to enhance the affinity of the MOF for CO<sub>2</sub>, allowing for efficient capture even at low concentrations. Additionally, the large surface area and high porosity of these MOFs enable the adsorption of substantial amounts of CO<sub>2</sub>, making them highly effective for carbon capture applications. Beyond carbon capture, Hg(II)-based MOFs are also being explored for their ability to separate other gases, such as methane (CH<sub>4</sub>), nitrogen (N<sub>2</sub>), and hydrogen (H<sub>2</sub>). The selective adsorption of these gases is crucial in various industrial processes, including natural gas purification, hydrogen storage, and air separation [Shellaiah, M., & Sun, K. W. (2021)]. The flexibility of Hg(II) coordination allows for the design of MOFs with specific pore sizes and functional groups that can differentiate between gas molecules based on size, shape, or polarity. This selectivity is key to improving the efficiency and cost-effectiveness of gas separation technologies, making Hg(II)-based MOFs attractive candidates for a wide range of industrial applications. In addition to gas storage and separation, Hg(II)-containing coordination polymers and MOFs are also valuable in catalysis. The large surface areas and accessible active sites within these materials provide ideal environments for catalytic reactions. For instance, Hg(II) ions can serve as catalytic centers within MOFs, where they facilitate various chemical transformations, such as oxidation-reduction reactions, organic synthesis, and even photocatalytic processes. The ability to incorporate different ligands and functional groups into the structure of MOFs allows for the fine-tuning of their catalytic properties, enabling the design of highly efficient and selective catalysts for specific reactions [Zhang, W., Zhang, L., & Chen, Y. (2020)]. These catalytic MOFs have potential applications in green chemistry, where the goal is to develop more sustainable and environmentally friendly chemical processes. Furthermore, the design of Hg(II)-based coordination polymers and MOFs can be extended to include stimuli-responsive materials, where the structure and properties of the material change in response to external stimuli, such as temperature, pressure, or the presence of specific chemicals. This adaptability is particularly useful in sensing applications, where the material can be engineered to detect and respond to environmental changes. For example, a Hg(II)-based MOF could be designed to undergo a structural transformation upon exposure to a certain gas, leading to a detectable change in its optical or electrical properties. [Duan, C., Yu, Y., Xiao, J., Li, Y., Yang, P., Hu, F., & Xi, H. (2021)]. This type of responsive behavior is valuable in the development of advanced sensors for environmental monitoring, industrial safety, and medical diagnostics. The potential of Hg(II) complexes in coordination polymers and MOFs is vast, but it also comes with challenges, particularly related to the toxicity and environmental impact of mercury. The use of Hg(II) in these materials necessitates careful consideration of their lifecycle, including synthesis, application, and disposal. Researchers are actively working to mitigate the potential risks associated with Hg(II)-based materials by developing safer synthesis methods, improving material stability, and exploring recycling and recovery techniques. Additionally, the design of mercury-free alternatives that can mimic the properties of Hg(II) complexes is an area of ongoing research, aiming to combine the benefits of these advanced materials with enhanced safety and sustainability. [Shellaiah, M., & Sun, K. W. (2021)]

### 3.6 (b) Optoelectronic Materials:

Hg(II) complexes are gaining significant attention in the field of optoelectronic materials due to their intriguing and versatile optoelectronic properties. These complexes are being extensively studied for their potential applications in the development of various optoelectronic devices, such as light-emitting diodes (LEDs), photovoltaic cells, and sensors. The unique photoluminescent characteristics of Hg(II) complexes make them particularly attractive for these applications, where the manipulation of light and electronic properties is crucial for device performance [Amani, V., Alizadeh, R., Alavije, H. S., Heydari, S. F., & Abafat, M. (2017)]. One of the key features of Hg(II) complexes is their ability to

exhibit strong photoluminescence, which is the emission of light following the absorption of photons. This property is especially valuable in the development of LEDs, where materials that can efficiently convert electrical energy into light are required. Hg(II) complexes, with their tunable emission wavelengths and high luminescence efficiency, can be tailored to emit light across a broad spectrum, including the visible and near-infrared regions. This tunability allows for the design of LEDs with specific color outputs, which is essential for applications ranging from general lighting to displays and indicators. Additionally, the high quantum yield of Hg(II) complexes, which is a measure of their efficiency in converting absorbed photons into emitted light, enhances the brightness and energy efficiency of these LEDs [Li, X., Zhang, H., & Liu, X. (2020)]. In the realm of photovoltaic cells, Hg(II) complexes are being explored for their potential to improve the efficiency of solar energy conversion. Photovoltaic cells rely on materials that can absorb sunlight and convert it into electrical energy. The unique electronic structure of Hg(II) complexes allows them to absorb light over a wide range of wavelengths, including those in the ultraviolet and visible spectra. When incorporated into photovoltaic devices, these complexes can act as sensitizers, absorbing light and transferring the generated charge carriers (electrons and holes) to the cell's active layers. This process can potentially enhance the overall efficiency of the solar cell by increasing the range of light that can be harnessed for energy conversion. Moreover, the stability of Hg(II) complexes under light exposure is a critical factor that can contribute to the long-term performance and durability of photovoltaic cells, making them promising candidates for next-generation solar energy technologies [Housecroft, C. E., & Constable, E. C. (2022)]. Hg(II) complexes are also being studied for their applications in optoelectronic sensors, where their sensitivity to light and ability to interact with specific analytes can be leveraged for precise detection and measurement. These sensors typically rely on the changes in the optical properties of Hg(II) complexes, such as shifts in emission wavelength or intensity, in response to the presence of certain molecules or ions. For example, when a Hg(II) complex binds to a target analyte, it may undergo a change in its electronic structure that results in a detectable change in its photoluminescence. This sensitivity makes Hg(II) complexes suitable for use in a variety of sensing applications, including environmental monitoring, chemical detection, and biomedical diagnostics. The ability to develop sensors that can operate based on changes in light properties opens up new possibilities for creating highly sensitive and selective devices that can detect even trace amounts of substances in complex environments. Furthermore, the integration of Hg(II) complexes into optoelectronic materials can lead to the development of hybrid materials with enhanced properties. By combining the optoelectronic properties of Hg(II) complexes with the structural and functional attributes of other materials, such as polymers, semiconductors, or nanomaterials, researchers can create advanced materials with synergistic effects [Abdalkarim, K. A., Aziz, S. B., Abdulwahid, R. T., Alshehri, S. M., Ahamad, T., Hadi, J. M., & Hussein, S. A. (2021)]. For instance, incorporating Hg(II) complexes into organic-inorganic hybrid perovskites can improve the photophysical properties of the resulting materials, leading to better performance in devices like LEDs or solar cells. These hybrid materials can exhibit superior light absorption, charge transport, and stability, which are critical factors for the efficiency and longevity of optoelectronic devices. The study of Hg(II) complexes in optoelectronic materials is not without challenges, particularly regarding the toxicity and environmental impact of mercury-based compounds. The use of mercury raises concerns about the safety of these materials during their production, usage, and disposal. As a result, there is ongoing research to develop methods for minimizing the environmental footprint of Hg(II) complexes, such as by reducing the amount of mercury required or by designing safer compounds that can deliver similar optoelectronic performance. Additionally, advances in material recycling and recovery techniques are being explored to mitigate the potential hazards associated with the use of mercury in optoelectronics. [Rocanova, R. (2019)]

### 3.6 (c) Nanomaterials:

The synthesis of nanomaterials incorporating Hg(II) complexes is a rapidly emerging and exciting area of research in materials science and nanotechnology. These advanced materials combine the unique properties of mercury(II) complexes with the remarkable characteristics of nanoscale structures, leading to the development of nanomaterials with enhanced performance and a wide range of potential applications. One of the primary motivations for incorporating Hg(II) complexes into nanomaterials is the potential to significantly enhance their catalytic activity. Nanomaterials inherently have a high surface area-to-volume ratio, which allows for more active sites and, consequently, more efficient catalytic reactions. When Hg(II) complexes are integrated into nanoparticles, nanowires, or thin films, they can provide additional catalytic functionalities, such as specific binding sites or redox-active centers, which further enhance the catalytic processes [Zhang, L., Wang, Y., & Zhang, X. (2019)]. This increased

catalytic activity has promising applications in various fields, including chemical synthesis, environmental remediation, and energy conversion. For example, Hg(II)-incorporated nanocatalysts could be used to break down pollutants in water or air, or to facilitate complex organic reactions with higher efficiency and selectivity. In the realm of sensing technologies, the incorporation of Hg(II) complexes into nanomaterials holds significant promise for improving sensor sensitivity and specificity. Hg(II) complexes are known for their strong interactions with specific analytes, particularly metal ions and organic molecules. When these complexes are embedded in nanomaterials, such as nanoparticles or nanowires, the resulting sensors can detect target analytes at very low concentrations, with greater precision and faster response times compared to conventional sensors. This is particularly valuable in environmental monitoring, where detecting trace levels of pollutants or toxic metals is crucial. Moreover, the unique electronic properties of nanomaterials, when combined with the chemical reactivity of Hg(II) complexes, can lead to the development of sensors that are not only more sensitive but also capable of operating in challenging environments, such as extreme temperatures or pH conditions. Another exciting aspect of nanomaterials incorporating Hg(II) complexes is the potential for novel magnetic or optical behaviors. Nanomaterials often exhibit quantum effects and other size-dependent phenomena that are not present in bulk materials [Yan, Z., Yuen, M. F., Hu, L., Sun, P., & Lee, C. S. (2014)]. When Hg(II) complexes are integrated into these nanostructures, they can influence the material's electronic and magnetic properties, leading to new functionalities. For instance, these materials could be engineered to exhibit unique magnetic behaviors that are useful in data storage technologies, spintronics, or magnetic resonance imaging (MRI) contrast agents. Similarly, the optical properties of Hg(II)-based nanomaterials could be tuned for applications in optoelectronics, photodetectors, or even in developing new types of light-emitting diodes (LEDs) and lasers. The potential applications of nanomaterials incorporating Hg(II) complexes extend into the field of electronics, where these materials can be used to create more efficient and smaller electronic components. Nanomaterials are already at the forefront of advancements in electronics due to their ability to conduct electricity with minimal resistance, among other properties. By integrating Hg(II) complexes into these materials, researchers aim to create electronic devices that are not only more compact but also possess enhanced functionalities, such as improved conductivity, greater stability, and the ability to operate under a wider range of conditions [Wang, L., Schubert, U. S., & Hoeppe, S. (2021)]. These advancements could lead to the next generation of transistors, sensors, and other components that are critical to the development of smaller, faster, and more powerful electronic devices. In catalysis, Hg(II) complex-based nanomaterials offer the potential to revolutionize industrial processes by providing catalysts that are more active, selective, and durable. The unique properties of nanomaterials, such as their large surface area and tunable surface chemistry, combined with the catalytic properties of Hg(II) complexes, can lead to the design of catalysts that operate under milder conditions, reduce the need for harmful chemicals, and increase the efficiency of chemical reactions. This could have a significant impact on industries ranging from pharmaceuticals to petrochemicals, where catalysis plays a central role in production processes. Despite the promising applications, the development of nanomaterials incorporating Hg(II) complexes also presents certain challenges, particularly in terms of safety and environmental impact. Mercury is a toxic element, and its use in any form requires careful consideration of the potential risks to human health and the environment. Researchers are actively exploring ways to minimize these risks, such as by developing methods for safely encapsulating Hg(II) complexes within nanomaterials, or by designing materials that can be easily recovered and recycled after use [Bendicho, C., Lavilla, I., Pena-Pereira, F., la Calle, I. D., & Romero, V. (2021)]

### 3.7 Analytical Chemistry

Hg(II) complexes hold a prominent and well-established position in the field of analytical chemistry, where they are widely employed for the detection and quantification of a broad range of analytes. Their unique chemical and physical properties make them indispensable tools for various analytical techniques, enabling accurate and reliable measurements across diverse applications. One of the key attributes of Hg(II) complexes is their ability to form stable and selective complexes with different analytes, including metal ions, organic molecules, and biomolecules. [Amico, D., Tassone, A., Pirrone, N., Sprovieri, F., & Naccarato, A. (2022)] This selectivity is critical in analytical chemistry, where the accurate identification and quantification of specific substances in complex mixtures is often required. By choosing the appropriate Hg(II) complex, chemists can design assays that are highly specific for the target analyte, minimizing interference from other components in the sample. In spectrophotometric analysis, Hg(II) complexes are used as chromogenic reagents to detect analytes based on their ability to absorb light at specific wavelengths. When Hg(II) complexes interact with an analyte, they often undergo

a change in their electronic structure, leading to the formation of a colored complex. This color change can be measured using UV-Vis spectroscopy, allowing for the precise quantification of the analyte. This technique is widely used in environmental monitoring to detect pollutants, in pharmaceuticals to ensure drug purity, and in food safety to measure the concentration of additives and contaminants. Another important application of Hg(II) complexes in analytical chemistry is in complexometric titrations[Wu, F., Cai, Y., Evans, D., & Dillon, P. (2004)]. In these titrations, Hg(II) complexes serve as titrants for the determination of metal ion concentrations. The formation of stable complexes between Hg(II) and the metal ions of interest allows for the accurate endpoint determination of the titration. This method is particularly valuable in industries such as metallurgy, where the precise quantification of metal ions is essential for maintaining product quality, and in water treatment, where monitoring metal ion levels is crucial for ensuring water safety. Hg(II) complexes are also integral to electrochemical sensors, where they are used to detect various ions and molecules based on their redox properties[Zhang, X., Li, Q., & Chen, M. (2022)]. These sensors rely on the ability of Hg(II) complexes to undergo electron transfer reactions in the presence of specific analytes, resulting in a measurable current or potential change. This electrochemical approach is highly sensitive and can be used for real-time monitoring of analytes in environmental samples, clinical diagnostics, and industrial process control. In addition to their established applications, Hg(II) complexes continue to be a focus of research and innovation in analytical chemistry. Scientists are exploring new ways to harness the unique properties of these complexes to develop more sensitive, selective, and environmentally friendly analytical methods. This ongoing research is expanding the range of analytes that can be detected and quantified using Hg(II) complexes, while also addressing the challenges associated with mercury toxicity[Li, M., Zhang, Y., & Liu, H. (2021)]. The versatility of Hg(II) complexes in analytical chemistry is further enhanced by their compatibility with a wide range of sample types and analytical instruments. Whether used in solution-phase assays, solid-phase extractions, or sensor-based devices, Hg(II) complexes can be adapted to meet the specific needs of different analytical challenges. This flexibility makes them valuable tools in both research and industrial settings, where the ability to accurately measure trace levels of analytes is often critical. However, the use of Hg(II) complexes in analytical chemistry is accompanied by considerations related to mercury's toxicity and environmental impact. Safe handling practices, proper disposal methods, and the development of alternative reagents are important aspects of working with Hg(II) complexes. Advances in green chemistry are driving the search for safer alternatives that can provide the same analytical performance without the associated health and environmental risks.[ Ali, S., Mansha, M., Baig, N., & Khan, S. A. (2022)]

### 3.7 (a) Complexometric Titrations:

Hg(II) complexes play a crucial role in complexometric titrations, a widely used analytical technique for the precise determination of metal ion concentrations. In these titrations, Hg(II) complexes act as titrants, reacting selectively with specific metal ions to form stable, colorless or slightly colored complexes. The endpoint of the titration is typically detected using an appropriate indicator, which changes color when all the metal ions have reacted, signaling the completion of the reaction. The application of Hg(II) complexes in complexometric titrations is particularly valuable in industries where accurate quantification of metal ions is essential. For instance, in metallurgy, the concentration of metal ions such as copper, zinc, nickel, and iron must be precisely controlled to ensure the quality and properties of alloys and metal products[Verma, K., Singh, A., & Sahu, N. (2019)]. By using Hg(II) complexes as titrants, metallurgists can accurately determine the concentration of these ions in ores, alloys, and finished products, facilitating quality control and optimizing production processes. In the water treatment industry, the ability to accurately measure metal ion concentrations is critical for maintaining water quality and ensuring the safety of drinking water supplies. Heavy metals such as lead, cadmium, and mercury pose significant health risks even at low concentrations. Complexometric titrations with Hg(II) complexes allow for the precise determination of these and other metal ions in water samples, enabling water treatment facilities to monitor and adjust treatment processes to meet regulatory standards and protect public health. Chemical manufacturing also relies on complexometric titrations to ensure the purity and consistency of products. In processes where metal ions act as catalysts or are involved in chemical reactions, their concentrations must be tightly controlled to achieve the desired reaction outcomes and product quality. Hg(II) complexes can be used to titrate these metal ions, providing chemists with the data needed to fine-tune reactions and optimize yields[Kumar, P., & Singh, A. (2020)]. This precision is particularly important in the production of high-purity chemicals, pharmaceuticals, and other specialized materials. The use of Hg(II) complexes in complexometric titrations is favored due to their ability to form

strong and selective complexes with a wide range of metal ions. This selectivity ensures that the titration results are accurate and reliable, even in the presence of other competing ions. Additionally, the formation constants of Hg(II) complexes with many metal ions are well-documented, allowing for precise calculations of metal ion concentrations based on the titration data. Furthermore, complexometric titrations with Hg(II) complexes are relatively straightforward to perform, requiring only basic laboratory equipment and reagents. This makes the technique accessible to a wide range of industries and laboratories, from large-scale industrial facilities to small research labs.[ Oram, P. D. (1996)] The method's simplicity and accuracy contribute to its widespread adoption for routine metal ion analysis. However, the use of Hg(II) complexes in complexometric titrations is not without challenges. The toxicity of mercury necessitates careful handling and disposal of the complexes to prevent environmental contamination and protect laboratory personnel. To address these concerns, researchers are exploring alternative complexing agents that can offer similar titration performance without the associated health and environmental risks. Nevertheless, Hg(II) complexes remain a valuable tool in situations where their unique chemical properties provide significant analytical advantages.[ Xu, P., Zhang, Y., & Li, F. (2019)]

### 3.7 (b) Spectrophotometric Methods:

The distinct electronic transitions observed in Hg(II) complexes render them highly suitable for spectrophotometric analysis, a technique that plays a crucial role in various fields such as environmental monitoring, pharmaceuticals, and food safety. The unique optical properties of Hg(II) complexes, which stem from their electronic structure, enable them to engage in specific interactions with analytes, leading to the formation of colored complexes. These colored complexes are detectable and quantifiable using UV-Vis (ultraviolet-visible) spectroscopy, making Hg(II) complexes valuable reagents in analytical chemistry. One of the key features of Hg(II) complexes is their ability to absorb light at specific wavelengths due to electronic transitions between energy levels within the complex[El-Gammal, O. A., Rakha, T. H., Metwally, H. M., & El-Reash, G. A. (2014)]. When Hg(II) complexes interact with an analyte, they often undergo a change in their electronic configuration, leading to a shift in their absorption spectrum. This change is typically manifested as the appearance of a new absorption peak or a shift in the wavelength of an existing peak, resulting in the formation of a colored solution. The intensity of the color, which corresponds to the absorbance measured by the UV-Vis spectrophotometer, is directly related to the concentration of the analyte in the sample. This characteristic makes Hg(II) complexes particularly effective as chromogenic reagents in spectrophotometric analysis. By carefully selecting the appropriate Hg(II) complex, it is possible to design assays that are highly specific for a particular analyte. For instance, Hg(II) complexes can be used to detect metal ions, such as lead or cadmium, in environmental samples[Patel, A., Singh, N., & Gupta, R. (2020)]. When the complex forms a colored compound with the target ion, the resulting absorbance can be measured and used to quantify the concentration of the ion in the sample. This capability is vital for monitoring pollutant levels in water, soil, and air, ensuring compliance with environmental regulations and protecting public health. In the pharmaceutical industry, spectrophotometric analysis using Hg(II) complexes is widely employed for the quality control and validation of drugs. These complexes can form colored derivatives with active pharmaceutical ingredients or impurities, allowing for their precise quantification. This technique is essential for ensuring that drug formulations meet stringent regulatory standards and are safe for consumer use[Selid, P. D., Xu, H., Collins, E. M., Face-Collins, M. S., & Zhao, J. X. (2009)]. The sensitivity of UV-Vis spectroscopy, combined with the specificity provided by Hg(II) complexes, enables the detection of even trace amounts of substances, making it a powerful tool for pharmaceutical analysis. Similarly, in the food industry, spectrophotometric analysis using Hg(II) complexes is utilized to detect and quantify various components in food products, such as additives, contaminants, or nutritional elements. For example, Hg(II) complexes can be used to measure the concentration of trace metals in food, ensuring that products are safe for consumption and meet food safety standards. The ability to perform rapid, accurate, and non-destructive analysis makes UV-Vis spectroscopy a preferred method in quality control laboratories. Furthermore, the versatility of spectrophotometric analysis extends to its application in complex matrices, such as biological samples or industrial waste[Desai, A., Mehta, R., & Patel, S. (2020)]. The robustness of Hg(II) complexes allows for reliable detection even in the presence of interfering substances, which is often a challenge in analytical chemistry. By optimizing the experimental conditions, such as pH and solvent composition, analysts can enhance the selectivity and sensitivity of the method, making it suitable for a wide range of applications. In addition to their practical applications, the use of Hg(II) complexes in spectrophotometric analysis also contributes to the advancement of analytical methodologies. Ongoing research into the development of new Hg(II) complexes with tailored optical properties is expanding the

scope of this technique, enabling the detection of a broader range of analytes and improving the precision and accuracy of measurements. However, it is important to acknowledge the environmental and safety concerns associated with the use of mercury-containing compounds[Escandar, G. M., & Olivieri, A. C. (2022)]. The disposal of Hg(II) complexes after use must be managed carefully to prevent mercury pollution. Advances in green chemistry are driving the development of alternative, less toxic complexes that can provide similar analytical benefits without the associated risks.[ Zhang, Y., & Liu, X. (2022)]

### 3.7 (c) Electrochemical Sensors:

Hg(II) complexes have found important applications in the development of electrochemical sensors, which are powerful tools for detecting a wide range of ions and molecules with high sensitivity and specificity. These sensors capitalize on the unique redox properties of Hg(II) complexes, which enable them to undergo electron transfer reactions when exposed to particular analytes. The result of these reactions is a measurable change in current or potential, which serves as the basis for detecting and quantifying the target substance. One of the key advantages of using Hg(II) complexes in electrochemical sensors is their ability to participate in reversible redox processes[Xie, X., & Li, H. (2023)]. Mercury in its Hg(II) state can accept and donate electrons, making it highly effective in mediating electron transfer between the sensor electrode and the analyte. This redox activity is central to the sensor's function, as it directly influences the sensor's output signal, whether that be a change in current (amperometry), potential (potentiometry), or impedance (impedimetry). In environmental monitoring, electrochemical sensors incorporating Hg(II) complexes are particularly valuable for detecting trace levels of pollutants and heavy metals in water, soil, and air. These sensors can be used to monitor the presence of harmful substances such as lead, cadmium, and arsenic, which are of great concern due to their toxic effects on both ecosystems and human health. The high sensitivity of Hg(II)-based sensors allows for the detection of these pollutants at very low concentrations, making them indispensable tools for ensuring environmental safety and compliance with regulatory standards[Zhang, H., & Sun, C. (2022)]. In the realm of clinical diagnostics, Hg(II) complex-based electrochemical sensors offer significant potential for the detection of biomolecules and ions that are critical indicators of health and disease. For example, these sensors can be designed to detect glucose, cholesterol, or metal ions such as calcium and potassium in blood samples, providing rapid and accurate measurements that are essential for patient care. The ability of these sensors to deliver real-time results with minimal sample preparation makes them particularly attractive for point-of-care testing, where quick decision-making is often required. Industrial process control is another area where Hg(II) complex-based electrochemical sensors play a vital role. These sensors can be integrated into manufacturing systems to monitor the concentration of specific ions or chemicals, ensuring that processes remain within optimal parameters. This is crucial for maintaining product quality, enhancing efficiency, and preventing contamination or hazardous conditions[Wang, J., & Li, J. (2020)]. For example, in the pharmaceutical industry, such sensors can be used to monitor the purity of drug formulations or to control the concentration of active ingredients during production. The versatility of Hg(II) complex-based electrochemical sensors is further enhanced by their ability to be tailored for specific applications. By modifying the chemical structure of the Hg(II) complex or the sensor's electrode material, researchers can fine-tune the sensor's selectivity, sensitivity, and stability. This adaptability allows for the development of highly specialized sensors designed to detect particular analytes under specific conditions, expanding their applicability across various fields. However, it is important to consider the potential environmental and health risks associated with the use of mercury in these sensors. While Hg(II) complexes offer excellent performance characteristics, the inherent toxicity of mercury necessitates careful handling and disposal of these sensors to prevent mercury contamination. Advances in sensor design are increasingly focused on minimizing the amount of mercury used or developing alternative materials that can provide similar electrochemical properties without the associated risks.[ Gao, X., & Zhang, Y. (2022)]

### 3.8 Toxicology and Environmental Health

While Hg(II) complexes offer a range of beneficial applications, particularly in fields such as chemistry, medicine, and industry, their inherent toxicity presents significant challenges that cannot be ignored. The toxicological impact of these complexes is a critical area of study, as it plays a pivotal role in ensuring their safe use and effective environmental management. Mercury, particularly in its Hg(II) form, is highly toxic to living organisms. This toxicity arises from mercury's strong affinity for thiol groups in proteins and enzymes, which leads to the disruption of essential biological processes. When Hg(II) complexes enter biological systems, they can bind to and alter the function of key proteins and

enzymes, leading to cellular damage, oxidative stress, and a host of other toxic effects[Cecilia, C., & Martin, M. (2022)]. These disruptions can have severe consequences for human health, including neurological damage, kidney dysfunction, and an increased risk of chronic diseases. The toxicological effects of Hg(II) complexes extend beyond direct human health impacts. These complexes can also cause significant harm to wildlife and ecosystems. Mercury's ability to bioaccumulate and biomagnify in the food chain means that even low environmental concentrations can lead to high levels of mercury in top predators, including fish, birds, and mammals. This bioaccumulation can lead to reproductive failures, behavioral changes, and population declines in affected species, disrupting entire ecosystems. Understanding the toxicological impact of Hg(II) complexes is essential for developing guidelines and regulations that minimize the risks associated with their use. This includes setting safe exposure limits, developing strategies for the safe disposal and management of mercury-containing wastes, and monitoring environmental mercury levels to prevent contamination[Counter, S. A., & Buchanan, L. H. (2004)]. Furthermore, toxicological research can inform the development of safer alternatives to Hg(II) complexes, reducing reliance on mercury in various applications. In addition to regulatory measures, environmental health practices must consider the long-term impacts of Hg(II) complexes. Given mercury's persistence in the environment, it is crucial to understand how these complexes interact with other pollutants, how they move through different environmental compartments, and how they degrade over time. This knowledge is vital for assessing the potential for long-term contamination and for developing remediation strategies to mitigate the impact of mercury pollution. The intersection of toxicology and environmental health is particularly important when considering vulnerable populations, such as children, pregnant women, and communities living near industrial sites or contaminated water bodies. These groups may be at higher risk of mercury exposure and its associated health effects. Understanding the toxicological impact of Hg(II) complexes in these contexts is crucial for developing targeted public health interventions and for ensuring that environmental policies protect the most vulnerable.[ Mutter, J., Naumann, J., & Guethlin, C. (2007)]

### 3.8 (a) Toxicological Studies:

Research into the toxicological effects of Hg(II) complexes is crucial for evaluating their safety in a wide range of applications, including industrial, pharmaceutical, and environmental uses. These studies delve deeply into the mechanisms by which Hg(II) complexes interact with biological systems, shedding light on the potential risks they pose to human health and the environment. One of the key areas of focus in toxicological research is understanding how Hg(II) complexes bind to proteins and enzymes within the body. Mercury has a high affinity for thiol (-SH) groups, which are commonly found in cysteine residues in proteins. This strong binding can lead to the inactivation of critical enzymes and proteins, disrupting essential cellular functions. For example, mercury can inhibit the activity of enzymes involved in antioxidant defense, leading to an imbalance in reactive oxygen species (ROS) and contributing to oxidative stress[Schaefer, K. C., & Mirochnitchenko, O. (2023)]. Oxidative stress is a major pathway through which Hg(II) complexes exert their toxic effects. The accumulation of ROS can damage cellular components such as lipids, proteins, and DNA, leading to a cascade of harmful effects. This damage can result in cell death, tissue injury, and the onset of various diseases, including neurodegenerative disorders and cancers. The brain is particularly vulnerable to mercury-induced oxidative stress, as mercury can cross the blood-brain barrier and accumulate in neural tissues, leading to neurological impairments. In addition to oxidative stress, Hg(II) complexes can disrupt other cellular processes, such as signal transduction, membrane integrity, and energy production. These disruptions can lead to a wide range of toxic effects, depending on the concentration of mercury, the duration of exposure, and the specific biological system affected. For instance, mercury's ability to interfere with mitochondrial function can lead to reduced ATP production, energy deficits, and ultimately, cell death. Understanding the toxicological profile of Hg(II) complexes also involves studying their biodistribution and excretion patterns. Research has shown that mercury can accumulate in various organs, including the kidneys, liver, and brain, leading to organ-specific toxicity[Zhao, M., Li, Y., & Wang, Z. (2022)]. Additionally, the body's ability to excrete mercury is limited, particularly in its inorganic forms, which can result in prolonged exposure and increased risk of chronic health effects. Given the significant health risks associated with Hg(II) complexes, ongoing toxicological research is vital for developing strategies to mitigate their toxic effects. This includes designing safer mercury-containing compounds with reduced toxicity, developing effective chelation therapies to remove mercury from the body, and implementing environmental regulations to limit mercury exposure. Furthermore, understanding the molecular mechanisms underlying mercury toxicity can inform the development of biomarkers for early detection

of mercury exposure and toxicity, enabling more effective prevention and treatment strategies.[ Wu, Y. S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., ... & Yap, P. S. (2024)]

### 3.8 (b) Environmental Impact:

The environmental impact of Hg(II) complexes is a significant concern due to their potential for long-term persistence and bioaccumulation within ecosystems. Mercury (Hg), especially in its mercuric (Hg(II)) form, poses serious risks because of its ability to remain in the environment for extended periods without degrading. This persistence can lead to the gradual accumulation of mercury in various environmental compartments, including soil, water, and sediments. The behavior of Hg(II) complexes in the environment is influenced by several factors, including their chemical stability, interactions with other pollutants, and environmental conditions such as pH and temperature. Hg(II) complexes can undergo complexation with organic and inorganic ligands, affecting their mobility and reactivity[Gonzalez-Raymat, H., Liu, G., Liriano, C., Li, Y., Yin, Y., Shi, J., ... & Cai, Y. (2017)]. This can impact how readily they move through soil and water systems, potentially leading to widespread contamination. Moreover, Hg(II) complexes can interact with other environmental pollutants, leading to synergistic or antagonistic effects that complicate the assessment of their impact. For instance, mercury can react with sulfur-containing compounds to form methylmercury, a highly toxic form of mercury that bioaccumulates in the food chain. The bioaccumulation of mercury in aquatic organisms is particularly concerning. Mercury can enter the food chain through the consumption of contaminated water and sediment, accumulating in fish and other wildlife [Zhu, S., Zhang, Z., & Žagar, D. (2018)]. This bioaccumulation can have detrimental effects on these organisms, leading to health issues such as neurological damage and reproductive failures. Additionally, when these organisms are consumed by humans, the mercury can pose serious health risks, including cognitive impairments and other systemic effects. Understanding the full scope of the environmental impact of Hg(II) complexes requires a comprehensive examination of their degradation pathways, mobility, and interactions with other pollutants. This includes studying how these complexes break down over time, how they move through different environmental media, and how their presence affects the overall health of ecosystems. Such knowledge is crucial for developing effective strategies to mitigate the environmental and health risks associated with mercury pollution.[ Rice, K. M., Walker Jr, E. M., Wu, M., Gillette, C., & Blough, E. R. (2014)]

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